Eco-based polymers: A review concerning bioplastics with greater manufacturing potential

https://doi.org/10.56238/sevened2024.026-027

Leonardo Luís Rossetto[1], Nycollas Stefanello Vianna[2], Altemir José Mossi[3] and Helen Treichel[4]

ABSTRACT

Currently, it is almost impossible to imagine a world without plastics. These are widely used in various sectors of the economy, such as packaging, construction, transport, healthcare, and electronics, due to their low cost, versatility, durability, and high strength/weight ratio. However, the durability of plastics after use becomes an environmental problem, as a large part of plastic waste ends up in landfills, is incinerated, or discarded illegally, contaminating ecosystems and contributing to global warming. A promising alternative to mitigate these impacts is the development of bioplastics, which are bio-based, biodegradable materials, or both. Bioplastics include poly(lactic acid) (PLA), polyhydroxyalkanoates (PHA), bio-based polyamide (PA), and polypropylene (PP), which have the potential to replace conventional plastics in various applications. Global production of bioplastics is growing, estimated to reach 7.43 million tons by 2028, driven by demand for more sustainable alternatives. Despite challenges, such as high production costs and even inferior properties compared to synthetic plastics, investments in research and development promise to improve these materials. This scope reviews the bioplastics with the most significant manufacturing potential in the coming years. With technological advancement and growing environmental awareness, bioplastics are expected to be crucial in transitioning to a low-carbon circular economy.

Keywords: Bioplastics, Poly (lactic acid), Polyamide, Polyhydroxyalkanoates, Polymers, Polypropylene.

---

[1] Laboratory of Microbiology and Bioprocesses, Federal University of Fronteira Sul, Environmental Science and Technology.

[2] Laboratory of Microbiology and Bioprocesses, Federal University of Fronteira Sul, Environmental Science and Technology.

[3] Laboratory of Microbiology and Bioprocesses, Federal University of Fronteira Sul, Environmental Science and Technology.

[4] Laboratory of Microbiology and Bioprocesses, Federal University of Fronteira Sul, Environmental Science and Technology.
E-mail: helentreichel@gmail.com

INTRODUCTION

Plastics are increasingly present throughout the economy, serving as an essential enabler for sectors as diverse as packaging, construction, transportation, healthcare, and electronics, and have brought enormous economic benefits to these sectors, thanks to the combination of low cost, versatility, durability and high strength/weight ratio. The success of plastics is reflected in the exponential growth of their production over the last half-century and the increasing substitution of other packaging materials (Neufeld et al., 2016).

The word "plastic" refers to a group of synthetic materials made from hydrocarbons, materials formed through polymerization, which consists of a series of chemical reactions with organic raw materials, mainly natural gas and crude oil. Different types of polymerization allow the production of plastics with specific properties, such as hard or soft, opaque or transparent, flexible or rigid (Zamora et al., 2020).

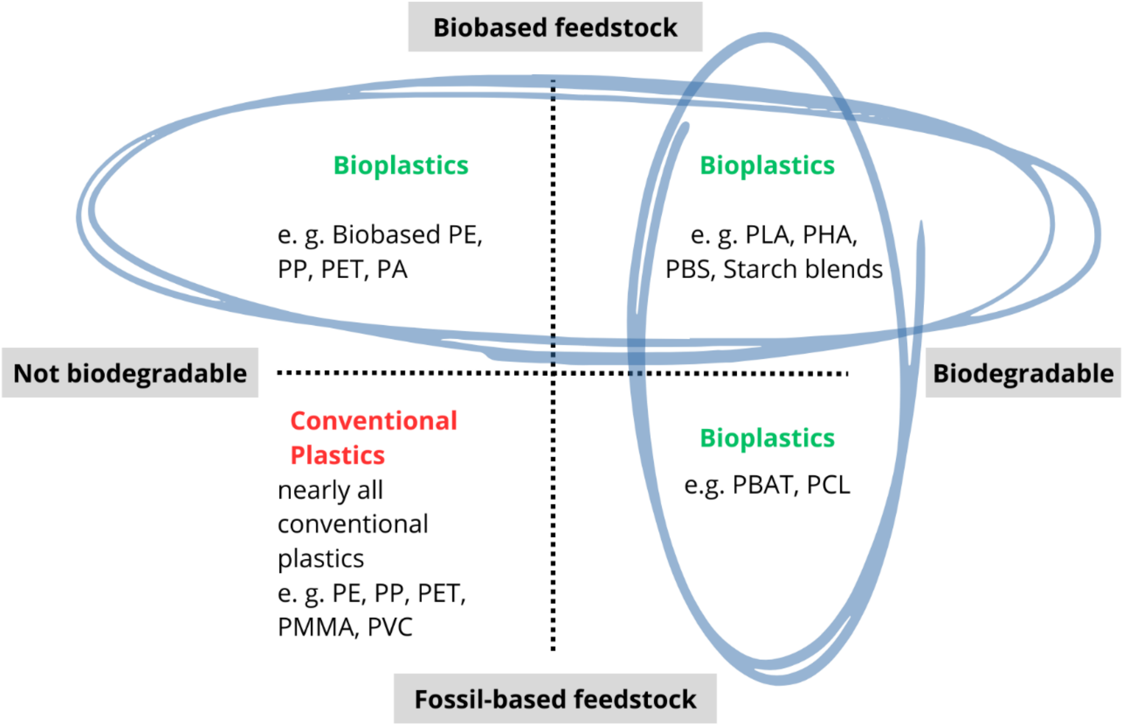
Plastic is considered by many to simplify modern life due to its usability and ease, but its outstanding post-use durability makes it a severe problem. A significant portion of plastic waste is incinerated in landfills, causing more pollution and contributing to global warming. Another portion of this waste is illegally discarded on streets, beaches, rivers, and oceans, contaminating ecosystems. In the oceans, plastic degrades into microplastics that marine fauna ingests, often captured and sold for human consumption. An excellent alternative to these problems would be to increase the use of plastic through recycling; however, its quality deteriorates with each reuse cycle. This implies that sooner or later, waste needs final disposal (Zamora et al., 2020).

Thus, biodegradable polymers represent an alternative to deal with the problems above. These materials combine the expected properties of plastics, allow efficient processing and usability of products, and are, at the same time, biodegradable (Šprajcar et al., 2012).

Polymers are high molecular mass compounds built through the interconnection of perennial basic blocks called monomers. Living organisms in metabolic processes synthesize different polymers that they need to perform various functions such as transporting genetic information (DNA), providing rigidity in cell walls (cellulose), storing energy (in some microorganisms, polyester), etc. In addition to the natural polymers mentioned, numerous synthetic polymers are, in principle, more or less similar to natural ones. Still, they are artificially produced by man and do not exist in nature. This group is responsible for almost all the plastics we use, with around 75% of all global plastic production being represented by polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyethylene (PE) (Šprajcar et al., 2012).

Bioplastics, in turn, comprise a whole family of materials with different properties and applications. According to European Bioplastics, a plastic material is defined as bioplastic if it is bio-based, biodegradable, or has both properties. The term “biobased” means that the material or product is derived from biomass, such as corn, sugar cane, or cellulose. The term "fossil base" or "fossil origin" means that the material or product is derived from petroleum. Thus, there are three groups of bioplastics, as shown in Figure 1: bio-based (or partially bio-based) plastics, bio-based and biodegradable plastics, and plastics based on fossil resources and biodegradable (European Bioplastics, 2022).

Figure 1 - Material coordinate system for bioplastics

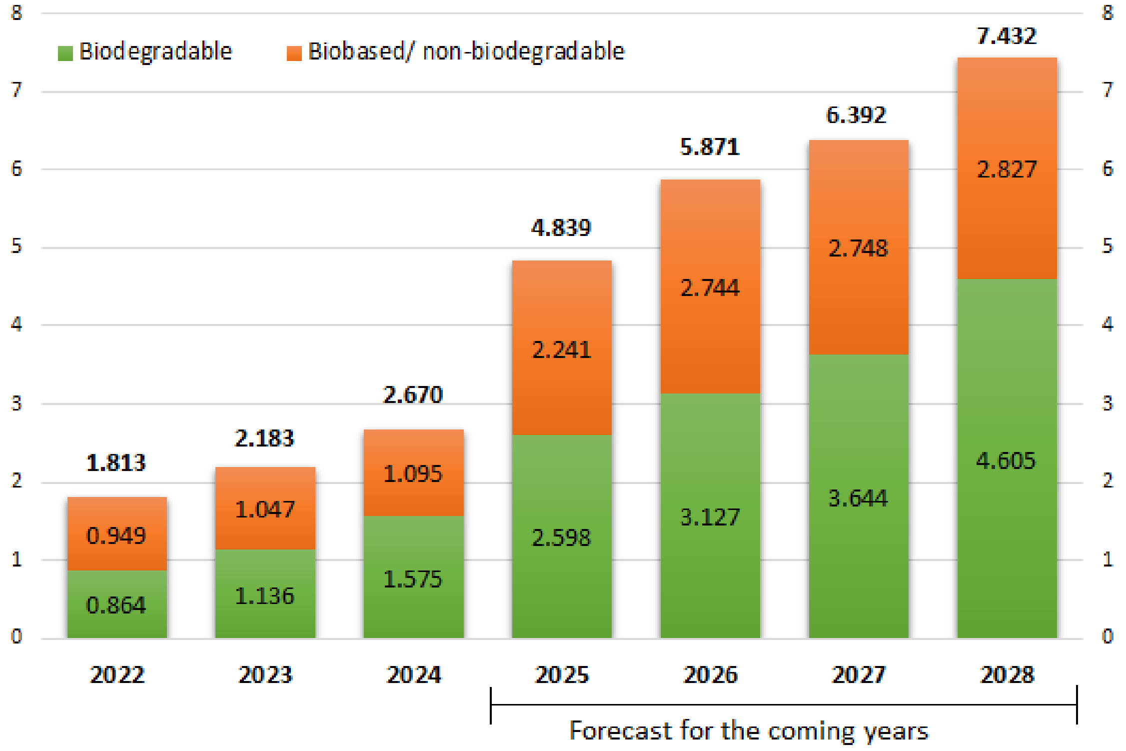


Source: Adapted from European Bioplastics (2022).

The rampant increase in the production and consumption of plastic materials, inadequate disposal, and growing concern about microplastic pollution are driving people and industry to seek more sustainable alternatives. In this context, the manufacture of bioplastics is gaining prominence, as, according to European Bioplastics, in 2022, the global production capacity of these materials reached 1.81 million tons, and it is estimated that this number will reach 7.43 million tons by 2028.

These new plastic materials can be processed into various products using conventional plastic processing technologies. The bioplastics industry is a young and innovative sector with notable economic and ecological potential, being able to use resources more efficiently, helping in the transition to a low-carbon circular bioeconomy. The global bioplastics market is estimated to grow continuously in the coming years, surpassing the two percent mark of global plastics production (European Bioplastics, 2022). Figure 2 presents the growing estimate of the worldwide production capacity of these materials, divided between non-biodegradable plastics made from renewable sources and biodegradable plastics.

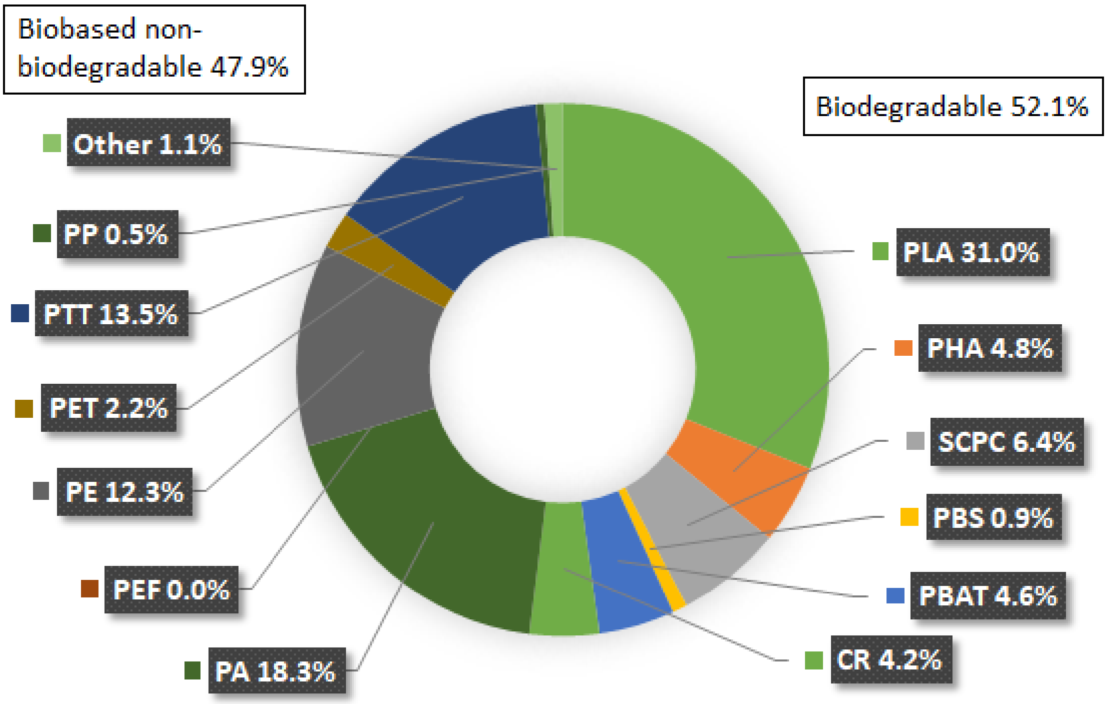
Figure 2 - Global bioplastics production capacities 2022-2028 at 1 million tons



Source: Adapted from European Bioplastics (2022).

Bioplastic alternatives exist for almost all conventional plastic materials and their corresponding applications. Due to the strong development of polymers such as poly(lactic acid) (PLA), polyhydroxyalkanoates (PHA), polyamides (PA), as well as a steady growth of polypropylene (PP), production capacities will continue to increase significantly over the next five years. Bioplastics are used for an increasing variety of applications, from packaging and consumer products to electronics, automotive, and textiles. Packaging continues to be the largest segment of these products, with 43% (934 thousand tons) of the total bioplastics market in 2023. Figure 3 shows the types of bioplastics most produced in 2023, according to European Bioplastics (2023).

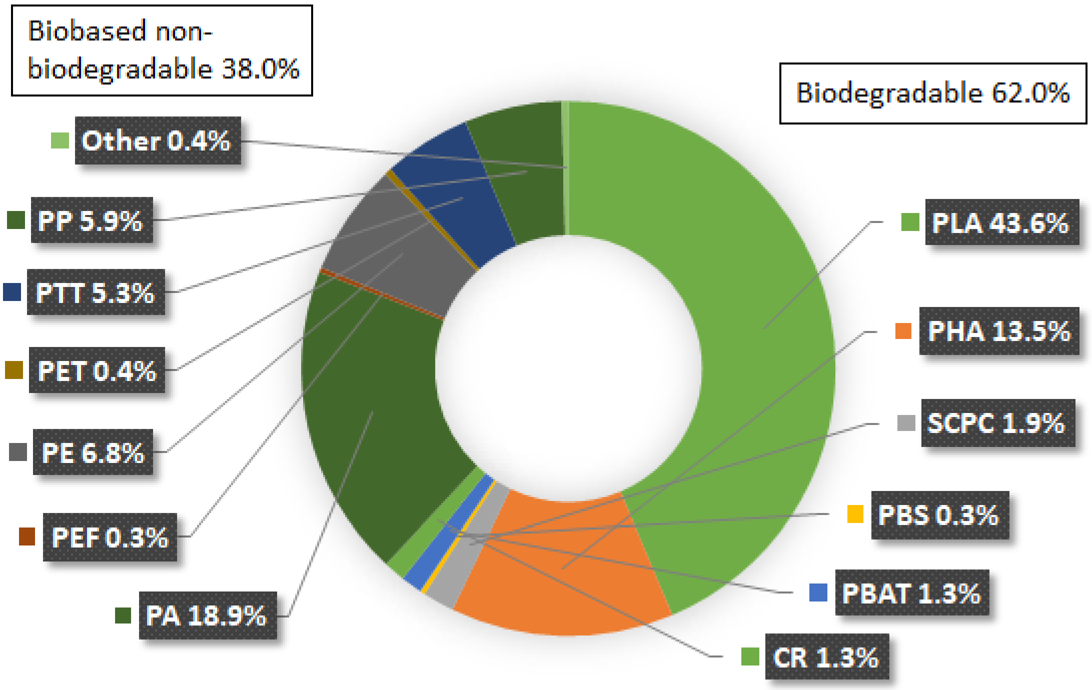
Figure 3 - Global bioplastics production capacities in 2023 by material type.



Source: Adapted from European Bioplastics (2023).

Next, Figure 4 shows the bioplastics that will potentially be the most produced in 2028 (European Bioplastics, 2023). Based on this information, a review of the literature is presented on the bioplastics that will probably have the highest production capacities in 2028: Poly (lactic acid) (PLA), Polyhydroxyalkanoates (PHA), and Polyamide (PA). In addition, Polypropylene (PP) is expected to increase from just 0.5% of global production capacity in 2023 to 5.9% in 2028.

Figure 4 - Estimated global bioplastic production capacities in 2028 by type of material.



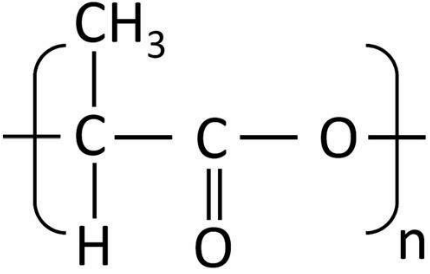
Source: Adapted from European Bioplastics (2023).

The methodology used in this study was bibliographic and exploratory research, where an extensive search for material was carried out in scientific articles and books published between 2000 and 2024, and the databases used in this research were CAPES Periodicals, Google Scholar, and ScienceDirect. The following topics were investigated from these databases: plastics, bioplastics, and bio-based polymers.

POLY (LACTIC ACID) (PLA)

Poly(lactic acid) (PLA) is currently the market leader in the bio-based and biodegradable plastics segment. At the same time, polymer is often considered to be closest to conventional plastics in terms of production costs. PLA is a thermoplastic aliphatic polyester obtained by polymerizing lactic acid from renewable resources such as corn starch, tapioca roots, and sugar cane. The general chemical structure of PLA is shown in Figure 5.

Figure 5 - Chemical structure of PLA.



As a thermoplastic polyester, it softens when heated and hardens when cooled. It can be cooled and heated several times without changing its mechanical and chemical properties. This allows the material to be shaped and processed by liquefaction and molding techniques and then recycled by similar processes. Due to its physical and chemical properties, flexibility, brightness, and light transmittance, PLA can technically compete with conventional plastics comparable to PE, PP, PVC, PS, and other plastics (Wellenreuther et al., 2022).

PLA is mainly used in the food industry to prepare disposable tableware, such as cups, cutlery, trays, plates, containers, and packaging for sensitive food products (Atiwesh et al., 2021). It has high strength but low toughness, so additives are necessary to balance stiffness and toughness, along with acceptable heat resistance (Nagarajan et al., 2016). Several commercial grades of PLA are explicitly designed for thermoforming and extrusion/injection molding processes. It can also be used for soil retention coatings, agricultural films, shopping bags, and packaging material. Additionally, PLA can be converted into fibers by spinning and used to manufacture disposable and biodegradable fabric items such as clothing, feminine hygiene products, and diapers (Atiwesh et al., 2021).

PLA production generally involves the following process steps: raw material extraction, glucose extraction, fermentation, and polymerization. PLA can be prepared by direct condensation of lactic acid or by ring-opening polymerization of cyclic lactide dimers (Elsawy et al., 2017). The exact process routes differ in the choice of biological raw materials used as a starting point in producing these polymers. Different production steps and inputs are required depending on the raw material, affecting process costs. Under natural conditions, PLA can be degraded into water and carbon dioxide in a controlled time and without causing severe environmental pollution, unlike petroleum-based plastics (Wellenreuther et al., 2022).

Figure 6 represents the life cycle of a PLA-based product. The initial process is photosynthesis (1). Then, starch is extracted from corn and other grains (2), which is fermented into lactic acid (3), which undergoes polymerization to produce PLA (4). This plastic is used to manufacture tableware packaging, among other products (5). After the use phase, PLA can be treated and disposed of in an environmentally friendly way (6). Through composting, PLA undergoes biodegradation (6), releasing water and carbon dioxide, which are essential for photosynthesis to occur (1), restarting the cycle (Peng and Sun, 2017).

Figure 6 - PLA production and degradation cycle

Source: Adapted from Peng and Sun (2017).

Choosing the raw material for PLA production is crucial both economically and technologically. Corn and sugar cane dominate the plant sources used for PLA, but new resources are being explored for lactic acid production. These include agricultural and industrial waste, such as straw and sugarcane bagasse, and byproducts from the food industry, such as cheese whey and food processing waste. Furthermore, there is a growing trend to exploit marine resources for raw materials such as algae. Production costs depend on raw material prices, technological progress, and process scaling costs. Political measures and fluctuations in oil prices also influence the demand for bio-based plastics and the expansion of PLA production capabilities (Wellenreuther et al., 2022).

Table 1 compares the results of some studies and presents the average production cost for one ton of PLA in US dollars. The values range from 1,048 to 3,558 USD per ton of PLA. The main cost factors identified in the studies were raw materials, energy, labor, and capital (Wellenreuther et al., 2022).

Table 1 - Comparison of literature results on PLA costs.

Reference	Raw material(s)	Annual production capacity (t)	Average cost per ton PLA (USD)
Chiarakorn et al. (2014)	Cassava	100,000	2,515
Jim Lunt & Associados (2010)	Potato; Wood	50,000	2,393
Kwan et al. (2018)	Waste of food	10,624	3,558
Manandhar e Shah (2020)	Corn grain	100,000	1,048
Sanaei e Stuart (2018)	Triticale	100,000	1,204

The wide variation in results arises from different process approaches, with differences in raw material selection and assumptions about the production process. Therefore, the results are not directly comparable. The choice of raw material is a crucial factor that influences not only the direct costs associated with its input but also impacts the subsequent stages of the process. Furthermore, the energy use and technology involved, especially in the PLA refinery, are significant for production costs, mainly when innovative raw materials are used. Additive and waste disposal costs also vary depending on the raw material chosen and the subsequent stages of the technological process (Wellenreuther et al., 2022).

Table 2 presents the average price per type of plastic of fossil origin (petroleum) per ton. There is a price range between 1,045 and 1,274 USD, depending on the type of plastic. Comparing Tables 1 and 2, it can be seen that although PLA can compete with conventional plastics from a technical point of view, PLA prices still cannot keep up with those of traditional plastics. PLA production costs exceed or, at most, equal the production costs of fossil-based plastics.

LA-based bioplastics are biodegradable under industrial composting conditions and anaerobic digestion but are hardly biodegradable in soil and aquatic environments. PLA requires specific high-temperature conditions and degrades through abiotic hydrolysis. Therefore, it is labeled as compostable in most Western countries (Choe et al., 2021).

At the same time, bioplastics also have environmentally friendly characteristics. For example, producing PLA saves two-thirds of the energy needed to make traditional plastics. Furthermore, it has been scientifically established that there is no net increase in carbon dioxide gas during the biodegradation of PLA bioplastics. This was evidenced by the fact that the plants from which they were produced absorb, through photosynthesis, the same amount of carbon dioxide released during the biodegradation of these plastics. Notably, PLA emits 70% fewer greenhouse gases when degraded in landfills. Other studies also cite that replacing traditional plastic with corn-based PLA bioplastics can reduce greenhouse gas emissions by 25%. Such examples assure that future production of new bioplastics can be realized through renewable energy and, at the same time, substantially reduce greenhouse gas emissions (Atiwesh et al., 2021).

Table 2 - Comparison of the costs of different types of fossil plastic.

Type of Plastic (fossil)	Average price per ton in 2019 (USD)
HDPE film	1,110
LDPE Film	1,045
PP homopolymer fiber	1,092
PS crystal	1,259
EPS (styrofoam)	1,274

PLA has many applications in Brazil, including food service utensils, films, and sheets; thermoformed rigid packaging; fibers; three-dimensional printing; and durable products. Unlike conventional petroleum-based plastics, this material can be recycled economically.

Although biodegradable, PLA cannot be disposed directly in nature or landfills. The product must be discarded in composting plants together with other organic waste. Thus, within 180 days and under ideal conditions, it will convert 90% of its mass into CO_2 (carbon dioxide) and water and 10% into biomass that can be used as fertilizer for gardens, vegetable gardens, and crops.

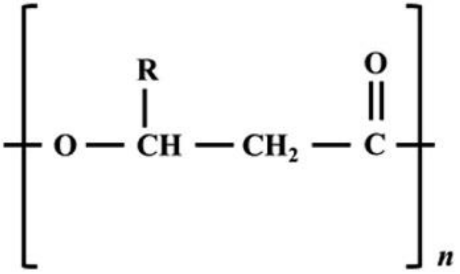
In short, PLA is a promising alternative to conventional plastics, as it is obtained from renewable resources, has properties similar to petrochemical plastics, and is biodegradable under specific conditions. The bioplastics industry's continued development, technological advances, and favorable policies could allow PLA to become a more competitive alternative to conventional plastics, favoring the transition to a more sustainable economy.

POLYHYDROXYALKANOATES (PHA)

Some bacteria can produce bioplastics as a way of storing energy and carbon. These bioplastics are biocompatible and, as they are edible by microorganisms, they are entirely biodegradable. They are produced by bacterial fermentation of lipids or sugar. Polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), and their byproducts are the most widely produced microbial bioplastics (Kumar et al., 2024).

PHAs are hydroxyalkanoate (HA) polyesters, and their chemical structure is shown in Figure 7. They are synthesized by different microorganisms inhabiting different ecological niches. This synthesis occurs in the cell under adverse conditions, such as a shortage of oxygen and essential nutrients such as phosphorus or nitrogen. However, the presence of a carbon source is a prerequisite for the biosynthesis of PHAs (Behera et al., 2022).

Figure 7 - Chemical structure of PHA



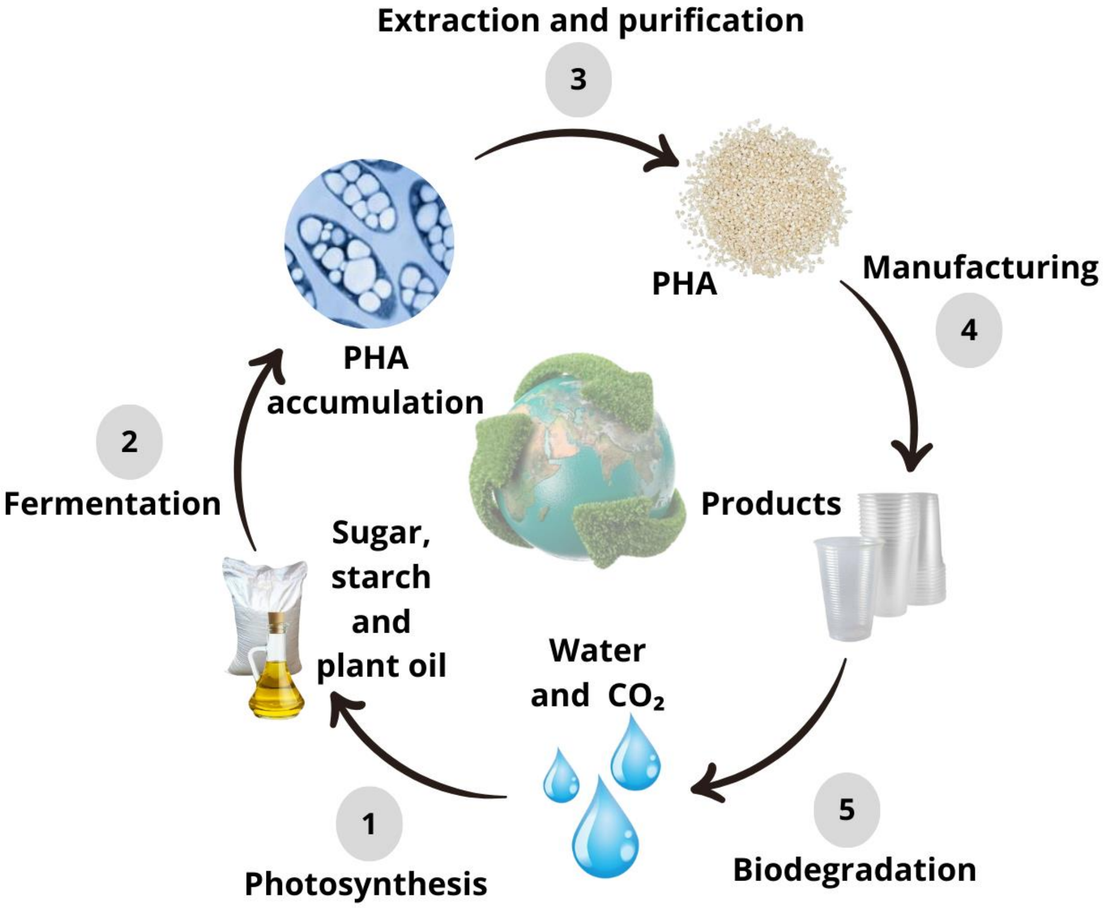
$$\left[-O-\overset{R}{\overset{|}{CH}}-CH_2-\overset{O}{\overset{\|}{C}}- \right]_n$$

In particular, PHA can be produced from methane released from feedstock in wastewater treatment facilities, landfills, composting facilities, waste haulers, and biorefinery operators. In this way, successful and low-cost commercial PHA production can be achieved. PHA can also be produced from biomass from wood, grass, and crop residues rather than the more expensive biomass obtained from edible crops. This new technology separates biomass from water and uses heat instead of acids, solvents, or enzymes to produce bioplastics. Thus, PHA can be used commercially in bioplastic packaging, shampoo bottles, or polyester fibers combined with natural clothing materials. Marine microorganisms can naturally digest PHA bioplastics and reach the ocean when broken down into methane. At the end of its life cycle, the developed bioplastic can be decomposed into virgin plastic, as it is compostable and degradable in the sea (Atiwesh et al., 2021).

Although chemical and biological approaches can be applied to synthesize PHA, those with higher molecular weight can be quickly produced by biological means compared to chemical methods. The metabolic pathway for PHA production varies significantly between different microbial groups. These biopolymers are synthesized in the stationary and exponential phases of microbial growth. PHAs are produced under favorable, balanced growth conditions in the exponential phase. In the stationary phase, limiting nutrients such as nitrogen, phosphorus, oxygen, and excessive carbon sources leads to the synthesis and accumulation of PHAs. Excess nutrients are stored by microbial cells in the form of PHAs and are then mobilized upon the advent of favorable growth conditions (Behera et al., 2022).

Figure 8 represents the life cycle of a PHA-based product. The initial process is photosynthesis (1). Through it, vegetables produce sugar, starch, or oil, fermented by microorganisms (2). Microbial accumulation of PHA occurs due to hydrocarbon degradation. After this accumulation, PHA is extracted and purified (3), giving rise to bioplastic used in industrial, biomedical, and environmental applications (4). At the end of the product's useful life, the PHA is discarded, undergoing biodegradation (5), producing biomass, water, and carbon dioxide that will later be consumed during the photosynthesis process (1), restarting the cycle (Choiniere, 2015).

Figure 8 - PHAs production and degradation cycle



Source: Adapted from Choiniere (2015).

Characteristics such as biodegradability, biocompatibility, non-toxicity, and other mechanical properties make PHAs suitable for various applications in diverse sectors. The industrial application of these biopolymers includes their use as packaging material, coating, and ecological bags. The reported antibacterial properties of polymers have led to increasing interest in their use in sanitary products, including diapers, feminine hygiene products, and cosmetic containers. The biocompatible nature of these polymers is beneficial for their use in biomedical sectors, including implants, bone grafts, tissue engineering, and drug delivery systems. It is possible to use PHA as a matrix for the controlled release of drugs such as antibiotics, immunogens, contraceptives, hormones, and other active substances (Behera et al., 2022). The continuous use of synthetic plastics has been one of the main reasons for environmental pollution, so that PHAs can be an excellent substitute.

PHAs are biodegradable in soil under aerobic and anaerobic conditions; therefore, their use in agriculture is promising. They are often used in agricultural nets, mulch films, and grow bags. PHAs produced in biofilms or bioplastics for mulch are used not only to protect crops but also to increase their yield (Saravanan et al., 2022).

PHAs are very promising polyesters as a source of biofuels, as they do not need to be of high purity. Thus, PHAs can be obtained from crops, activated sludge, or nutritious wastewater, making them cost-effective while addressing the controversies between food versus fuel and fuel versus land. After being used as bioplastics, PHAs can undergo methyl esterification in biofuels, which further expands their application value. However, much research is still needed to make them profitable. PHA-based biofuels can be an alternative to existing biofuels, such as biodiesel, ethanol, methane gas, and hydrogen. Furthermore, biorefineries can produce several other metabolites with PHAs (Riaz et al., 2021).

Different microorganisms produce PHA with various molecular structures, monomer ratios, and molecular weights. Poly-3-hydroxybutyrate (PHB) stands out as the most abundant and extensively studied, synthesized by many bacteria, including Gram-negative *Cupriavidus necator*, *Ralstonia eutropha*, *Halomonas bluephagesis* and certain Gram-positive *Bacillus* and *Streptomyces* sp. Approximately 92 bacterial genera have demonstrated the ability to produce PHA under anaerobic and aerobic conditions, with more than 160 PHA monomers known. New synthetic monomers are added yearly (Park et al., 2024).

Several factors contribute to the environmental impact of PHA and other biomaterials. As mentioned previously, PHA brings benefits in terms of environmental impact due to its biodegradability and renewable origin using green raw materials. Energy consumption during the fermentation process to produce PHAs is considered less intense than traditional plastic production, which involves the extraction and refining of fossil fuels. Petrochemical processes emit significant greenhouse gases and consume substantial amounts of energy. Minimizing energy expenditure and using aggressive chemicals during downstream processing of PHA production is essential to reduce the environmental impact of this biomaterial. More research is needed to reduce the costs of this processing (Park et al., 2024).

Commercial production of value-added PHAs has been achieved using microorganisms such as bacteria, microalgae, and fungi. The chemical-mechanical properties of these biopolymers can be changed by copolymerization. Thus, various PHAs exhibiting modified physical properties can be synthesized by varying their chemical composition (Behera et al., 2022).

However, the microbial synthesis of PHAs has not yet been fully explored. A wide range of microorganisms with vast potential for large-scale production of these biopolymers remains unexplored. The main obstacles in the microbial production of PHAs include efficient strain selection, the high cost of carbon sources, the energy required for the cultivation and fermentation process, and the choice of efficient and environmentally friendly extraction methods. The development of advanced and energy-efficient strategies and the use of renewable carbon sources could be helpful for the economical production of these biodegradable materials. Furthermore, the development of genetically modified microorganisms can increase PHA yield. Using these biopolymers as plastic substitutes can ultimately reduce environmental pollution caused by petroleum-based plastics (Behera et al., 2022).

The cost of production remains a challenge, and PHA remains more expensive than petroleum-based polymers. The demand for PHA in different industries, especially high-end applications, can strategically reduce production costs. As demand for sustainable and biodegradable alternatives increases, economies of scale and technological advances could help make PHAs more cost-competitive with traditional plastics (Park et al., 2024).

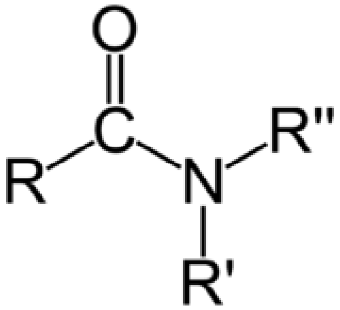
More than 25 companies, producing 30 different brands, integrate PHA into their production processes or final products. However, despite extensive research, only a limited selection of PHAs have achieved successful large-scale production and are commercially available as biodegradable materials (Koller and Mukherjee, 2022).

In summary, PHAs are produced by microorganisms from renewable carbon sources and represent a promising alternative to conventional plastics due to their sustainable and versatile properties. Continued research and development can help make their production and use even more efficient in the future.

POLYAMIDE (PA)

Polyamides (PAs) are probably best known by the colloquial name “nylon,” originating from the widely successful introduction of PA66 for women's pantyhose in the 1940s. Although the name “nylon” was initially limited to the trademark PA66, it has since become synonymous with the nomenclature of all polyamides. Polyamide resins are linear condensation polymers with a high degree of crystallinity with repetitions of amide bonds (–CO–NH–) in their molecular chain (Brehmer, 2013). Figure 9 shows the chemical structure of the organic amide function.

Figure 9 - Chemical structure of the amide



Currently, most polyamide raw materials are synthesized from petrochemical resources. With the increasing depletion of these sources, research into bio-based polyamides is becoming increasingly important. The production cost of bio-based aromatic monomers is high, and the performance of bio-based aromatic polyamides still has a particular gap compared with traditional petroleum-based aromatic polyamides. Currently, industrially produced bio-based polyamides are still limited to aliphatic polyamides. In general, if the source of polymer monomers contains materials derived from biomass and is obtained through biomanufacturing, it can be called a bio-based polyamide. Fortunately, with the development of metabolic engineering and biocatalysis, more and more raw materials can come from biology. Although polyamides can be synthesized and produced using bio-based monomer raw materials, this does not guarantee their biodegradability. Only PA-4 and itaconic acid-derived PA have been reported as biodegradable polyamides (Zheng et al., 2024).

Bio-based aliphatic polyamides (bio-PAs) are PAs fully or partially synthesized from renewable resources such as vegetable oils, fatty acids, cellulose, and lignin. Bio-PAs are obtained by several methods: (i) from raw or chemically modified natural polymers; (ii) through the reaction of a mixture of monomeric raw materials obtained from biomass and petroleum; (iii) through the polymerization of chemically tailored monomers that are entirely obtained from biomass feedstocks after complex chemical transformations to synthesize bio-PAs. The low solubility of these natural polymers limits their processing and applications, and it is challenging to remove various organic impurities and undesirable chemical compounds, which negatively influence their properties. Bio-PAs synthesized from mixtures of petroleum-based and bio-based resources or exclusively bio-based resources are more applicable routes in this field. Vegetable oils and fats have long been the primary biomass raw materials for bio-PA synthesis. Oil was the oldest known source of monomeric raw material obtained from its chemical transformation process (Khedr, 2023).

Castor oil from the Ricinus communis plant is used as the primary biomass feedstock in commercially available bio-PA production. This oil has long been considered a raw material for manufacturing essential consumer products such as soaps, lubricants, and coatings. Today, castor oil appears as a valuable raw material for biorefineries. It is non-edible and non-competitive in the food chain, making it suitable for manufacturing biofuels, biochemicals, and biopolymers (Khedr, 2023).

It has recently been discovered that bio-based polyamides 4,4 and 5,4, consisting of 1,4-diaminobutane, 1,5-diaminopentane, and succinic acid, which are produced by recombinant bacteria, are degraded by Brevundimonas vesicularis. They have emerged as practical solutions to current plastic problems, while polyamides produced in recent decades have shown low biodegradability due to their hydrogen bonds between polyamide molecular chains. These discoveries have opened a new chapter in the production of bio-based polyamides, suggesting the possibility of using them as recyclable polyamides and, as a result, providing environmental benefits through recycling. Therefore, producing polyamide monomers such as diamines, amino carboxylic acids, and diacids from renewable resources is also expected to impact the bioplastics industries significantly. However, the bio-based processes for producing these platform chemicals are still in the research and development phase (Son et al., 2023).

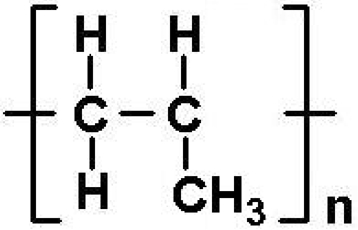
Towards the immediate replacement of petroleum-derived monomers with biomass-derived monomers, ongoing efforts are to develop a complete biorefinery process – a superior microbial cell factory and efficient pilot-scale fermentation and purification processes. With this step fully developed, a hybrid biochemical process for the biological production of polyamide monomers can be envisaged through bio-based monomers' chemical conversion. Furthermore, this process can be improved by identifying and developing enzymes that efficiently catalyze the reaction of ring formation, ring-opening polymerization, and polyamide degradation to establish microbial chassis for the production of fully sustainable bio-based and biodegradable polyamide (Son et al., 2023).

In short, bio-based “nylons” can be totally or partially derived from renewable sources, exhibiting excellent mechanical, thermal, and water absorption properties. They offer a path to reducing a company's carbon footprint while meeting consumer expectations for more sustainable products and materials.

POLYPROPYLENE (PP)

Polypropylene (PP), as a polymer catalytically prepared from propylene, was discovered in 1954 and gained strong popularity very quickly due to its lowest density among commercial plastics. The general chemical structure of PP is shown in Figure 10. It is one of the most widely used thermoplastics, offering an advantageous combination of toughness, tension, tear, flexural strength, and chemical resistance to heat and moisture (Gijsman and Fiorio, 2023).

Figure 10 - Chemical structure of polypropylene



Furthermore, PP can be processed using the most relevant techniques, such as injection molding, film and fiber extrusion, thermoforming, and blow molding. PP has been extensively used as a fundamental polymeric material, covering automobiles, cosmetics, textiles, and consumer packaging due to its excellent processability, chemical resistance, and moisture barriers. Almost a quarter of the world's thermoplastic demand is polypropylene (Gijsman and Fiorio, 2023).

PP is the second most popular base plastic in the petrochemical industry; however, more than 90% of its environmental impacts are attributed to the manufacturing phase, according to a recent life cycle assessment (LCA) of PP products. Consequently, continuous efforts are being made to produce bio-based PP at an industrial level through environmentally friendly processes. Biopolypropylene (bio-PP) is still in the pilot production phase and has not been fully commercialized, accounting for 1.9% of the bioplastics market. Sustainable methods of obtaining propylene from renewable biological resources are being investigated to reduce the environmental effect and depletion of fossil fuels (Wang et al., 2023).

Propylene can be generated in several ways from biological sources. The most popular is the fermentation of sugar cane to produce bioethanol, one of the primary intermediates for bio-PP synthesis. In this process, bioethanol is first converted into ethylene through dehydration, which is subsequently transformed into butene through dimerization. Finally, propylene monomer is obtained by metathesis of ethylene and butene. Another approach is through a thermochemical process, which employs different carbon-rich biomass feedstock (e.g., corn, grass, agricultural waste, etc.) that could be gasified to generate synthetic biogas. However, the gasification approach has much higher capital expenditure than the fermentation route. Furthermore, hydrotreatment of vegetable oil or used cooking oil can also be used to produce green propylene (Wang et al., 2023).

The main challenge faced by bio-PP producers is the development of process technologies that are cost-competitive with PP produced from fossil fuels. As large-scale production of bio-based PP began in 2019, the market is still in its early stages. Due to its versatile and diverse properties, bio-PP is predicted to become more widespread across several end-use sectors. Based on its application, the packaging sector mainly dominates the market due to strong demand in various industries, including food and beverage, consumer products, and automobiles. This material can also be used in the construction sector to manufacture panels, tubes, insulating, or flame retardant materials (Wang et al., 2023).

Kikuchi et al. (2017) carried out a life cycle assessment to verify the reduction in greenhouse gas emissions due to replacing products derived from fossil fuels with products derived from biomass. The results show reduced greenhouse gas emissions when using bio-PE and bio-PP resins. However, the reduction rate of bio-PE is higher than that of bio-PP because the reaction steps are increased and consume additional energy in the synthesis of propylene. Bio-based PP would be an immediate solution, featuring the same technical properties and recyclability found in the current PP portfolio today with the added benefit of a negative carbon footprint. It can be summarized that bio-PP is still in the pilot production phase, accounting for a small fraction of the bioplastics market. Its development faces significant challenges, including cost competition with conventional PP. However, bio-PP is expected to gain popularity across sectors due to its versatile properties and sustainability.

FINAL CONSIDERATIONS

Advances in the research and development of bio-based polymers such as poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), polyamide (PA), and polypropylene (PP) represent a significant shift in the plastics industry toward more flexible materials. Sustainable and environmentally friendly, these polymers are finding new applications in various industrial sectors, with growing demand driven by environmental and regulatory concerns.

Although biopolymers represent a promising alternative to traditional plastics, they face several significant challenges. Firstly, its large-scale production is still more expensive than conventional plastics. Furthermore, some bio-based polymers may have inferior properties to their synthetic counterparts. Another critical point is that the output of certain biopolymers can compete with food production due to the use of the same raw materials. These factors combined create considerable obstacles to society's widespread adoption of these new polymers.

However, investments in research and development have the potential to lead to advances that not only lower production costs but also improve the performance of bio-based polymers. Collaborations between companies, academic institutions, and government entities can catalyze innovation and speed up the adoption of sustainable polymers. Additionally, educating consumers about the advantages of biopolymers and highlighting the importance of recycling can foster greater acceptance of these materials.

Therefore, bio-based polymers, such as PLA, PHAs, PA, and PP, offer a promising alternative to traditional plastics derived from fossil fuels. With the continued advancement of technology and increased focus on sustainability, these materials are expected to play a vital role in transitioning to a greener and more circular economy.

LIST OF ABBREVIATIONS

Not applicable

DECLARATIONS

NOVELTY STATEMENT

This review offers a promising alternative to traditional plastics derived from fossil fuels. With the continued advancement of technology and increased focus on sustainability, these materials are expected to play a vital role in transitioning to a greener, more circular economy.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable

CONSENT FOR PUBLICATION

All authors agreed with this publication.

AVAILABILITY OF DATA AND MATERIALS

The datasets generated for this study are available upon request from the corresponding author.

COMPETING INTERESTS

There are no competing interests

FUNDING

CAPES, CNPq and FAPERGS

AUTHORS' CONTRIBUTIONS

LR, NSV: research of paper and manuscript organization.

AM, HT: research coordinators

ACKNOWLEDGMENTS

The authors thank the Brazilian Funding Agencies: Brazilian National Council for Scientific and Technological Development (CNPq - 302484/2022-1), Coordination of the Superior Level Staff Improvement (CAPES), the support of the Bioprocess and Biotechnology for Food Research Center

(Biofood), which is funded through the Research Support Foundation of Rio Grande do Sul (FAPERGS-22/2551-0000397-4), Federal University of Fronteira Sul (UFFS) and Federal University of Santa Catarina (UFSC) for the financial support.

REFERENCES

1. Atiwesh, G., Mikhael, A., Parrish, C. C., & Le, T. T. (2021). Environmental impact of bioplastic use: A review. *Heliyon, 7*(9). https://doi.org/10.1016/j.heliyon.2021.e07918.

2. Behera, S., Priyadarshanee, M., Vandana, & Das, S. (2022). Polyhydroxyalkanoates, the bioplastics of microbial origin: Properties, biochemical synthesis, and their applications. *Chemosphere, 294*, 133723. https://doi.org/10.1016/j.chemosphere.2022.133723.

3. Brehmer, B. (2013). Polyamides from biomass derived monomers. In *Bio-Based Plastics: Materials and Applications* (pp. 275–296). https://doi.org/10.1002/9781118676646.ch10.

4. Choe, S., Kim, Y., Won, Y., & Myung, J. (2021). Bridging three gaps in biodegradable plastics: Misconceptions and truths about biodegradation. *Frontiers in Chemistry, 9*, 671750. https://doi.org/10.3389/fchem.2021.671750.

5. Choiniere, P. (2015). Development of polyhydroxyalkanoate nanoparticles for cancer therapy. [Thesis, Syracuse University].

6. Elsawy, M. A., Kim, K., Park, J., & Deep, A. (2017). Hydrolytic degradation of polylactic acid (PLA) and its composites. *Renewable and Sustainable Energy Reviews, 79*, 1346–1352. https://doi.org/10.1016/j.rser.2017.05.143.

7. European Bioplastics. (2023). *Market data report 2023*. Disponível em: https://docs.european-bioplastics.org/publications/market_data/2023/EUBP_Market_Data_Report_2023.pdf. Acesso em: 23 abr. 2024.

8. European Bioplastics. (2022). *What are bioplastics?: Material types, terminology, and labels – an introduction*. Disponível em: https://docs.european-bioplastics.org/publications/fs/EuBP_FS_What_are_bioplastics.pdf. Acesso em: 23 abr. 2024.

9. Gijsman, P., & Fiorio, R. (2023). Long term thermo-oxidative degradation and stabilization of polypropylene (PP) and the implications for its recyclability. *Polymer Degradation and Stability, 208*, 110260. https://doi.org/10.1016/j.polymdegradstab.2023.110260.

10. Khedr, M. S. F. (2023). Bio-based polyamide. *Physical Sciences Reviews, 8*(7), 827–847. https://doi.org/10.1515/psr-2020-0076.

11. Kikuchi, Y., Oshita, Y., Mayumi, K., & Hirao, M. (2017). Greenhouse gas emissions and socioeconomic effects of biomass-derived products based on structural path and life cycle analyses: A case study of polyethylene and polypropylene in Japan. *Journal of Cleaner Production, 167*, 289–305. https://doi.org/10.1016/j.jclepro.2017.08.179.

12. Koller, M., & Mukherjee, A. (2022). A new wave of industrialization of PHA biopolyesters. *Bioengineering, 9*, 74. https://doi.org/10.3390/bioengineering9020074.

13. Kumar, R., Lalnundiki, V., Shelare, S. D., Abhishek, G. J., Sharma, S., Sharma, D., Kumar, A., & Abbas, A. (2024). An investigation of the environmental implications of bioplastics: Recent advancements on the development of environmentally friendly bioplastics solutions. *Environmental Research, 244*, 117707. https://doi.org/10.1016/j.envres.2023.117707.

14. Nagarajan, V., Mohanty, A. K., & Misra, M. (2016). Perspective on polylactic acid (PLA) based sustainable materials for durable applications: Focus on toughness and heat resistance. *ACS

Sustainable Chemistry and Engineering, 4*(6), 2899–2916. https://doi.org/10.1021/acssuschemeng.6b00321.

15. Neufeld, L., Stassen, F., Sheppard, R., & Gilman, T. (2016). *The new plastics economy: Rethinking the future of plastics*. World Economic Forum.

16. Park, H., He, H., Yan, X., Liu, X., Scrutton, N. S., & Chen, G. (2024). PHA is not just a bioplastic! *Biotechnology Advances, 71*, 108320. https://doi.org/10.1016/j.biotechadv.2024.108320.

17. Peng, T., & Sun, W. (2017). Energy modelling for FDM 3D printing from a life cycle perspective. *International Journal of Manufacturing Research, 12*(1), 83–98. https://doi.org/10.1504/IJMR.2017.10003722.

18. Plastic Portal. (2024). *Weekly commodity price report*. Disponível em: https://www.plasticportal.eu/en/cenove-reporty/. Acesso em: 23 abr. 2024.

19. Riaz, S., Rhee, K. Y., & Park, S. J. (2021). Polyhydroxyalkanoates (PHAs): Biopolymers for biofuel and biorefineries. *Polymers, 13*, 253. https://doi.org/10.3390/polym13020253.

20. Saravanan, K., Umesh, M., & Kathirvel, P. (2022). Microbial polyhydroxyalkanoates (PHAs): A review on biosynthesis, properties, fermentation strategies and its prospective applications for a sustainable future. *Journal of Polymers and the Environment, 30*, 4903–4935. https://doi.org/10.3390/polym13020253.

21. Son, J., Sohn, Y. J., Baritugo, K., Jo, S. Y., Song, H. M., & Park, S. J. (2023). Recent advances in microbial production of diamines, aminocarboxylic acids, and diacids as potential platform chemicals and bio-based polyamides monomers. *Biotechnology Advances, 62*, 108070. https://doi.org/10.1016/j.biotechadv.2022.108070.

22. Šprajcar, M., Horvat, P., & Kržan, A. (2012). *Biopolymers and bioplastics: Plastics aligned with nature*. Ljubljana: National Institute of Chemistry.

23. Wang, S., Muiruri, J. K., Soo, X. Y. D., Liu, S., Thitsartarn, W., Tan, B. H., Suwardi, A., Li, Z., Zhu, Q., & Loh, X. J. (2023). Bio-polypropylene and polypropylene-based biocomposites: Solutions for a sustainable future. *Chemistry – An Asian Journal, 18*(2), e202200972. https://doi.org/10.1002/asia.202200972.

24. Wellenreuther, C., Wolf, A., & Zander, N. (2022). Cost competitiveness of sustainable bioplastic feedstocks – A Monte Carlo analysis for polylactic acid. *Cleaner Engineering and Technology, 6*, 100411. https://doi.org/10.1016/j.clet.2022.100411.

25. Zamora, A. M., et al. (2020). *Atlas do plástico: Fatos e números sobre o mundo dos polímeros sintéticos*. Rio de Janeiro: Fundação Heinrich Böll no Brasil.

26. Zheng, L., Wang, M., Li, Y., Xiong, Y., & Wu, C. (2024). Recycling and degradation of polyamides. *Molecules, 29*(8), 1742. https://doi.org/10.3390/molecules29081742.