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Panorama of the Brazilian Plastic Packaging Sector and Global Technological Trends: the Role of Developed and Developing Countries in Achieving Environmental Sustainability and a Better Quality of Life Worldwide

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Abstract: The plastic packaging industry has changed its production processes. Population growth, allied to society's new consumption pattern and uncontrolled urbanization, increased solid waste generation, is the main cause of environmental pollution and degradation. Some specific data indicate that the volume of used packaging will continue to grow over the next few years. In this study, we present an overview of the Brazilian plastic packaging sector, the current scenario of urban solid waste with a focus on plastic waste, and global trends in the plastic packaging market in terms of technologies that minimize its impact on the environment. Furthermore, we also highlight the case of the USA. This developed country published most patents on monolayer, multilayer, and nanotechnology packaging from 2010 to 2021. Still, it showed how investing in technologies for the packaging sector was not enough for the population's welfare due to the high social inequality in the country. We conclude that solutions to issues regarding the planet's social welfare and environmental sustainability include the adoption of circular economy models, investment in clean technologies, accountability of rich countries regarding greenhouse gas emissions in their territories, and, in the case of developing countries, public policies that encourage effective actions.

Keywords: circular economy; plastic packaging; recycling; solid waste; social responsibility; sustainability.

1. Introduction

Plastic usage has increased approximately 24 times in the last 54 years, growing from 15 million tonnes in 1964 to approximately 360 million tonnes in 2018. At this rate, this amount may double in the next 20 years. This volume has produced 250 million tonnes of plastic waste worldwide, causing a negative impact on the environment since both plastic production and the incineration of its waste emit into the atmosphere approximately 400 million tonnes of CO_2 per year [1,2]. Given this scenario, many efforts have been made to fight plastic pollution. Usually, they focus on improving waste management and banishing or reducing plastic usage. However, studies show that none of these strategies work isolated, which means that a more comprehensive approach – one that values recycling, use of raw materials obtained from renewable sources, and employment of circular economy models – is needed to reduce waste volume while ensuring stronger economic, social, and climate benefits [1-6].

In this sense, circular economy (CE) has attracted global attention, mainly as an alternative to the linear economy of extraction, transformation, and disposal, offering opportunities to reduce dependence on finite materials and non-renewable energy sources and generating innovation actions, value creation, and market differentiation [1,2]. One of the main challenges of the packaging market is the recycling of materials whose composition has different polymers (multilayer packaging) and technologies (nanotechnology). Thus, studies that provide a better understanding of the impact of innovations on the viability of CE models contribute positively to the value capture in the chain and economic strength and better environmental results [1-8].

This study addressed different aspects of the Brazilian plastic packaging sector, including information on plastic waste and technology trends that minimize environmental impacts.

2. Literature review

2.1. Overview of the plastics and plastic packaging sectors in Brazil and worldwide.

As the population grows, transformations in cities and urban life intensify, especially from the economic point of view, as shown by the increase in industrialization, trade activities, and consumption. Consequently, it is necessary to meet the demands of product transportation (from the producing region to the place of consumption), protection, and conservation. This context promoted the development of processing and preservation techniques, contributing to the emergence of packaging, whose primary function is to preserve the products until their use or consumption [9-11]. Packaging enables urban life because it promotes the supply and consumption of the population. In the consumer goods market, there is a time and space interval between the producer and the final user; since many factors can cause unwanted changes to a product in this process, the packaging must protect it against external factors and preserve its intrinsic properties. Thus, packaging plays an important role as a tool to contain, preserve, protect, and enable products' transport and storage. Data from the Brazilian Packaging Association (ABRE) show that Brazil reached a gross value of R$92.9 billion in packaging's physical production in 2020, a growth of 22.3% over the previous year [10-12].

Consumers evaluate the packaging material by criteria such as participation in the circular economy, natural appearance, and design in European countries. The environmental impact of paper/cardboard and metal is rated by consumers according to these materials' scientific measures, whereas plastic is underestimated, and glass and biodegradable plastic are highly overestimated [13,14].

Figure 1 shows that plastic represents the largest share of Brazilian packaging production, accounting for 40% of the total. Regarding packaging's physical production by class, plastic and paper/corrugated cardboard packaging stood out with production increases of 6.8% and 1.0%, respectively. On the other hand, there is a decrease in the physical production of wood, glass, and metal packaging. In Brazil, plastic bags have been changing in recent years. Every hour, approximately 1.5 million plastic bags are distributed by supermarkets in the country, corresponding to more than 13 billion bags per year and greatly impacting the environment. Nonetheless, retail chains are already changing their approach to consumers by offering biodegradable bags or even encouraging the use of cloth bags or cardboard boxes in order to contribute to sustainability [12].

In 2020, direct exports of the packaging sector had a turnover of $520.4 million, which represents a reduction of 4.6% from the previous year. Metal packaging accounts for 37.6% of total exports, followed by plastic packaging, with 31.8%. Paper, paperboard, and cardboard packaging are in third place, accounting for 23.2% of total exports, followed by glass (4.1%) and wood (3.3%). As for imports, $626.7 million were handled in 2020, representing a reduction of 0.8% in relation to the previous year. The plastic packaging sector corresponds to 50.8% of total imports, followed by metal (21.2%), glass (20.4%), paper/cardboard (7.5%), and wood (0.1%) packaging [12].

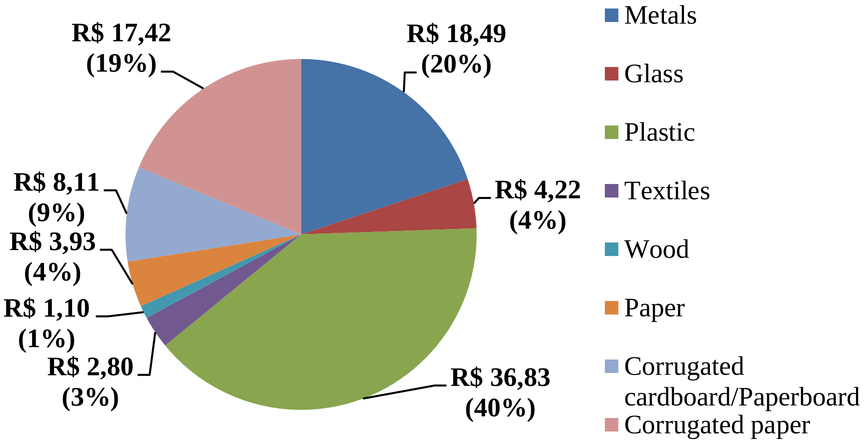

Figure 1. Brazilian packaging production by material in billions of reais (R$) (elaborated by the authors, based on the literature data) [12].

Plastic has many properties that correspond to the new demands of society. For instance, its durability allows a relevant degree of reuse and recovery, its lightness contributes to lower vehicles' fuel consumption, and its safety and asepsis benefit medical-hospital applications [7,8,13]. Plastic can be subdivided into two categories: conventional and bioplastics. Conventional plastics are obtained from petroleum products and can be recycled and transformed into other products. On the other hand, although they have similar properties, bioplastics can be produced from different raw materials and renewable sources such as soy, rice starch, corn, and sugar cane [7,8,13].

Although they have a renewable origin, bioplastics may or may not be biodegradable. When submitted to a composting process under specific conditions of heat, humidity, light, oxygen, and organic nutrients, the biodegradable plastic is decomposed by microorganisms in up to 180 days, becoming an alternative to feed biogas-based thermoelectric biodigesters. Nevertheless, it is worth noting that this material only has a minimized environmental impact when properly composted since the lack of criteria at this stage generates methane gas, which is 28 times more polluting than CO_2 and, therefore, aggravates the already existing environmental challenges. Thus, biodegradable plastics require the implementation of composting plants so that biodegradation can occur without harming the environment [7,13-15].

According to the Brazilian Plastic Industry Association (ABIPLAST, 2020), only 55% of the industry's total capacity can produce biodegradable plastics (Figure 2). Furthermore, 45% of the global bioplastic production capacity is concentrated in Asia and 12% in South America. Brazil, for its part, holds 9.5% of the world's capacity and has produced approximately 200,000 tonnes of this material in 2019 [6].

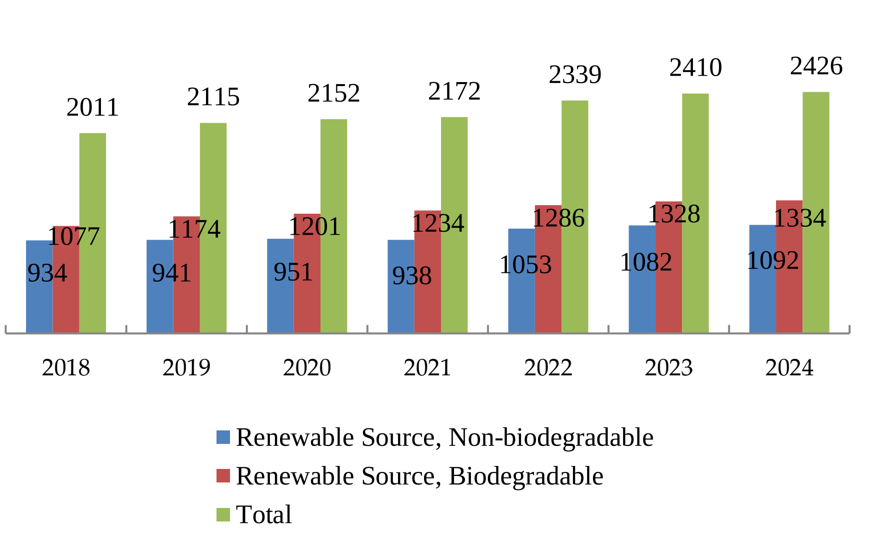

Figure 2. Global bioplastic production capacity in thousand tonnes from 2018 to 2024 and discrimination between plastics obtained from non-biodegradable and biodegradable renewable sources (elaborated by the authors, based on the literature data) [12,6].

However, despite its growth, the bioplastics sector still faces challenges regarding the market insertion of its products. Environmental issues, production costs, and favorable and unfavorable policies, among others, show the need for more research related to the possibilities of bioplastics' market insertion and how to classify them as a potential product for companies' investments. In Brazil, Braskem is the largest producer of plastic obtained from renewable sources and is the only company globally that produces green polyethylene using ethylene obtained from the dehydration of sugarcane ethanol, with an annual production capacity of 200,000 tonnes. However, other non-biodegradable biopolymers such as polypropylene (PP) and ethylene-vinyl acetate (EVA) can also be obtained from green ethylene and have the potential for industrial production and commercialization [6,12-17].

The significant presence of plastic in the modern economy results from the combination of its functional properties and low cost. Nevertheless, the same characteristics that make these materials useful – especially durability, lightness, and low cost – contribute to disposal and solid waste generation issues. According to Figure 3, the apparent consumption of processed plastics amounted to R$ 106 billion, which exceeded the production of the same period (R$ 91.7 billion), indicating that the sector has good profitability even in times of low economic activity [7].

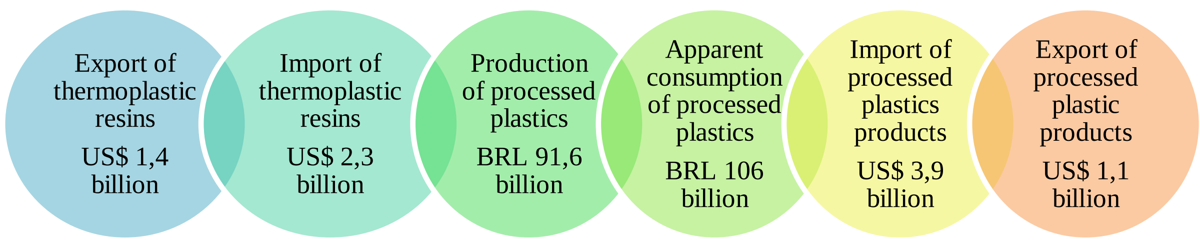

Figure 3. Brazilian overview of the transformed plastic industry in the year 2020 (graph elaborated by the authors, based on the literature) (elaborated by the authors, based on the literature data) [7].

Figure 4 shows the main plastic resins consumed in Brazil in 2020, with emphasis on polypropylene (PP – 20.1%), high-density polyethylene (HDPE – 13.2%), poly (vinyl chloride) (PVC – 13.1%), linear low-density polyethylene (LDPE – 11.8%), and recycled plastics (10.6%), materials used mainly by the packaging sector (ABIPLAST, 2020). The resins with consumption lower than 11% in Brazil are low-density polyethylene (LDPE – 8.0%), engineering plastics (9,9%), which comprises polyamide (PA), polyurethane (PU), acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), polybutylene terephthalate (PBT), polymethylene oxide (PMO), polyphenylene oxide (PPO), polysulfone (PSU), and polytetrafluoroethylene (PTFE – 6.9%). Other resins with low consumption include polyethylene terephthalate (PET – 6.2%), polystyrene (PS – 4.8%), ethylene-vinyl acetate (EVA – 1.6%), and expanded polystyrene (EPS – 0.9%).

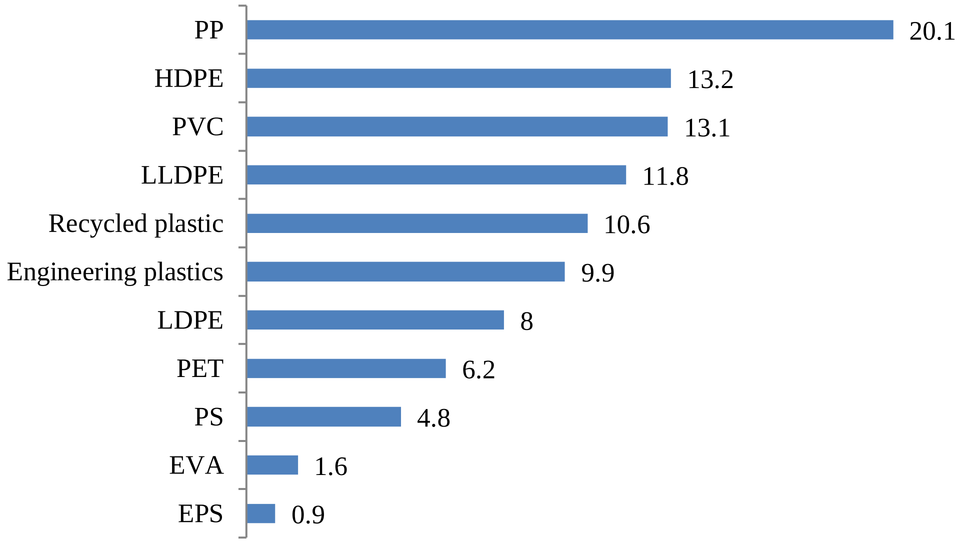

Figure 4. Main plastic resins consumed in the Brazilian market in 2020 (%) (elaborated by the authors, based on the literature data) [7].

Data from the EUROPEAN BIOPLASTIC (2019) show that the largest application of plastic is for the packaging sector, accounting for 40% of the world's total production. Moreover, according to the institution, the production of plastic and the incineration of its waste generate approximately 400 million tonnes of CO_2 per year. Thus, the use of recycled plastics can contribute to environment preservation, reducing the dependence on fossil raw materials and the consequent emission of CO_2 into the atmosphere. The potential for energy saving, considering the use of all the plastic waste generated worldwide, is equivalent to 3.5 billion barrels of oil per year. Furthermore, carbon credits that can be obtained through polymer recycling, a clean development mechanism, represent another advantage of recycling [6,12,14-17].

One of the conditions for packaging to fulfill its role is the ability to impede the passage of gases (O_2, Nitrogen, and CO_2) and moisture since this is what defines the shelf-life of the product. One of the technological strategies adopted to meet this requirement was the development of multilayer and multi-material packaging, which em-ploy polyethylene (PE), polypropylene (PP), poly (ethylene terephthalate) (PET), biaxially oriented polypropylene (BOPP), polyamide (PA), poly (ethylene vinyl alcohol) (EVOH), among other polymers with structures of the type PE/PP, PET/PE, PET/BOPP/PE and BOPP/PE [6,18,19].

Moreover, it is also worth mentioning the new technologies that provide active or intelligent functionalities to packaging. Active packaging has additive agents that protect and interact with the product and internal environment, responding to effective changes and communicating to the consumer that the product has expired, for example, through a color change. Intelligent packaging, in turn, contains technologies such as indicators of time and temperature, ripeness and freshness, oxygen, ethylene, pathogenic microorganisms and toxins, carbon dioxide, as well as tampering sensors and biosensors for pathogen detection [20-33].

According to the technologies applied, intelligent packaging can be classified into three systems: data carriers (information intended for the supply chain, such as storage, distribution, and traceability); indicators (quality information); and sensors (detection and monitoring of presence, activity, composition, or concentration of certain chemical or physical substances that can alter product quality) [19-24]. Active and intelligent packaging concepts are often associated and, when combined into a single product, are named smart packaging [20-33]. In terms of packaging market participation, products that combine active and intelligent functionalities accounted for 5% of the global packaging production in 2010. In 2017, the global smart packaging market reached $17.5 billion and was expected to reach $32.7 billion by 2025 [34]. Despite being effective in some aspects, these types of packaging present production, use, and, especially, disposal limitations, representing a challenge for reuse and recycling logistics [12]. In order to understand the impact of this scenario on the environment, data regarding municipal solid waste and recycling are addressed below.

2.2. Overview of solid waste and recycling in Brazil and worldwide.

Municipal Solid Waste (MSW) comprises waste from households (domestic waste), including leftover food or unused consumer goods and their respective packaging, and waste from urban cleaning services, such as street sweeping and public spaces cleaning. They are classified into wet waste (organic materials, mainly leftover food) and dry waste (post-consumer packaging materials). One of the best treatments for wet waste is using it to generate energy in biogas thermoelectric units, and Brazil already has some of these companies throughout the country [27-29].

According to the Brazilian Association of Public Cleaning and Special Waste Companies [29], MSW generation in Brazil increased from 67 million to 79 million tonnes per year between 2010 and 2019. Likewise, the per capita waste generation increased from 348 kg per year to 379 kg per year.

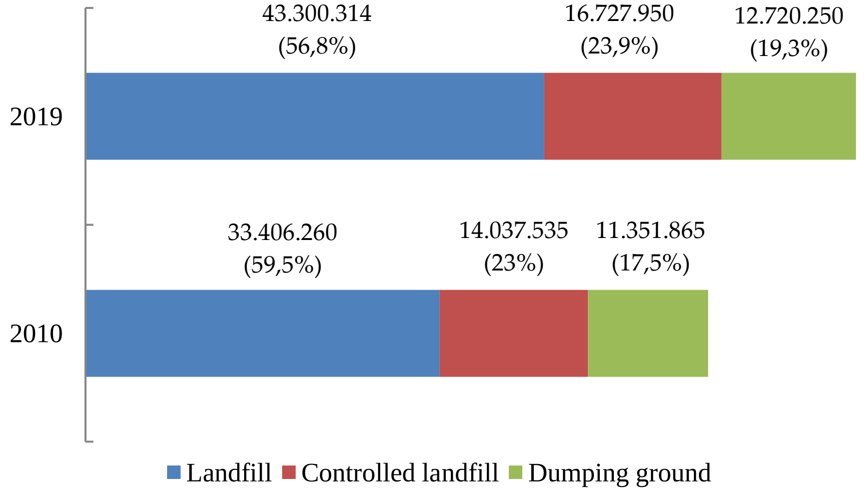

Figure 5. Final disposal of municipal solid waste in Brazil for the years 2010 and 2019 in tonnes per year (elaborated by the authors, based on the literature data) [35-37].

MSW collection has increased in all regions of the country. According to ABRELPE (2020), it went from 59 million tonnes to 72.7 million tonnes in a decade, and collection coverage went from 88% to 92%. Additionally, waste disposal in sanitary landfills is one of the alternatives to the environmentally appropriate final disposal established by the Brazilian National Policy for Solid Waste (PNRS), provided operational standards to avoid damage or risk to public health, safety, and environment are met (BRASIL, Law No. 12305).

In Brazil, most of the MSW collected is disposed of in sanitary landfills. In the last decade, MSW disposal increased from 33 million tonnes to 43 million tonnes per year. Likewise, the amount of waste disposed of in inadequate units (dumps and controlled landfills) has also grown, increasing from 25 million tonnes to approximately 29 million tonnes per year [35-37]. Figure 5 shows that there has been a waste volume reduction in all disposal sites. Information regarding solid waste composition contributes to the planning of its adequate treatment, especially when it comes to the definition of strategies, public policies, and specific processes to ensure environmentally adequate disposal of MSW, as recommended by the PNRS. Thus, an important property to be analyzed is the solid waste gravimetric composition, which represents the physical characteristic of the waste by expressing the percentage of each component in relation to the total weight of the analyzed sample [35-37].

The Brazilian waste gravimetric composition presented in Figure 6 was estimated based on the weighted average of the total MSW generation, which, in turn, used the income range of the municipalities and their respective gravimetric compositions, considering population and MSW generation per capita [35-37].

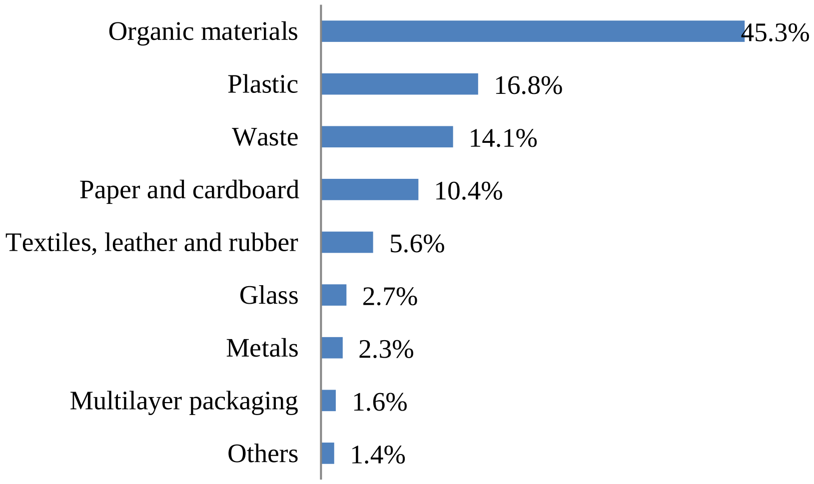

Figure 6. Gravimetric composition of the selective waste collection performed in Brazil for 2019 in % (elaborated by the authors, based on the literature data) [35-37].

According to the data, the organic fraction is the main component of MSW, accounting for 45.3% of it. Dry recyclable waste totals 35% and is composed mainly of plastic (16.8%), paper and cardboard (10.4%), glass (2.7%), metals (2.3%), and multilayer packaging (1.4%). The rejects, in turn, correspond to 14.1% and are mainly composed of sanitary materials. The remaining fractions include textile, leather, and rubber waste (5.6%), and other types of waste (1.4%), consisting of several materials that are, in theory, objects of reverse logistics. Data from ABRELPE (2020) show that in 2019 the waste sector accounted for 4% of the total greenhouse gas (GHG) emissions in Brazil, corresponding to 96 million tonnes of CO_2eq emitted. Considering 2010 as a benchmark, there was an increase of 23% in GHG emissions, equivalent to two-thirds of the amount produced by MSW final disposal activities, including sanitary landfills, controlled landfills, and dumps.

In Brazil, the systems for capturing and using biogas from sanitary landfills are not yet a reality in all units. According to the United Nations Framework Convention on Climate, 49 biogas recovery projects are currently published in the country. It is important to emphasize that the absence of a gas collection system results in the emission of 1,170 kg CO2 eq/tonne, or 47 kg CH_4/tonne (28 times more potent than carbon dioxide). Therefore, the collection of biogas needs to be prioritized since it generates an emission of only 819 kg CO_2 eq/tonne, or 33 kg CH_4/tonne, representing a reduction of 30% [35-37].

According to the Brazilian Business Commitment to Recycling [36] report in the Paris Agreement, approved in 2015 by 195 countries, Brazil committed to reducing greenhouse gases by 37% until 2025 and by 43% until 2030 – values calculated based on this on 2005 indexes. As a result, one of the planned strategies focuses on increasing the share of sustainable bioenergy in the energy matrix by 18% until 2030, which includes the use of biogas from landfills.

According to the UN, a 2ºC increase in global temperature would imply severe consequences to the planet. In this case, it would be necessary to slow warming by 1.5ºC, requiring a 45% cut in GHG emissions within twelve years. In the case of Brazil, better waste management can contribute to a 20% carbon reduction, considering the projections of temperature increase expected for 2020 [36].

Given this scenario, shutting down inadequate disposal areas is a priority, and the transition to sanitary landfills must be followed by emission mitigation measures combined with solid waste valorization projects aligned with the PNRS. In the particular case of packaging, reuse and recycling processes contribute positively to these strategies, which is why knowing the plastic composition of solid waste plays a fundamental role in the progress of these actions [38-42]. According to CEMPRE (2019), the elements that stand out in the gravimetric composition of the plastic fraction of MSW are PET (32%), the result of bottles blown with this material, and what is named "mixed" element (24%), which include packaging composed of more than one type of plastic, making it difficult to separate and reprocess. As stated in the PNRS, some sectors are obliged to structure and implement appropriate collection systems for the following products: pesticides (their waste and packaging); batteries; tires; lubricating oils (their waste and packaging); fluorescent lamps (of sodium and mercury vapor, and mixed light); and electro-electronic products. There are still no specific requirements regarding the selective collection of consumer goods packaging [38-42].

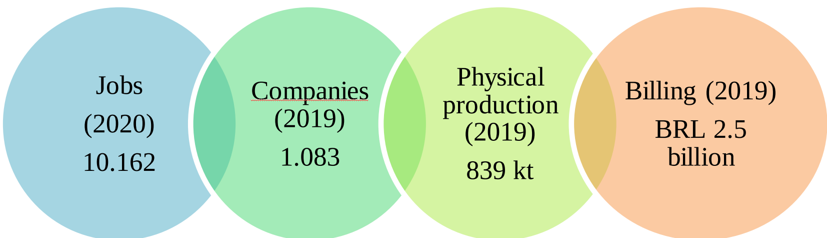

Figure 7. Data from the post-consumer plastics recycling industry in Brazil in 2019-2020 (elaborated by the authors, based on the literature data) [7].

According to ABIPLAST (2021), the volume of post-consumer plastic resins produced in Brazil in 2019 was 839,000 tonnes, indicating a recycling rate of 24%. Also, according to ABIPLAST, the consumption of post-consumer recycled plastic resins is very diverse: the largest consumer markets are personal hygiene and household cleaning, which corresponds to 27% of the total, followed by civil construction (30%), and household appliance (37%).

Recycled plastic is also consumed by the automotive, agricultural, toy, electronics, and footwear industries. Figure 7 shows that the post-consumer plastic resins market has relevant commercial potential.

To ensure its sustainability, recycling requires public policies, tax justice, and legal security for new investments in recycling park innovation and infrastructure. This scenario also includes developing innovative business models and sustainable solutions for the companies' production chains to replicate actions that promote changes in production and consumption patterns. Such an approach results from the demands of a new low-carbon economy to mitigate climate change-related risks. Thus, the development of new technologies that allow the reuse of synthetic materials is fundamental to reaching these objectives [36,43-45].

Since the Industrial Revolution, the global economy has taken a steep growth path, driven mainly by technological advances, so that high labor costs and availability of materials, combined with how affordable they are, have encouraged the industry to adopt a linear approach to production, in which goods are produced from virgin raw materials, sold, used and discarded as waste [1,3]. Plastic production relies mainly on fossil raw materials, with significant carbon impact, which becomes even greater as its consumption increases. About 90% of the plastics produced come from virgin fossil raw materials, accounting for 6% of the world's oil consumption. Suppose the forecast for growth in plastic use continues as predicted. In that case, the plastics sector will account for 20% of the total consumption of fossil raw materials, which will be equivalent to 15% of the world's annual carbon budget by 2050 (the budget necessary to meet the international goal of keeping global warming below 2°C). Therefore, addressing the greenhouse gas impact of plastic production and its post-use treatment is crucial [1,3].

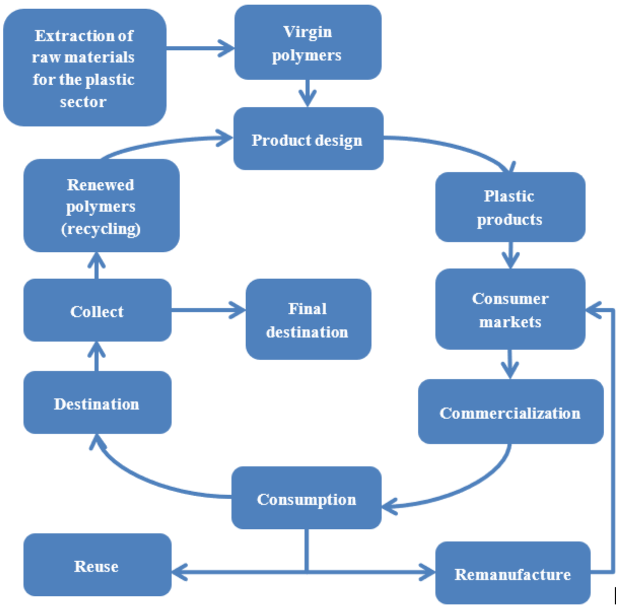

Figure 8. Stages of the circular model of plastics' production and consumption (elaborated by the authors, based on the literature data) [7-8].

With the volatility in raw material prices and the pressure on resource use seen in recent years, many business managers and governments have reassessed their use of materials and energy. They learned that working for efficiency alone, aiming to reduce resource consumption and fossil fuels per unit of economic output, does not change the finite nature of material reserves. As a result, a new production model called Circular Economy Model emerged

[1,46,47]. There are multiple definitions for the circular economy. GENG and DOBERSTEIN (2008) consider CE a flow of materials in a closed loop that spreads across the entire economic system. VELIS (2015), on the other hand, defines it as a model that establishes the use of resources that temporarily become waste and part of the production cycle in a way that prevents them from becoming environmental waste [48,49]. In the traditional manufacturing model (linear model), products are made according to the "extract - produce - discard" logic. In the circular model (Figure 8), disposal is not the end of a product's life. After being discarded, it returns to the production process, becoming raw material for new applications and thus reducing the amount of generated waste [2-6].

CE promotes a comprehensive view on developing alternative solutions throughout the entire life cycle of processes, establishing interactions between processes, the environment, and the economy. As for plastics, the challenge involves the entire waste management structure addressing basic sanitation, selective collection, conscious consumption, and environmentally adequate disposal [2-6]. The transition from linear to circular economy has already occurred, especially with the new business models and the current technological trends, such as digitalization, product as a service, sharing, and connectivity, promoting greater access to information and integration of value chains and new partnerships. Moreover, the CE model is based on innovation, focusing on the system's effectiveness in generating positive impacts for all parties involved [2-6]. In the new plastics economy, which is based on CE, the material needs to be reintroduced into the economy as a technical or biological nutrient after it becomes waste. This model aims to deliver better economic and environmental outcomes by creating a post-use economy of plastics, drastically reducing their presence in natural systems (particularly in the oceans) and other negative externalities, while also promoting a decoupling from fossil raw materials [2-6,50].

Another important factor for global GHG control is achieving lower social inequality, indicated by a lower Gini coefficient (GC) and a higher human development index (HDI), which considers education, income per capita, and longevity. Norway has the highest HDI (0.954) and lowest Gini coefficient (27.5) globally, while the USA's and Brazil's rates are 0.920 and 41.5, and 0.761 and 53.3, respectively. Therefore, HDI alone is not enough for a country to be developed; the nation must also have less social inequality, and a lower Gini index. Countries like Switzerland and Germany, which present HDI of 0.946 and 0.939 respectively, pollute much less because they also present low social inequality (GC of 32.3 and 31.7 respectively) [51,52].

3. Materials and Methods

To establish a panorama of technological trends for the plastic packaging segment, a survey of patent filings worldwide in the last 10 years was conducted. The study's objective was to map innovations related to materials (polymers), structures (design), and additives used in packaging to provide gains in sustainability. The survey was conducted using the WIPO (World International Property Organization) PatentScope database, adopting a publication interval from 2010 to 2021 [53]. To better understand and detail the information found in the patent documents and cover the different categories in which the technologies associated with packaging can be classified, nine individual search strategies were adopted, as illustrated by the flowchart in Figure 9. The results were arranged in three blocks. In the first one, published patents involving monolayer structures were evaluated considering the variables resin type (PP, PE, PET, EVOH, PS, PVC, PA, and BOPP) and functionality. As a result of the search strategy, by combining the terms from the titles, abstracts, and assertions, 1588 patent documents related to monolayer packaging were found. At the end of the qualitative analysis, 65 documents were selected, from which 12 non-duplicate patents of interest were obtained.

In the second block, the published patents related to packages with multilayer structures were analyzed considering the same variables of the first block. Using the same search strategy, 3906 patent documents related to multilayer packaging were found. At the end of the qualitative analysis, 270 documents were selected, from which a total of 86 non-duplicate patents of interest were obtained.

The third and last one was the block of nanotechnological plastic packaging, containing different types of fillers (nanocellulose, monocrystal, nanofiber, nanoparticle, and nanosilver). Using the same search strategy, 670 patent documents related to the subject were found. At the end of the qualitative analysis, 19 non-duplicate documents were selected.

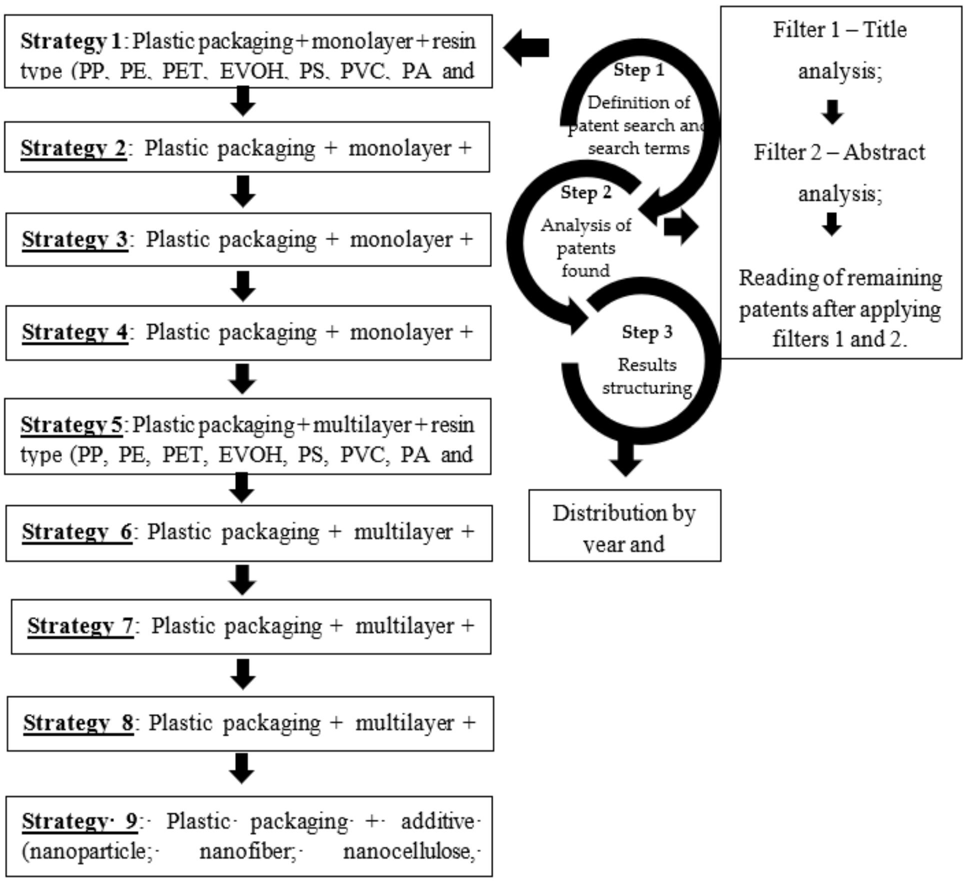

Figure 9. Flowchart detailing the steps of the patent search process (elaborated by the authors).

4. Results and Discussion

In total, 28 searches were conducted, and the data were exported to an Excel spreadsheet for refinement. 6164 patent documents related to the packaging were found. After analyzing the documents collected, we observed a very high concentration of patents filed for plastic packaging based on polyethylene (PE), polypropylene (PP), and poly (ethylene terephthalate) (PET). In their case, the main technological aspects identified were: the use of recycled films made from polyethylene or polyamide in the packaging production; the development of biodegradable films by incorporating resins made from polylactic acid (PLA) or bio-based plastics; and methodologies for the recovery and recycling of plastics. Furthermore, the documents reveal a concern with the conservation and protection of the products since polymers and structures with higher filing rates grant protection to packaging mainly through properties such as a high anti-mold and antibacterial barrier to gases and moisture.

Figure 10 shows the worldwide distribution of patents related to monolayer structures per year. The United States (US) stands out with 58% of the patents published in the analyzed period.

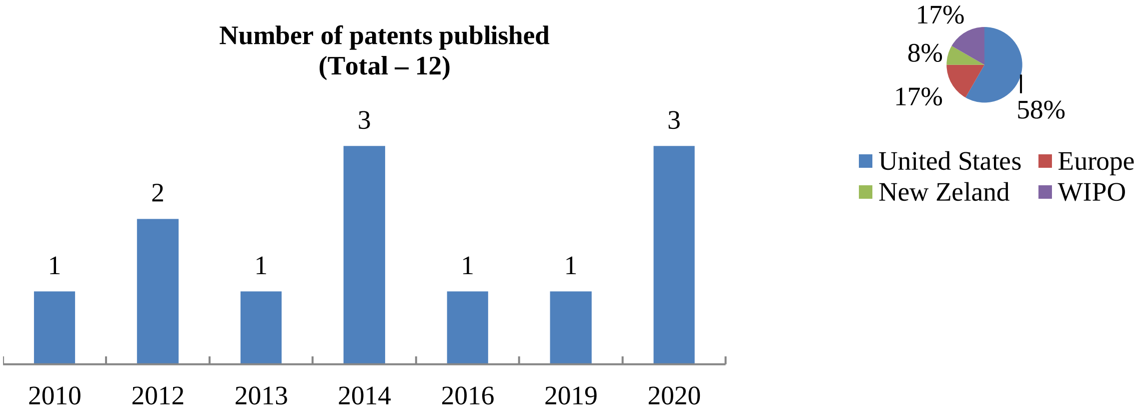

Figure 10. Worldwide distribution of published patents related to monolayer structures per year (elaborated by the authors).

We also observed a very high concentration of patents filed for plastic packaging made from polyethylene (PE), polypropylene (PP), poly (ethylene terephthalate) (PET), poly (ethylene vinyl alcohol) (EVOH), and polyamide (PA). In their case, the main technological aspects identified were: a method for segregation of post-consumer plastic packaging; packaging containing recycled material or obtained from a renewable source; labels compatible with the recycling process; recycling of polyethylene obtained from household waste; use of biodegradable films made from polypropylene and poly (ethylene vinyl alcohol) (PP-EVOH) containing bioactive and hydrophilicity properties; use of recyclable films, employing thermoforming processes; use of recyclable films with a high barrier; and use of films with moisture barrier and biodegradability properties.

Figure 11 shows the worldwide distribution of patents related to multilayer structures per year, with 41% of the patents filed by the World International Patent Office (WIPO) and 27% by the United States (US).

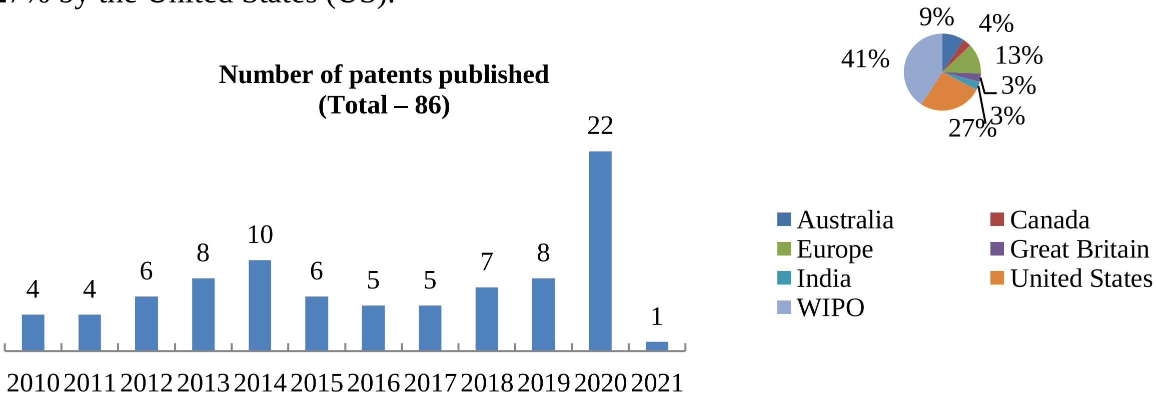

Figure 11. Worldwide distribution of published patents related to multilayer structures per year (elaborated by the authors).

Furthermore, a very high concentration of patents filed for plastic packaging containing nanoparticles was likewise observed. In these patents, the main technological aspects identified were: formulations and methods of manufacturing composites using recycled paper and plastic packaging and/or textile fibers and protein-based bioplastics (preparation methods and uses);

emulsion of biopolymers for the production of active packaging (manufacturing method and uses); use of recyclable or compostable films as a substitute for aluminum-laminated structures; production of pH-sensitive biodegradable polymers; processes for recycling plastics; production of high-barrier plastic packaging from renewable sources; methods for the decomposition of contaminated plastic waste and plastic waste decomposition products (their analysis and separation).

Figure 12 shows the worldwide distribution of patents related to the subject per year, with 48% of the patents filed by the United States (US), and 37% by the World International Patent Office (WIPO).

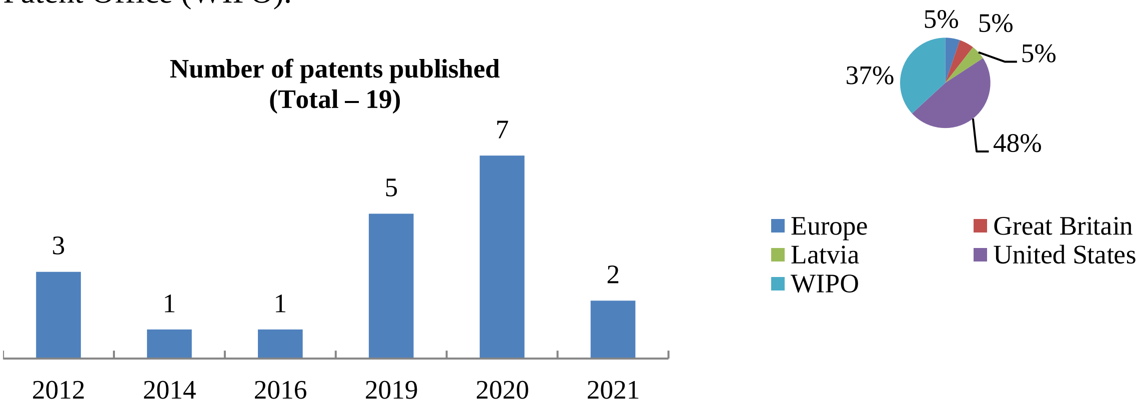

Figure 12. Worldwide distribution of published patents related to nanotechnology per year (elaborated by the authors).

European countries, Japan, and others considered developed by the HDI (Human Development Index) do not stand out as major investors researching and developing sustainable plastic packaging. For some of these countries, the current challenge is to measure the results of the sustainable strategies that have already been implemented. With the creation of the United Nations (UN) Sustainable Development Goals (SDGs), many governments have committed to sustainability and the environmental cause. In this scenario, developing countries have to face a series of challenges to achieve their global sustainable development goals. For developing countries with pronounced social inequality, such as Brazil, the main challenge lies in the actions related to technology transfer since they tend to use technologies from developed countries [54-55].

5. Conclusions

Although the environmental scenario stands as a challenging one, numerous actions are underway to minimize the impact of human activity on the environment. The data presented in this study show that many problems are already mapped. The pace of implementing actions to achieve the proposed improvements will result in less or more environmental degradation. In the period between 2010 and 2021, the USA stood out in the publication of patents for monolayer packaging (58% of the total number of patents), multilayer packaging (27%), and packaging involving nanotechnology (37%). Despite being a developed country that contributes greatly to research and development in the packaging sector, it suffers from great social inequality. In Brazil, a country with enormous social inequality, the disposal of plastic packaging contributes significantly to environmental pollution.

In addition to the economic responsibility of developed countries to help the developing ones achieve better HDI's and, therefore, a better quality of life, it is also their responsibility to promote public policies that reduce social inequality in their territories. Investments in clean technologies for the production of consumer goods, incentives to reuse and recycle packaging, and use of bioenergies (biogas from landfills, the solar, wind, and hydroelectric energy), as well as the adoption of CE, lead to the reduction of GHG emissions, with consequent environmental and social benefits for the planet.

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Conflicts of Interest

The funders had no role in the study's design, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

References

1. Ellen Macarthur Foundation, **2016**. The New Plastics Economy: Rethinking the future of plastics. Available online: https://www.ellenmacarthurfoundation.org/publications (accessed 01 September 2021).
2. Kirchherr, J., Reike, D. and Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221-232, https://doi.org/10.1016/j.resconrec.2017.09.005.
3. Ellen Macarthur Foundation, **2015**. Rumo à Economia Circular: O Racional de Negócio para Acelerar a Transição. Available online: https://www.ellenmacarthurfoundation.org/publications (accessed 01 September 2021).
4. Morseletto, P. Targets for a circular economy. *Resour. Conserv. Recycl*. **2020**, *153*, 105553, https://doi.org/10.1016/j.resconrec.2019.104553.
5. Foster, G. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resour. Conserv. Recycl*. **2020**, *152*, 104507, https://doi.org/10.1016/j.resconrec.2019.104507.
6. Corvellec, H., Stowell, A. F. and Johansson, N. Critiques of the circular economy. *J. Ind. Ecol*. **2021**, https://doi.org/10.1111/jiec.13187.
7. ABIPLAST, Associação Brasileira da Indústria do Plástico - Perfil **2019**. Available online: http://www.abiplast.org.br/publicacoes/perfil2019/2020 (accessed 26 June 2021).
8. ABIPLAST, Associação Brasileira da Indústria do Plástico - Perfil **2020**. Available online: http://www.abiplast.org.br/publicacoes/perfil2020/2021 (accessed 04 September 2021).
9. Mestriner, F. Design de Embalagem – Curso Básico, 2nd ed., Pearson Education do Brasil, São Paulo, Brasil, **2002**.
10. ABRE, Associação Brasileira de Embalagens, Meio ambiente e a indústria de embalagem, **2007**. Available online: http://www.abre.org.br/wp-content/uploads/2012/07/cartilha_meio_ambiente.pdf (accessed 26 June 2021).
11. Lindh, H.; Williams, H.; Olsson, A.; Wikstrom, F. Elucidating the Indirect Contributions of Packaging to Sustainable Development: A Terminology of Packaging Functions and Features. *Packag. Technol. Sci.* **2016**, *29*, 225-246, https://doi.org/10.1002/pts.2197.
12. ABRE, Associação Brasileira de Embalagem, Estudo ABRE Macroeconômico da Embalagem e Cadeia de Consumo, **2021**. Available online: https://www.abre.org.br/dados-do-setor/ano2019 (accessed 26 June 2021).

13. EUROPEAN BIOPLASTICS. Facts and figures - **2019**. Available online: https://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf (accessed 05 September 2021).
14. Otto, S.; Strenger, M.; Maier-Noth; A.; Schmid, M. Food packaging and sustainability - Consumer perception vs. correlated scientific facts: A review. *J. Clean. Prod*. **2021**, *298*, https://doi.org/10.1016/j.jclepro.2021.126733.
15. Omoleke, S.A.; Bayugo, Y.V.; Oyene, U.E.; Abrahams, J.; Gobat, N.; Good, S.; Manandhar, M.; Elfeky, S.; Hernandez Bonilla, A.G.; Valentine, N. WHO Community Engagement Package: A Reinforcement of an Inclusive Approach to Global Public Health. *International Journal of Epidemiology and Health Sciences* **2021**, *2*, http://doi:10.51757/IJEHS.2.7.2021.244835.
16. Wandosell, G.; Parra-Merono, M. C.; Alcayde, A.; Banos, R. Green Packaging from Consumer and Business Perspectives. *Sustainability* **2021**, *13*, 1356, https://doi.org/10.3390/su13031356.
17. Mendes, A.C; Pedersen, G. A. Perspectives on sustainable food packaging:– is bio-based plastics a solution? *Trends Food Sci Technol*. **2021**, *112*, 839-846, https://doi.org/10.1016/j.tifs.2021.03.049.
18. Escursell, S.; Llorach-Massana, P.; Blanca Roncero, M. Sustainability in e-commerce packaging: A review. *J. Clean. Prod*. **2021**, *280*, 124314, https://doi.org/10.1016/j.jclepro.2020.124314.
19. BRASKEM. Available online: http://plasticoverde.braskem.com.br/site.aspx/PE-Verde-Produtos-e-Inovacao (accessed 26 June **2021**).
20. Hellvig, E. L. F.; Flores-Sahagun, T. H.S. The Importance of Public Policies That Encourage Companies to Decarbonize The Environment And Invest In Clean Technologies In Brazil. *Rer. Mex. Ing. Quim*. **2021**, *20*, 899-910, https://doi.org/10.24275/rmiq/Poly2363.
21. Petris, S.; Laurienzo, P.; Malinconico, M.; Pracella, M.; Zendron, M. Study of blends of nylon 6 with EVOH and carboxyl-modified EVOH and a preliminary approach to films for packaging applications. *J. Polym. Sci. Wiley & Songs, Inc*. **1998**, *68*, 637-648, https://doi.org/10.1002/(SICI)1097-4628(19980425)68:4<637::AID-APP15>3.0.CO;2-O.
22. Pettersen, M. K.; Gallstedt, M.; Eie, T. Oxygen Barrier Properties of Thermoformed Trays Manufactured with Different Drawing Methods and Drawing Depths. *Packag. Technol. Sci. John Wiley &Sons Ltd* **2004**, 17:43-52, https://doi.org/10.1002/pts.642.
23. Sarantopoulos, C. I. G. L.; Rego, R. A. As Tendências de Embalagem. In: Brasil Pack Trends **2020**. 1st ed.. Campinas: ITAL, 2012; 69-85. Available online: http://www.ital.sp.gov.br/documentos.php (accessed July 2021).
24. Goswami, K.; Awasthi, P. Intelligent Packaging, 3rd ed., AGRICULTURE & FOOD: e-NEWSLETTER, **2021**, 672-675.
25. Festila, A.; Chrysochu, P.; Hieke, S.; Massi, C. Public sense making of active packaging technologies: A feature-based perspective. *Public Underst. Sci*. **2001**, 1–17, https://doi.org/10.1177/09636625211015830.
26. Yam, K.L.; Takahistov, T.; Miltz, J. Intelligent Packaging: Concepts and Applications. *J. Food Sci*. **2005**, *70*, 1, R1–R10, https://doi.org/10.1111/j.1365-2621.2005.tb09052.x.
27. Vedove, T. M. A. R. D.; Maniglia, B. C.; Tadini, C. C. Production of sustainable smart packaging based on cassava starch and anthocyanin by an extrusion process. *J. Food Eng*. **2021**, *289*, 110274, https://doi.org/10.1016/j.jfoodeng.2020.110274.
28. Tavassoli, M.; Sani, M. A.; Khezerlou, A.; Ehsani, A.; McClements, D. J. Multifunctional nanocomposite active packaging materials: Immobilization of quercetin, lactoferrin, and chitosan nanofiber particles in gelatin films. *Food Hydrocoll*. **2021**, *118*, 106747, https://doi.org/10.1016/j.foodhyd.2021.106747.
29. Tan, C.; Han, F.; Zhang, S.; Li, P.; Shang, N. Novel Bio-Based Materials and Applications in Antimicrobial Food Packaging: Recent Advances and Future Trends. *Int. J. Mol. Sci.* **2021**, *22*, 9663, https://doi.org/10.3390/ijms22189663.
30. Kerry, J. P.; O'Grady, M. N.; Hagan, S. A. Past, current and potential utilization of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat Sci.* **2006**, *1*, 74, 113-130, https://doi.org/10.1016/j.meatsci.2006.04.024.
31. Ghaani, M.; Cozzolino, C. A.; Castelli, G.; Farrisi, S. An overview of the intelligent packaging technologies in the food sector. *Trends Food Sci. Technol*. **2016**, *51*, 1-11, https://doi.org/10.1016/j.tifs.2016.02.008.
32. Müller, P.; Schmid, M. Intelligent Packaging in the Food Sector: A Brief Overview. *Foods* **2019**, *8*, 16, https://doi.org/10.3390/foods8010016.
33. Vanderroost, M.; Ragaert, P.; Devlieghere, F.; DE Meulenaer, B. Intelligent food packaging: The next generation. *Trends Food Sci. Technol. Cambridge* **2014**, *39*, 1, 47-62, https://doi.org/10.1016/j.tifs.2014.06.009.

34. MarketWatch. Active & Intelligent Packaging Market Size In 2022 : 6.2% CAGR with Top Countries Data, What are the strategies adopted by the top market players to penetrate across emerging regions? Available online: https://www.marketwatch.com/press-release/active-intelligent-packaging-market-size-in-2022-62-cagr-with-top-countries-data-what-are-the-strategies-adopted-by-the-top-market-players-to-penetrate-across-emerging-regions-in-depth-145-pages-report-2022-03-23 (accessed 31 July 2021).
35. Karaski, T. U.; Ribeiro, F. M.; Pereira, B. R.; Artega, L. P. S. CETESB, CETEA e ABRE – Embalagem e Sustentabilidade – Desafios e orientações no contexto da economia circular, 1st ed., CETESB, São Paulo, Brasil, **2016**.
36. CEMPRE - Compromisso Empresarial para a Reciclagem. CEMPRE – Review **2019**. Available online: http://cempre.org.br (accessed 01 September 2021).
37. ABRELPE, Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais – Panorama dos Resíduos Sólidos no Brasil **2020**, Available online: https://abrelpe.org.br (accessed 26 June 2021).
38. BRASIL. Governo Federal, Constituição da República Federativa do Brasil. Brasília: Senado, 1988. Lei nº 12305, de 2 de agosto de 2010, que institui a Política Nacional de Resíduos Sólidos (PNRS); altera a Lei no. 9.605, de 12 de Fevereiro de 1998; e dá outras providências. Diário Oficial da União, Brasília, 03 Ago. 2010.
39. Guarnier, P.; Cerqueira-Streit, J. A.; Batista, L. C. Reverse logistics and the sectoral agreement of packaging industry in Brazil towards a transition to circular economy. *Resour. Conserv. Recycl*. **2020**, *153*, 104541, https://doi.org/10.1016/j.resconrec.2019.104541.
40. Mastellone, M. L. Technical description and performance evaluation of different packaging plastic waste management's systems in a circular economy perspective. *Sci. Total Environ*. **2020**, *718*, 137233, https://doi.org/10.1016/j.scitotenv.2020.137233.
41. Guarnier, P.; Camara e Silva, L.; Vieira, B. O. How to Assess Reverse Logistics of e-Waste Considering a Multicriteria Perspective? A Model Proposition. *Logistics* **2020**, *4*, 25, https://doi.org/10.3390/logistics4040025.
42. Mahmoudi, M.; Parviziomran, I. Reusable packaging in supply chains: a review of environmental and economic impacts, logistics system designs, and operations management. *Int. J. Prod. Econ*. **2020**, *228*, 107730, https://doi.org/10.1016/j.ijpe.2020.107730.
43. Hellvig, E. L. F.; Flores-Sahagun, T. H.S. Investments in Braskem green polymers: extraordinary profits instead of decarbonization of the environment. *Int. J. Sustain. Dev. World Ecol*. **2021**, *7*, 17-27, https://doi.org/10.20944/preprints202012.0036.v1.
44. Sundqvist-Andberga, H.; Åkermanb, M. Sustainability governance and contested plastic food packaging- An integrative review. *Journal Clean. Prod*. **2021**, *306*, https://doi.org/10.1016/j.jclepro.2021.127111.
45. Beghetto, V.; Sole, R.; Buranello, C.; Al-Abkal, M.; Facchin, M. Recent Advancements in Plastic Packaging Recycling: A Mini-Review. *Materials* **2021**, *14*, 4782, https://doi.org/10.3390/ma14174782.
46. Lacy, P.; Rutqvist, J. Waste to Wealth. The Circular Economy Advantage, 1st ed., Palgrave Macmillan, London, UK, **2014**.
47. Ashby, M. F. Materials and Sustainable Development, 1st ed., Butterworth-Heinemann, Oxford, UK, 2016.
48. Geng, Y.; Doberstein, B. Developing the circular economy in China: Challenges and opportunities for achieving leapfrog development. *International Int. J. Sustain. Dev. World Ecol*. **2008**, *15*, 231–239, https://doi.org/10.3843/SusDev.15.3:6.
49. Velis, C. A. Circular economy and global secondary material supply chains. *Waste Manag. Res*. **2015**, *33*, 5, 389-391, https://doi.org/10.1177/0734242X15587641.
50. Meherishi, L.; Narayana, S. A.; Ranjani, K. S. Sustainable packaging for supply chain management in the circular economy: A review. *J. Clean. Prod*. **2019**, *237*, https://doi.org/10.1016/j.jclepro.2019.07.057.
51. Anand, S.; Sen, A. Sustainable human development: concepts and priorities. In: UNDP – UNITED NATIONS DEVELOPMENT PROGRAMME. Human development index: methodology and measurement. New York: Human. Devel-opment Report Office, **2014**.
52. PNUD. Programa das Nações Unidas para o Desenvolvimento. Desenvolvimento Humano e IDH. Available online: http://www.br.undp.org/content/brazil/pt/home/idh0.html (accessed 26 June **2021**).
53. PatentScope database - World International Property Organization (WIPO). Available online: http://www.wipo.int/patentscope/search/en/search.jsf (accessed 01 May **2021**).
54. Radosevic, S. International technology transfer and catch-up in economic development. Massachusetts: Edward Elgar, **1999**.
55. Pearson, B. Market failure: why the clean development mechanism won't promote clean development. *J. Clean. Prod*. **2007**, *15*, 247-252, https://doi.org/10.1016/J.JCLEPRO.2005.08.018.