POLYMERS AND SUSTAINABILITY: OVERVIEW OF THE USE OF CONVENCIONAL AND BIODEGRADABLE POLYMERS

POLÍMEROS E SUSTENTABILIDADE: VISÃO GERAL DO USO DE POLÍMEROS CONVENCIONAIS E BIODEGRADÁVEIS

EPOLÍMEROS Y SOSTENIBILIDAD: VISIÓN GENERAL DEL USO DE POLÍMEROS CONVENCIONALES Y BIODEGRADABLES

NICOLAS DE SOUZA SCHAULET | UFRGS – Universidade Federal do Rio Grande do Sul, Brasil
VINICIUS GADIS RIBEIRO, Dr.| UFRGS – Universidade Federal do Rio Grande do Sul, Brasil
JOCELISE JACQUES DE JACQUES, Dra. | UFRGS – Universidade Federal do Rio Grande do Sul, Brasil

ABSTRACT

This article aims to provide an overview of important moments in the consolidation of the use of conventional and biodegradable polymers throughout history. It begins by discussing the definition of conventional and biodegradable plastics, followed by a historical contextualization of petroleum-derived plastics, referred to here as conventional plastics, highlighting significant events in their evolution. The article then emphasizes the development and growth of biodegradable polymer applications. To this end, a literature review was conducted, supported by data collection from publications discussing polymer technologies. The studies highlight the environmental advantages of biodegradable polymers, despite their still higher production costs. Although biodegradable polymers are a viable alternative to petroleum-derived polymers, there are cases in which their use is not yet feasible, depending on the context of application, economic conditions, and consumer experience.

KEYWORDS

Biodegradable Polymer; Synthetic Polymer; Sustainable Development of Products, Design and Technology.

RESUMO

Este artigo tem como objetivo fornecer uma visão geral dos momentos importantes na consolidação do uso de polímeros convencionais e biodegradáveis ao longo da história. Ele começa discutindo a definição de plásticos convencionais e biodegradáveis, seguido por uma contextualização histórica dos plásticos derivados do petróleo, referidos aqui como plásticos convencionais, destacando eventos significativos em sua evolução. O artigo então enfatiza o desenvolvimento e crescimento das aplicações de polímeros biodegradáveis. Para isso, foi realizada uma revisão da literatura, apoiada pela coleta de dados de publicações que discutem tecnologias de polímeros. Os estudos destacam as vantagens ambientais dos polímeros biodegradáveis, apesar de seus custos de produção ainda serem mais altos. Embora os polímeros biodegradáveis sejam uma alternativa viável aos polímeros derivados do petróleo, há casos em que seu uso ainda não é viável, dependendo do contexto de aplicação, das condições econômicas e da experiência do consumidor.

PALAVRAS-CHAVE

Polímero Biodegradável; Polímero Sintético; Desenvolvimento Sustentável de Produtos, Design e Tecnologia.

http://dx.doi.org/10.29183/2447-3073.MIX2024.v10.n4.113-125
ISSN: 2447-0899 (IMPRESSA) | 2447-3073 (ONLINE)

RESUMEN

Este artículo tiene como objetivo proporcionar una visión general de los momentos importantes en la consolidación del uso de polímeros convencionales y biodegradables a lo largo de la historia. Comienza discutiendo la definición de plásticos convencionales y biodegradables, seguido de una contextualización histórica de los plásticos derivados del petróleo, referidos aquí como plásticos convencionales, destacando eventos significativos en su evolución. El artículo luego enfatiza el desarrollo y crecimiento de las aplicaciones de polímeros biodegradables. Para ello, se realizó una revisión de la literatura, respaldada por la recopilación de datos de publicaciones que discuten tecnologías de polímeros. Los estudios destacan las ventajas ambientales de los polímeros biodegradables, a pesar de que sus costos de producción aún sean más altos. Aunque los polímeros biodegradables son una alternativa viable a los polímeros derivados del petróleo, hay casos en los que su uso aún no es factible, dependiendo del contexto de aplicación, las condiciones económicas y la experiencia del consumidor.

PALABRAS CLAVE

Polímero Biodegradable; Polímero Sintético; Desarrollo Sostenible de Productos, Diseño y Tecnología.

1. INTRODUCTION

Conventional synthetic polymers emerged as catalysts for innovation and the development of various products in the 20th century. However, the variety and widespread use of these materials led to environmental damage, for which we sought solutions at the beginning of the 21st century, such as improper disposal and the landfills' overcrowding and other environments designed for waste deposition. According to Allison et al. [1], the accumulation of plastic waste is a growing threat, endangering health and sustainability on a global scale. On the other hand, public awareness of the solid waste problem is increasing, and plastics, due to their extensive use in packaging, have become a significant part of this issue [2].

Nascimento et al. [3] point out that the increase in plastic waste may be linked to the development of smaller packaging, changes in consumption habits, and the reduction in household sizes. Poor management of plastic waste poses serious environmental challenges, including the clogging of sewage systems and health risks [4]. According to Brito et al. [5], many problems arise from the disposal of this material due to its high resistance to degradation, as it takes many years to decompose. Additionally, the degradation of very small portions of some plastics, which are not visible, accumulates in ecosystems in large quantities.

In this context, it is important to understand that conventional synthetic polymers are produced to take advantage of their properties during the usage phase and can be derived from fossil or biological sources [6]. However, considering the end of the life cycle, we observe the need for polymers that meet biodegradability conditions and biocompatibility with low-toxicity degradation as alternatives to existing conventional synthetic polymers [7].

According to Mukherjee et al. [4], polymers can be classified into natural biodegradable polymers (polysaccharides and proteins), synthetic biodegradable polymers (esters, amides, ethers, urethanes), and synthetic biopolymers (or hybrid systems). Figure 1 presents the classification of polymers.

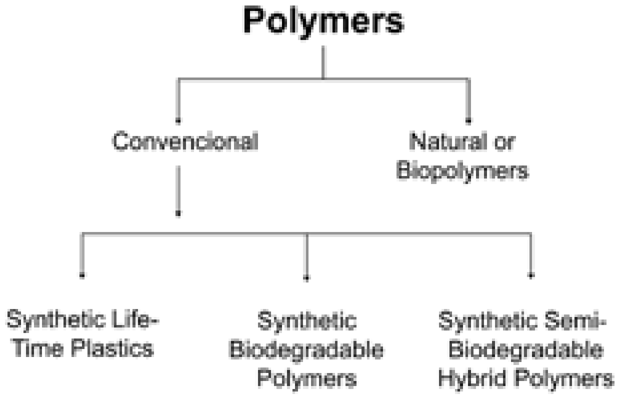

Figure 1: Polymer Classifications. Source: Adapted from Mukherjee et al. [8]

It is important to note that biodegradable plastics are not strictly linked to renewable resources, as biodegradation is related to the chemical structure of the compound rather than its origin [9]. Decomposition criteria in the environment need to be established and communicated to ensure that users and end consumers are aware of the biodegradation capabilities of these bioproducts [10]. Soil burial is widely used to test degradation, but reproducing results is challenging due to the lack of control over climate and microorganisms at the test site [11]. The decomposition period depends on the chemical structure, but for practical purposes, if degradation takes many years under such conditions, the polymer is not considered biodegradable [12]. Therefore, to achieve significant results with biodegradable polymers, it is important to implement industrial-scale composting, just as we plan reverse logistics, sorting centers, and recycling processes. This issue can guide the feasibility of bioplastic implementation.

In a competitive market, it is crucial to offer products that not only meet customer needs but are also produced with reduced costs, lower material and energy consumption, and minimized environmental impacts [13, 14]. Simultaneously, companies with a more advanced strategic vision focus on sustainability, considering not only eco-efficiency, which encompasses economic and environmental impacts, but also social impacts and ethical aspects of their operations [15]. Contemporary design, in response to societal and market demands, is increasingly aligned with the concepts of sustainable development, innovation, and social well-being [16]. Thus, in the development of products with biodegradable polymers, several phases up to their final disposal should be considered, and the goal of implementing this technology is precisely to ensure that the end of the product lifecycle is positive and does not harm the environment. Another important characteristic is that many biodegradable polymers come from renewable sources; however, it is crucial to understand that some biodegradable plastics come from non-renewable sources. This article focuses on biodegradable plastics also considered bioplastics, i.e., derived from renewable sources.

Significant advances have been made in the production of biodegradable plastics from renewable resources, aiming to achieve materials with performance comparable to petroleum-based polymers [17]. Some environmental and socioeconomic factors related to the growing interest in biopolymers include: (a) significant environmental impacts, (b) extraction processes for petroleum-derived polymers, and (c) oil scarcity and price increases [5]. Therefore, the use of raw materials such as corn, cassava, algae, among others, could reduce the reliance on oil for polymer production, representing a transition from non-renewable to renewable sources.

These attributes contribute to the rise of biopolymers. The increased interest in these materials, combined with growing environmental concerns, has led to a significant rise in research into their use [18]. The relevance of biodegradable polymers has also increased in the industrial market over the past decades, particularly with the growing focus on sustainability and environmental impacts since the 1990s. According to Araújo et al. [19], global biopolymer production reached approximately 2.05 million tons in 2017 and 2.18 million tons in 2023, with projections to increase to 7.43 million tons by 2028 [20]. However, several limitations hinder the expansion of these materials, such as cost, applicability, purpose, and disposal adequacy.

To contribute to a state-of-the-art scenario, this article employs a literature review methodology, providing insights into key moments in the consolidation of conventional and biodegradable polymer use. The research aims to be systematic and comprehensive [21]. The study addresses two main topics: (1) the historical context of the emergence and evolution of conventional synthetic plastics, and (2) the concept of sustainability and the emergence and development of biodegradable plastics. Data were collected from academic publications, books, and journals, recognized as both classic and contemporary materials, from national and international sources, covering the publication period from 1990 to 2023. It is important to note that this work did not follow a linear path, allowing for some flexibility in theoretical development.

The focus will be on biodegradable polymers, but a historical context regarding petroleum-derived plastics will be presented, highlighting events that marked the evolution of this technology. Subsequently, the characteristics of biodegradable plastic use will be mapped, including the origin of the technology, its usage segments, limitations, and opportunities.

2. HISTORICAL CONTEXT OF THE EMERGENCE AND EVOLUTION OF CONVENTIONAL SYNTHETIC PLASTICS

There are several contextual axes that depict the beginning of the discovery of conventional polymers. The first plastic material technology was based on nitrocellulose and was developed by Parkes in 1862 and Hyatt in 1866 [22]. Around 1860, John Wesley Hyatt developed a cellulose derivative [17]. He combined camphor with cellulose nitrate, obtained by dissolving cotton fibers in an alcohol solution, to create celluloid [23]. Celluloid was first marketed as an imitation ivory, used to make a surprisingly wide range of objects, especially small personal items [24]. After cellulose nitrate, formaldehyde was the next creation to evolve in plastic technology [17]. By mid-1887, casein (milk protein mixed with formaldehyde) was used to develop non-flammable whiteboards [25].

According to Crespy, Bozonnet, and Meier [26], Bakelite was the first synthetic thermosetting plastic and significantly contributed to the onset of the "plastic age." Bakelite was discovered in 1907 by Baekeland through the polycondensation of phenol with formaldehyde [22]. It was widely used in the manufacture of telephones, saucepan handles, pipe stems, radio cabinets, and other products in the electrical and automotive industries [23]. As Crespy, Bozonnet, and Meier [26] report, despite Bakelite's qualities, it declined after World War II due to its strong residual odor being associated with wartime desperation and memories, as well as the poor quality of resins synthesized at that time.

Murder and Knot [27] cite the year 1912 as the time when polyvinyl chloride (PVC) was discovered, showing flexibility and resembling rubber or leather when heated in the presence of a liquid with a high boiling point [22]. PVC is widely recognized as the trivial name for polyvinyl chloride and, in terms of global production, is one of the three most relevant polymers, alongside polyethylene and polystyrene [11].

Polyethylene (PE) was discovered by Reginald Gibson and Eric Fawcett in 1933, two chemists working for ICI (Imperial Chemical Industries). It was first synthesized as a low-density resin (LDPE) in 1935 [28]. This polymer, originally called high-pressure polyethylene (HDPE), resulted from Nobel Laureate Robert Robinson's interest in ultra-high-pressure reactions as an ICI consultant [29]. Besides PVC and PE, polystyrene (PS) is also one of the most important polymers in use [11]. Its practical use was considered in 1902 by Kronstein and Matthews in 1911 [22]. Matthews filed a patent describing the polymerization processes of the styrene monomer to produce a substance for manufacturing items previously made of wood, hard rubber, celluloid, and glass [30]. Commercial production of PS began in the 1930s by the German company BASF and was introduced to the United States in 1937 [28]. The production of PS since 1946 was due to the spread of knowledge and the availability of high-purity styrene monomer in factories during World War II as part of the synthetic rubber program [30]. The polymer is relatively resistant and is primarily used as protective packaging material, especially for electrical equipment, or as sintered sheets to replace paper or cardboard [31].

All these polymers, which have been and continue to be widely used, come from non-renewable sources and are not biodegradable. Therefore, the historical context of conventional synthetic plastic technologies has had a significant impact on society throughout the 20th century. According to Geyer [32], the invention of modern consumer society and sustained economic growth in the post-war period created a perfect environment for these new materials. Feldman [22] adds that polymers were previously seen as a chemical specialty, but from then on, they became associated with plastics, fibers, and elastomers, as well as with engineering through the products´ design and manufacturing .

From the last decade of the 20th century, the growing focus on sustainability in various sectors has driven the development of new alternatives to conventional polymer sources. Biodegradable plastics have been present in the market for several years and are used in a variety of sectors, particularly those derived from renewable sources, i.e., bioplastics.

Material selection is a fundamental part of product design, examining the overall context of this polymer category is essential to understanding the interactions of these technologies throughout products´ development.

2.1 The Concept of Sustainability, Emergence and Development of Biodegradable Plastics, and the Biological Cycle of the Circular Economy

Biodegradable plastic is intrinsically linked to the concept of sustainability, playing a significant role in the sustainable development of products across various sectors. By the end of the 20th century, climate change and restrictions on fossil resources were already driving the development of plants for producing materials needed by humans from renewable sources [17]. According to Horn et al. [33], in 1987, the concept of sustainability was defined by the United Nations Commission led by Gro Brundtland. This concept emerged with considerable challenges, such as economic crises, social inequality, drug trafficking, political instability, and particularly characterized by the notion of scarcity [34]. Sustainable development faced significant limitations at its inception, related to market growth and its needs. In Brazil, sustainable development became popular in the 1990s, with Rio-92 presenting negotiation processes on the Climate Change Convention, the Biodiversity Convention, the Forest Protocol, the Earth Charter, and Agenda 21 [35].

As Campos [36] notes, the concept of sustainability implies limits that are not absolute but are imposed by technology, social organization, natural resources, and the capacity to absorb waste at a given historical moment. Concern for sustainable development drove the advancement of studies on integrating environmental challenges into design from the early 2000s. Researchers like Bahmed, Boukhalfa, and Djebabra [37] highlighted the need for a methodological approach to incorporate environmental challenges into product development due to the high complexity and uncertainties of that period. An additional challenge was that few companies openly shared their design processes that included environmental or social aspects of sustainability or adopted a systemic view of sustainability [38].

However, by the 1990s, there was evidence that design could help designers evaluate the quality and cost of a project in the initial phase, with more than 70% of the product cost determined at this stage [39]. Bahmed, Boukhalfa, and Djebabra [37] reinforced that to incorporate environmental parameters effectively, it was crucial to act from the development phase, when 80% of the product impacts are defined. This understanding aligns with the more contemporary view of McAloone and Pigosso [40], which emphasizes that the more advanced the project, the more difficult and even impossible it becomes to make necessary changes, as materials, technologies, and product lifespan are decided in the initial phase.

The disposal of plastic packaging reflects behaviors within an industrial context shaped by various factors, including the actions of consumers, producers, and large industries [1]. Consumers play an essential role in the packaging lifecycle, and it is crucial that they understand the importance of environmentally appropriate disposal [41]. At the same time, packaging design needs to be improved not only in terms of functionality but also to avoid the increase of poorly classified packaging and plastic waste that does not return to the productive cycle [42].

According to Idumah and Nwuzor [43], the management of plastics recovered from municipal solid waste (MSW) is a particularly sensitive industry due to the continuous growth in the plastics´ amount, their low biodegradability, and their environmental impact. Huang et al. [44] observe that plastic waste degrades slowly, persisting in the environment for hundreds of years, characterizing it as non-biodegradable waste.

Although various companies and systems are involved from concept to end-of-life (EoL) and in recycling products, a joint effort is needed to implement sustainability throughout the entire lifecycle [45]. Silva and Palsson [46] emphasize that the environmental impact at EoL is not limited to the negative effects of waste treatment but also includes the potential savings this process can generate. Nyström et al. [47] add that while companies may invest in more durable products to reduce future costs, they face the risk of not recovering these investments due to premature obsolescence and future uncertainties.

Geyer, Jambeck, and Law [48] state that the only way to permanently eliminate plastic waste is through destructive thermal treatment, such as incineration and pyrolysis. However, these processes can release gases that contribute to air pollution and the greenhouse effect [42, 49]. Alassali et al. [50] point out that the global amount of plastic waste incinerated and recycled is still low compared to the amount deposited in landfills.

An additional concern is the fate of these wastes in rivers and oceans. Ritchie and Roser [51] report that the world generates 350 million tons of plastic waste annually, with almost a quarter, about 82 million tons, being poorly managed. Of this amount, approximately 19 million tons are released into the environment, with 13 million tons affecting terrestrial environments and 6 million tons polluting rivers, coasts, and oceans. Chamas et al. [52] highlight that this pollution is strongly linked to the lack of efficient waste management infrastructure.

The end-of-life scenarios outlined above underscore the importance of considering design and questioning the cyclical flow. As McDonough and Braungart [53] argue, in 2002, in their book Cradle to Cradle, products should be designed so that at the end of their useful life, they can either be reused or recycled without losing their quality as technical nutrients or can safely return to the environment decomposed as biological nutrients. Based on this concept, returning to the productive cycle through recycling or reuse is the most employed approach for conventional polymers.

At the beginning of the 21st century, also in 2002, Manzini and Vezzoli [54] indicated that the view on sustainability needed to be broad and systemic. The authors presented a refined view of sustainable development listing some general requirements: (I) fundamentally relying on renewable resources to ensure renewal; (II) optimizing the use of non-renewable resources (understood as air, water, and land); (III) not accumulating waste that the ecosystem cannot renaturalize (i.e., return to its original mineral substances and, importantly, to their original concentrations). These requirements relate to goals in plastic development, material choice in product design, and consumer purchasing decisions.

Adopting a systemic view can impact the three dimensions of sustainability: economy, environment, and society [55]. Chiu and Chu [13] highlight that this concept is widely known as the Triple Bottom Line (TBL), where profit, environment, and society are assessed integratively. Rachuri, Sriram, and Sarkar [56] reinforce this perspective, emphasizing that measuring product impacts on sustainability should consider these three indicators jointly within the TBL framework.

According to Luckachan and Pillai [7], one of the first studies on polymer degradation was Wolfram Schnabel's classic work in 1981, which discussed three modes of degradation through (i) thermal, (ii) mechanical, and (iii) photoelectric processes. Later, Narayan in 1993 [57] published a study addressing the use of biodegradable plastics in industry, marketing, design, and engineering. The author mentions that in that context, in response to environmentally conscious plastic disposal, two new industries emerged: recyclable plastics and biodegradable plastics.

The growing adoption of biodegradable plastics has paved the way for new application possibilities. Petersen et al. [58] examined the potential of biodegradable plastics, focusing particularly on packaging, especially for food. This study evaluated the feasibility of using bioplastics in food packaging for animal products, fruits, vegetables, and frozen foods. While the studies were underway, the future perspective of polymer technology for packaging was based on renewable resources. However, limitations associated with these materials could vary in terms of performance, processing, and cost [58, 59]. On the other hand, Gross and Kalra [60] conducted research on the opportunities offered by biodegradable polymers for the environment. They highlighted that one of the main benefits of renewable raw materials, compared to petroleum, is the reduction in CO2 emissions from fossil fuels. The emergence of new biodegradable polymer technologies that meet degradability, environmental compatibility, and low-toxicity degradation product requirements is the definitive solution to these types of problems [7].

The Circular Economy (CE) concept, established in 2015, also grounded in the defense of cyclical flow, can influence and promote the reduction of environmental impacts through one of its fundamental cycles: the biological cycle. According to Oliveira, Silva, and Moreira [61], the term "circular" is attributed to the concept due to the existence of two main cycles that sustain the model: the biogeochemical or biological cycle and the technical cycle. In the biological cycle, components are, at a minimum, non-toxic and potentially beneficial, allowing them to be safely returned to the biosphere [62]. On the other hand, the technical cycle encompasses durable goods, such as engines and computers, composed of technical materials unsuitable for the biosphere, such as metals and most plastics [63]. Below, Figure 2 illustrates the simplified structure of the biological cycle.

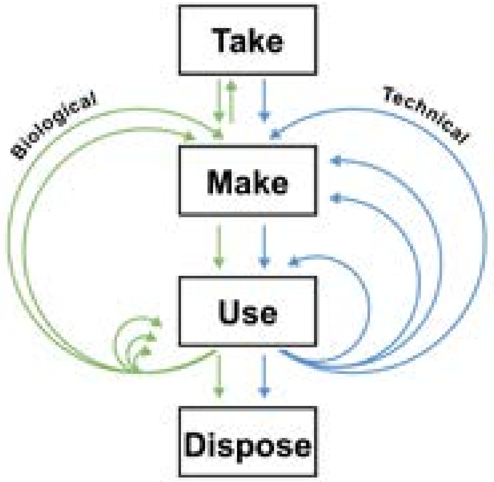

Figure 2: Simplified butterfly diagram. Source: Velenturf et al. [64]

Various academic contributions have sought strategies to promote the circularity of plastics, such as banning the recycling of problematic plastics that may harm terrestrial and aquatic environments, standardizing plastic formulations, extending product lifespans, and developing guidelines for circularity [65]. Jürgens and Endres [66] also discuss the use of bio-based plastics and mechanical recycling to recover plastic materials at the end of their life cycle. In addition to these strategies, other studies investigate the challenges organizations face in implementing Circular Economy (CE) and sustainability strategies, such as investing in new technologies and infrastructure, changing user behavior [67], lack of education on the topic, and accountability for the end-of-life of products [68].

Turkcu and Tura [69] suggest that companies can adopt strategies such as creating ecosystems for waste management, forming strategic partnerships, innovating business models, and using communication approaches to effectively integrate sustainability. Feldman et al. [68] emphasize that CE requires a complete transformation of the supply chain, with active participation from governments, businesses, researchers, and consumers. For CE to succeed, it is crucial that consumers are willing to buy recycled products and adopt practices such as repair and reuse [67]. The growing consumer interest in sustainable practices is a positive indicator for achieving these goals [68]. Thus, understanding and overcoming barriers related to low consumer engagement can help companies develop strategies that better inform the public and encourage the adoption of circular products and services [70].

Considering only the end of life, there are three classes of biodegradable polymers presented by Chandra and Rustgi [71], which are: (a) First class are synthetic polymers with vulnerable groups susceptible to hydrolysis attacks by microbes; (b) Second class are natural bacterial polymers, such as polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV), which are highly biodegradable and susceptible to bacterial action; (c) Third class are mixtures of polymers and additives that are easily consumed by microorganisms, such as mixtures of starch with polyethylene (PE).

According to Mukherjee et al. [8], "the basic characteristics of natural biodegradable polymers are their availability and derivation from natural and relatively inexpensive sources, such as polysaccharides, lignin, chitosan, starch, cellulose, guar gum, collagen, and albumin." Van Beilen and Poirier [72] note that although the focus is on using plants for biofuels, such as bioethanol and biodiesel, plants are a potential source of a much wider range of useful chemicals and biomaterials. Plastics composed of renewable resources (corn, tapioca, potatoes, sugar and algae) and that are totally or partially bio-derived, biodegradable, or compostable are referred to as bioplastics.

According to Pathak and Sneha [17], biological materials have potential advantages for balancing greenhouse gases and environmental impacts throughout life cycles and with the use of renewable resources, in contrast to finite resources. On the other hand, Van Beilen and Poirier [72] comment that biomaterials often lack performance quality, affecting characteristics such as durability and strength, and do not have the cost competitiveness required for their use in low-value, large-scale consumer products. Lambert and Wagner [73] emphasize that bio-based polymers, even if not biodegradable, can potentially be used in a wider variety of applications where biodegradability is not a desired atribute.

Biodegradable polymers require adequate resistance for applications such as construction materials, hygiene products, and packaging, reducing disposal issues, such as reduced resistance to microbial degradation when they are in the environment [8]. In the technological advancement of biodegradable polymers, there are studies on the development and improvement of materials, such as the production of polyhydroxyalkanoates (PHA), bacterial cellulose, silk, xanthan, and polyesters from fermentation, also called white biotechnology, or by chemical methods [72].

Corn sugar in the U.S. and sugarcane in Brazil have been the preferred renewable feedstock for fermentation-based biofuels (ethanol) and for producing bio-based products, including polylactic acid (PLA) [74]. According to Mores et al. [75], in Brazil, bioplastic production from sugarcane is feasible due to the country's climatic advantages and the extent of available land for this crop. Demmer [76] mentions alternatives such as algae and sugarcane for the plastic industry in the U.S., but highlights that corn and soybeans are significant and economically attractive commercial crops for the country. Some authors describe high-cell-density systems with low-cost starch, rice bran, or wheat bran as the primary carbon source for producing PHA in semicontinuous culture [77]. Thus, there is a search for natural sources for various applications, which aligns with Herman Daly's statement, cited by Meadows et al. [78], arguing that the sustainable use of non-renewable resources occurs when it happens at the same rate of replacement by renewable sources. However, it is still not evident that this is being done at the necessary time and quantity.

For practical use, biodegradable materials are currently most important in medical sciences, where they can be used as implants to replace bones or other body parts, and in surgeries as sutures [12]. The main applications in Brazil are in food packaging, bags, agricultural films, and consumer products, using biopolymers, biodegradable polymers, and green polymers [5].

Thus, it can be asserted that biodegradable polymers can play a significant role in material recovery, reducing landfill waste volume, and utilizing renewable resources [79]. According to Lambert and Wagner [73], the main application areas for the development of biodegradable polymers include packaging, disposable food utensils, and agricultural films.

3. CONCLUSION

With the purpose of examining the historical panorama of the use of conventional and biodegradable plastics, this study presented two periods of polymer technology evolution throughout the history of materials. One of these periods dates to the early stages of research, development, and refinement of technology, while the other emerged at a time of increasing interest in sustainability across various sectors, which has driven the search for new alternatives to conventional polymer sources.

Biodegradable polymers hold significant importance in the industrial market due to their varied applications. Unlike conventional synthetic polymers derived from petroleum, biodegradable polymers degrade more quickly. Biodegradation is a highly promising solution as it is less harmful to the environment and completes the carbon and nitrogen cycles.

It is evident from the literature reviewed and presented in the article that the use of biodegradable polymers influences and benefits causes that implement sustainability as a strategic pillar. The interest in exploring biodegradable polymers, combined with heightened environmental concern, has led to a significant increase in research into their use, as indicated by the consulted literature.

Biodegradable polymers follow a biological cycle in which, upon safe degradation, they transform into nutrients for the soil. In this context, the biological cycle structured in the circular economy plays an important role by encouraging the use of biodegradable materials that can be integrated into the product life cycle based on circularity.

The role of consumers is crucial in the proper disposal of biodegradable and non-biodegradable polymers, given the growing involvement and concern with sustainability. Understanding and overcoming challenges related to consumer disengagement should be a targeted strategy for companies to develop approaches that encourage the use of sustainable products, identifying opportunities to engage and sensitize consumers to adopt these practices.

The technology of biomaterials is on the rise, driving the demand for sustainable products that have a lower environmental impact. In developing products with biodegradable polymers, designers should adopt strategies that consider the entire product life cycle, especially its end phase, aiming to minimize environmental harm. Therefore, despite the commercial and physical constraints of biodegradable polymers, they offer a notable opportunity to advance products and ventures that do not harm the environment. On the contrary, solutions that incorporate biopolymers have the potential to positively impact environmental sustainability.

It is concluded that the pursuit of achieving structural performance like conventional synthetic polymers is driven by socioeconomic and environmental challenges, such as oil scarcity and rising extraction costs.

Thus, there is a broad field of opportunities to conduct further studies on various biodegradable polymers. As future applications or adaptations of this article, it is suggested that deeper research be conducted on the implementation of biodegradable plastics in the industry, understanding the limitations and opportunities for companies using such materials in product development. Due to the complexity of accessing internal company information, it would be beneficial for future research to seek such data to understand the use of biopolymers as corporate strategies. Integrating design within the context of this work, another possibility would be to deepen the study to understand the role of design in the end-of-life phase of products incorporating biodegradable polymers in their composition. These approaches can significantly contribute to advancing environmental sustainability and developing innovative solutions to contemporary challenges.

REFERENCES

ALLISON, Ayşe Lisa et al. Barriers and enablers to buying biodegradable and compostable plastic packaging. **Sustainability**, v. 13, n. 3, p. 1463, 2021.

BOHLMANN, Gregory M. Biodegradable packaging life-cycle assessment. **Environmental Progress**, v. 23, n. 4, p. 342-346, 2004.

NASCIMENTO, Tauana et al. Interação entre usuários e embalagens: percepções dos usuários no reuso de embalagens. In: **Engenharia de materiais e meio ambiente: reciclagem, sustentabilidade, novos processos e desafios.** Ponta Grossa: Aya, p. 90-104, 2022.

IDUMAH, Christopher Igwe; NWUZOR, Iheoma C. Novel trends in plastic waste management. **SN Applied Sciences**, v. 1, p. 1-14, 2019.

BRITO, G. F; AGRAWAL, P; ARAÚJO, E. M; MÉLO, T. J. A. Biopolímeros, Polímeros Biodegradáveis e Polímeros Verdes. **Revista Eletrônica de Materiais e Processos (REMAP)**, v.6.2, p. 127-139, 2011.

HAHN, Stefan; HENNECKE, Dieter. Final Report WP4 - **Comparison between natural and synthetic polymers**. 2022.

LUCKACHAN, Gisha E.; PILLAI, C. K. S. Biodegradable polymers-a review on recent trends and emerging perspectives. **Journal of Polymers and the Environment**, v. 19, p. 637-676, 2011.

MUKHERJEE, Chandrapaul et al. Recent advances in biodegradable polymers–Properties, applications and future prospects. **European Polymer Journal**, p. 112068, 2023.

ASGHER, Muhammad et al. Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. **Food Research International**, v. 137, p. 109625, 2020.

AMARAL, Murilo Alves do; BORSCHIVER, Suzana; MORGADO, Cláudia do Rosário Vaz. Análise do segmento de bioplásticos: prospecção tecnológica em “plásticos verdes”, PHA e PLA. **Engevista**, v. 21, n. 2, p. 228-241, 2019.

NICHOLSON, John. The chemistry of polymers. 3. ed. **The Royal Society of Chemistry**, p. 1-191, 2006.

PAVLATH, Attila E. Biodegradable polymers: Why, what, how. **Physical Sciences Reviews**, 2020.

CHIU, Ming-Chuan; CHU, Chih-Hsing. Review of sustainable product design from life cycle perspectives. **International Journal of Precision Engineering and Manufacturing**, v. 13, p. 1259-1272, 2012.

PENG, Qingjin et al. Tools for Sustainable Product Design: Review and Expectation. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. **American Society of Mechanical Engineers**, 2013. p. V004T05A044.

HAUSCHILD, Michael; JESWIET, Jack; ALTING, Leo. From life cycle assessment to sustainable production: status and perspectives. **CIRP annals**, v. 54, n. 2, p. 1-21, 2005.

CAVALCANTE, Ana Luisa Boavista Lustosa et al. Design para a Sustentabilidade: um conceito Interdisciplinar em construção. **Projetica**, v. 3, n. 1, p. 252-263, 2012.

PATHAK, Swati; SNEHA, C. L. R.; MATHEW, Blessy Baby. **Bioplastics: its timeline based scenario & challenges**. J. Polym. Biopolym. Phys. Chem, v. 2, n. 4, p. 84-90, 2014.

FALCONE, Daniele M. B.; AGNELLI, José Augusto M.; FARIA, Leandro I. L. de. Panorama Setorial e Perspectivas na Área de Polímeros Biodegradáveis. Polímeros: **Ciência e Tecnologia**,vol. 17, n. 1, p. 5-9, 2007.

ARAÚJO, Bruna Aline; et al. A aplicação de polímeros biodegradáveis como uma alternativa sustentável. **Research, Society and Development,** v. 10, n. 9, p. e49010918248-e49010918248, 2021.

EUROPEAN BIOPLASTICS. **Bioplastics market development update 2023**. European Bioplastic, Berlin, Germany, 2023. Disponível em: <https://www.european-bioplastics.org/bioplastics-market-development-update-2023-2/>. Acesso em: 11/03/2024.

AZEVEDO, D. **Revisão de Literatura, Referencial Teórico, Fundamentação Teórica e Framework Conceitual em Pesquisa – diferenças e propósitos**. Working paper, 2016. Disponível em: < https://shre.ink/8PnN > Acesso em 09 set.2023.

FELDMAN, Dorel. Polymer history. **Designed monomers and polymers**, v. 11, n. 1, p. 1-15, 2008.

ANDERSON, Kevin J. Bakelite: 80 Years Since the First Synthetic Resin. **MRS Bulletin**, v. 14, n. 7, p. 69-69, 1989.

REILLY, Julie A. Celluloid objects: their chemistry and preservation. J**ournal of the American Institute for Conservation**, v. 30, n. 2, p. 145-162, 1991.

KRÄTZ, Otto. Aufstieg und Niedergang des Galaliths. **Chemie in unserer Zeit**, v. 38, n. 2, p. 133-137, 2004.

CRESPY, Daniel; BOZONNET, Marianne; MEIER, Martin. 100 Years of Bakelite, the Material of a 1000 Uses. **Angewandte Chemie International Edition**, v. 47, n. 18, p. 3322-3328, 2008.

MURDER, Karel; KNOT, Marjolijn. PVC plastic: a history of systems development and entrenchment. **Technology in Society**, v. 23, n. 2, p. 265-286, 2001.

ANDRADY, Anthony L.; NEAL, Mike A. Applications and societal benefits of plastics. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 364, n. 1526, p. 1977-1984, 2009.

SEYMOUR, Raymond Benedict; CHENG, T. C. (Ed.). Advances in polyolefins: The world's most widely used polymers. **Springer Science & Business Media**, 1987.

TEACH, William Charles; KIESSLING, George Curt. Polystyrene. Reinhold, New York, NY, 1960.

SCOTT, Gerald. **Polymers and the Environment**. Cambridge: Royal Society of Chemistry, p. 1-148, 1999.

GEYER, Roland. **Production, use, and fate of synthetic polymers. In: Plastic waste and recycling**. Academic Press, 2020. p. 13-32.

HORN, Bibiana Silveira; et al. **O uso do triple bottom line como uma ferramenta alternativa de sustentabilidade empresarial na sociedade de risco.** Caminhos para a Sustentabilidade através do Design. In: Caminhos para a sustentabilidade através do Design. Porto Alegre: Ed. UniRitter, 2014. p. 119-132.

AMORIM, Ricardo. **A tecnologia e o meio ambiente. Programa de Apoio à formação profissional.** Gazeta Mercantil. 1993.

CAPOBIANCO, João Paulo. **O que podemos esperar da Rio 92**. São Paulo em Perspectiva, São Paulo, v. 6, n. 1-2, p. 13-17, 1992.

CAMPOS, Carlos Silva. Relatório Brundtland – a versão original. Disponível em: <https://ambiente.wordpress.com/2011/03/22/relatrio-brundtland-a-verso-original/>. Acesso em: 03 out. 2023.

BAHMED, Lylia; BOUKHALFA, Ali; DJEBABRA, Mebarek. Eco-conception in the industrial firms: methodological proposition. **Management of Environmental Quality: An International Journal**, v. 16, n. 5, p. 530-547, 2005.

WAAGE, S. A. Re-considering product design: a practical "road-map" for integration of sustainability issues. **Journal of Cleaner Production**, Oxford, v. 15, n. 7, p. 638-649, 2007.

NATIONAL RESEARCH COUNCIL et al. **Improving engineering design: Designing for competitive advantage**. National Academies Press, 1991.

MCALOONE, Tim C.; PIGOSSO, Daniela CA. Ecodesign implementation and LCA. Life Cycle **Assessment: Theory and Practice**, p. 545-576, 2018.

OTTONI, Breno Luiz et al. Communication and biodegradable packaging relationship: a paradigm for final disposal. **Journal of Applied Packaging Research**, v. 10, n. 1, p. 2, 2018.

NEMAT, Babak et al. Design affordance of plastic food packaging for consumer sorting behavior. **Resources, Conservation and Recycling**, v. 177, p. 105949, 2022.

IDUMAH, Christopher Igwe; NWUZOR, Iheoma C. **Novel trends in plastic waste management.** SN Applied Sciences, v. 1, p. 1-14, 2019.

HUANG, Saimin et al. Plastic waste management strategies and their environmental aspects: A scientometric analysis and comprehensive review. **International Journal of Environmental Research and Public Health**, v. 19, n. 8, p. 4556, 2022.

RAMANI, Karthik et al. **Integrated sustainable life cycle design: a review.** 2010.

SILVA, Nathalie; PÅLSSON, Henrik. Industrial packaging and its impact on sustainability and circular economy: A systematic literature review. **Journal of Cleaner Production**, v. 333, p. 130165, 2022.

NYSTRÖM, Thomas et al. Managing circular business model uncertainties with future adaptive design. **Sustainability**, v. 13, n. 18, p. 10361, 2021.

GEYER, Roland; JAMBECK, Jenna R.; LAW, Kara Lavender. Production, use, and fate of all plastics ever made. **Science advances**, v. 3, n. 7, p. e1700782, 2017.

EVODE, Niyitanga et al. **Plastic waste and its management strategies for environmental sustainability.** Case Studies in Chemical and Environmental Engineering, v. 4, p. 100142, 2021.

ALASSALI, Ayah et al. Towards higher quality of recycled plastics: Limitations from the material's perspective. **Sustainability**, v. 13, n. 23, p. 13266, 2021.

RITCHIE, Hannah; ROSER, Max. **How much plastic waste ends up in the ocean?**. Our World in Data, 2023.

CHAMAS, Ali et al. Degradation rates of plastics in the environment. ACS **Sustainable Chemistry & Engineering**, v. 8, n. 9, p. 3494-3511, 2020.

MCDONOUGH, William; BRAUNGART, Michael. **Cradle to Cradle: Remaking the way we make things**. New York: North Point Press, 2002.

MANZINI, Ezio; VEZZOLI, Carlo. **O desenvolvimento de produtos sustentáveis: Os requisitos ambientais dos produtos industriais.** Editora da Universidade de São Paulo, p. 25-25, 2002.

TARNE, P.; TRAVERSO, M.; FINKBEINER, M. Review of life cycle sustainability assessment and potential for its adoption at an automotive company. **Sustainability**, Basel, v. 9, n. 4, art. 670, 2017. Disponível em: <https://www.mdpi.com/2071-1050/9/4/670>. Acesso em: 20 Fev. 2024.

RACHURI, S.; SRIRAM, R. D.; SARKAR, P. **Metrics, standards and industry best practices for sustainable manufacturing systems.** In: IEEE INTERNATIONAL CONFERENCE ON AUTOMATION SCIENCE AND ENGINEERING, 2009, Bangalore, India. Proceedings […].). New York: IEEE, 2009. p. 472-477.

NARAYAN, Ramani. Biodegradable plastics. **Opportunities for innovation: biotechnology**, NIST GCR, p. 93-633, 1993.

PETERSEN, Karina et al. Potential of biobased materials for food packaging. **Trends in food science & technology**, v. 10, n. 2, p. 52-68, 1999.

DEMMER, Brian. **Comparison and analysis of biobased/biodegradable and petrochemical cutlery flexibility**. 2011.

GROSS, Richard A.; KALRA, Bhanu. Biodegradable polymers for the environment. **Science**, v. 297, n. 5582, p. 803-807, 2002.

OLIVEIRA, Adna Caroline Vale; SILVA, Aline de Souza; MOREIRA, Ícaro Thiago Andrade. Economia Circular: Conceitos e Contribuições na Gestão de Resíduos Urbanos. **RDE-Revista de Desenvolvimento Econômico**, v. 3, n. 44, 2020.

MACARTHUR, Ellen et al. Towards the circular economy: Accelerating the scale-up across global supply chains. **Journal of Industrial Ecology**, v. 3, n. 1, p. 23-44, 2014.

MACARTHUR, Ellen et al. Towards the circular economy: Opportunities for the consumer goods sector. **Journal of Industrial Ecology**, v. 2, n. 1, p. 23-44, 2013.

VELENTURF, A. P. M. et al. **A new perspective on a global circular economy**. 2019.

LISIECKI, M. et al. Circular economy initiatives are no guarantee for increased plastic circularity: A framework for the systematic comparison of initiatives. **Resources, Conservation and Recycling**, v. 197, p. 107072, 2023.

JÜRGENS, Meret; ENDRES, Hans-Josef. Environmental impacts of circular economy practices for plastic products in Europe: Learnings from life cycle assessment studies. **Procedia CIRP**, v. 122, p. 312-317, 2024.

CHENAVAZ, Régis Y.; DIMITROV, Stanko. From waste to wealth: Policies to promote the circular economy. **Journal of Cleaner Production**, p. 141086, 2024.

FELDMAN, Jessica et al. **Circular economy barriers in Australia: How to translate theory into practice?**. Sustainable Production and Consumption, 2024.

TURKCU, Deniz; TURA, Nina. **The dark side of sustainable packaging: Battling with sustainability tensions.** Sustainable Production and Consumption, v. 40, p. 412-421, 2023.

RAINATTO, Graziela Maira et al. How can companies better engage consumers in the transition towards circularity? Case studies on the role of the marketing mix and nudges. **Journal of Cleaner Production**, v. 434, p. 139779, 2024.

CHANDRA, R.; RUSTGI, Renu. **Biodegradation of maleated linear low-density polyethylene and starch blends.** Polymer Degradation and Stability, v. 56, n. 2, p. 185-202, 1997.

VAN BEILEN, Jan B.; POIRIER, Yves. Production of renewable polymers from crop plants. **The Plant Journal,** v. 54, n. 4, p. 684-701, 2008.

LAMBERT, Scott; WAGNER, Martin. Environmental performance of bio-based and biodegradable plastics: the road ahead. **Chemical Society Reviews**, v. 46, n. 22, p. 6855-6871, 2017.

SNELL, Kristi D.; PEOPLES, Oliver P. PHA bioplastic: A value-added coproduct for biomass biorefineries. **Biofuels, Bioproducts and Biorefining:** Innovation for a sustainable economy, v. 3, n. 4, p. 456-467, 2009.

MORES, Giana de Vargas; FINOCCHIO, Caroline Pauletto Spanhol; BARICHELLO, Rodrigo; PEDROZO, Eugenio Avila. Sustainability and innovation in the Brazilian supply chain of green plastic. J**ournal of**

cleaner production, v. 177, p. 12-18, 2018.

DEMMER, Brian. **Comparison and analysis of bio-based/biodegradable and petrochemical cutlery flexibility**. 2011.

HUANG, Ting-Yen; DUAN, Kon-Jen; HUANG; Shih-Yow; CHEN, C. Will. Production of polyhydroxyalkanoates from inexpensive extruded rice bran and starch by Haloferax mediterranei. **Journal of Industrial Microbiology and Biotechnology**, v. 33, n. 8, p. 701-706, 2006.

MEADOWS, D. H., J. Randers, et al. **The limits to growth: the 30- year update. White River Junction**, Vt: Chelsea Green Publishing Company. 2004. xxii, 338 p.

DAVIS, Georgina; SONG, J. H. **Biodegradable packaging based on raw materials from crops and their impact on waste management.** Industrial crops and products, v. 23, n. 2, p. 147-161, 2006.

AUTHORS:

ORCID: 0000-0002-3330-2449
NICOLAS DE SOUZA SCHAULET, MESTRANDO. | UFRGS | PGDesign | Porto Alegre, RS - Brasil | Av. Geúlio Vargas, 1232 - Apto 104, Menino Deus, Porto Alegre - RS, 90150-004 | nicolasschaulet@gmail.com

ORCID: 0000-0001-7727-2088
VINICIUS GADIS RIBEIRO, DOUTOR. | UFRGS| PGDesign | Porto Alegre, RS - Brasil | Km 92, RS-030, Emboaba, Tramandaí, RS, 95590-000 | vinicius.gadis@ufrgs.br

ORCID: 0000-0003-2109-0677
JOCELISE JACQUES DE JACQUES, DOUTORA. | UFRGS| PGDesign | Porto Alegre, RS - Brasil | Av. Osvaldo Aranha, 99 - 4º Andar - Sala 408, Centro - Porto Alegre, RS, 90035-190 | jocelise.jacques@ufrgs.br

HOW TO CITE THIS ARTICLE:

SCHAULET, Nicolas de Souza; RIBEIRO, Vinicius Gadis; JACQUES, Jocelise Jacques de. Polymers and Sustainability: Overview of the use of concencional and biodegradable polymers. **MIX Sustentável**, v. 10, n. 4, p. 85-97, 2024. ISSN 2447-3073. Disponível em: <http://www.nexos.ufsc.br/index.php/mixsustentavel>. Acesso em: _/_/_.doi: <https://doi.org/10.29183/2447-3073.MIX2024.v10.n4.85-97>.

SUBMITTED ON: 10/09/2024
ACCEPTED ON: 13/09/2024
PUBLISHED ON: 30/09/2024
RESPONSIBLE EDITORS: Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli

Record of authorship contribution:
CRediT Taxonomy (http://credit.niso.org/)

NSS: formal analysis, investigation, methodology, project admnistration, supervision, visualization, writing - original draft and writing - review and editing;

VGR: supervision and writing - orginal draft.

JJJ: methodology, project admnistration, supervision, visualization, writing - original draft and writing - review and editing;

Conflict declaration: nothing has been declared.