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ARTICLE

Bioplastics Life Cycle: Potential to Enhance Positive Environmental Impacts in the Circular Economy

Ciclo de Vida dos Bioplásticos: Potencial para Ampliar Impactos Ambientais Positivos na Economia Circular

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ABSTRACT | Objective: This article aims to critically analyze the life-cycle-related environmental potential of bioplastics and their technical, economic, and regulatory limitations within the circular economy. **Method:** The study is exploratory and qualitative and adopts a narrative bibliographic and documentary review with a structured search protocol. Peer-reviewed literature and institutional documents on circular economy, life cycle assessment, bioplastics, microplastics, waste management, and environmental regulation were selected using explicit eligibility criteria and analyzed through deductive-inductive thematic categorization. **Results:** The results indicate that bioplastics can contribute to reducing dependence on fossil resources, mitigating greenhouse gas emissions, and diversifying end-of-life routes, such as mechanical recycling, industrial composting, chemical recycling, anaerobic digestion, and energy recovery. However, these benefits depend on the type of raw material, production route, polymer characteristics, collection and treatment infrastructure, adequate labeling, consumer behavior, and supportive public policies. **Originality/Relevance:** The article contributes to the debate on bioplastics by emphasizing that their environmental performance cannot be assumed generically, but must be assessed through a life cycle and circular economy perspective **Theoretical/methodological contributions:** The study systematizes the main opportunities and limitations of bioplastics, connecting material classification, end-of-life alternatives, microplastic risks, and regulatory challenges. **Social/management contributions:** The findings support decision-making by companies, policymakers, and waste management actors seeking more sustainable material strategies.

Keywords | Circular economy; Sustainability; Sustainable development; Life cycle assessment; Bioplastics.

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RESUMO | Objetivo: Este artigo tem como objetivo analisar criticamente o potencial ambiental dos bioplásticos sob a perspectiva do ciclo de vida, bem como suas limitações técnicas, econômicas e regulatórias no contexto da economia circular. **Método:** O estudo caracteriza-se como exploratório e qualitativo e adota uma revisão narrativa bibliográfica e documental com protocolo de busca estruturado. Literatura científica e documentos institucionais sobre economia circular, avaliação do ciclo de vida, bioplásticos, microplásticos, gestão de resíduos e regulação ambiental foram selecionados mediante critérios explícitos de elegibilidade e analisados por categorização temática dedutivo-indutiva. **Resultados:** Os resultados indicam que os bioplásticos podem contribuir para reduzir a dependência de recursos fósseis, mitigar emissões de gases de efeito estufa e diversificar rotas de fim de vida, como reciclagem mecânica, compostagem industrial, reciclagem química, digestão anaeróbica e recuperação energética. Contudo, esses benefícios dependem do tipo de matéria-prima, da rota produtiva, das características do polímero, da infraestrutura de coleta e tratamento, da rotulagem adequada, do comportamento do consumidor e de políticas públicas de apoio. **Originalidade/Relevância:** O artigo contribui para o debate sobre bioplásticos ao destacar que seu desempenho ambiental não pode ser assumido de forma genérica, devendo ser avaliado sob a perspectiva do ciclo de vida e da economia circular. **Contribuições teórico-metodológicas:** O estudo sistematiza as principais oportunidades e limitações dos bioplásticos, articulando classificação dos materiais, alternativas de fim de vida, riscos associados aos microplásticos e desafios regulatórios. **Contribuições sociais/gerenciais:** Os achados apoiam a tomada de decisão de empresas, formuladores de políticas públicas e atores da gestão de resíduos que buscam estratégias mais sustentáveis de materiais.

Palavras-chave | Economia circular; Sustentabilidade; Desenvolvimento sustentável; Avaliação do ciclo de vida; Bioplásticos.

1 INTRODUCTION

Over the past three decades, the idea of sustainability has advanced, leading to important initiatives across the public, social, and business spheres. Since the Rio-92 Conference, the issue of sustainable development has resonated globally, with discussions about approaches to reduce resource use and about new ways of producing, using, and disposing of products that are less polluting and less harmful to the environment (Braungart et al., 2007; Hawken et al., 1999).

The initial milestone of the concept of sustainable development occurred in 1987, with the presentation of the Brundtland Report, produced by the World Commission on Environment and Development, which defined sustainable development as development that meets present needs without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987).

In this scenario, organizations have become more aware of the need to reduce the environmental impacts of their operations through environmental management tools (Hofer et al., 2012). Social and environmental pressures have also encouraged industrial systems to adopt cleaner production, recycling, and waste-valorization practices (Mussatto et al., 2006; Raupp et al., 2008).

Innovation in products and services, production systems, and business models, based on a new sustainability paradigm, is essential to generate economic development, social well-being, and ecological restoration within ecosystem limits. In business contexts, this transition requires reducing virgin material use, preventing waste, and increasing reuse, repair, remanufacturing, and recycling (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017).

Global production and consumption systems continue to intensify demand for materials and increase waste generation. Population growth, urbanization, and rising consumption amplify pressure on finite resources and on ecosystems' capacity to absorb emissions and residues. Consequently, organizational development models increasingly need to combine economic viability with resource productivity, waste prevention, and environmental regeneration (Ellen MacArthur Foundation, 2013; OECD, 2022).

In this context, bioplastics are increasingly relevant to the transition toward lower-impact materials because they may be produced from renewable biomass sources, such as sugarcane, corn, cassava, and biological residues (Barros et al., 2023; Castro, 2019; Pooja et al., 2023; Rosenboom et al., 2022). In Brazil, renewable polymers are particularly associated with sugarcane and ethanol, as illustrated by Braskem's I'm green™ bio-based polyethylene (Braskem, n.d.).

Bioplastics still represent a small share of the global plastics market, despite the expansion of installed capacity and applications (European Bioplastics, 2016). Their relevance to the bioeconomy and circular economy depends on whether production, use, and end-of-life routes are assessed across the life cycle rather than inferred solely from renewable feedstock or biodegradability claims (Rosenboom et al., 2022; Spierling et al., 2020).

Recent studies indicate that some bioplastics may present a smaller carbon footprint than fossil-based alternatives and may be compatible with existing recycling streams or controlled biodegradation routes. These benefits are conditional and vary according to polymer type, energy matrix, agricultural practices, additives, system boundaries, and end-of-life infrastructure (Bishop et al., 2021; Rosenboom et al., 2022; Van Roijen & Miller, 2022).

A critical life cycle assessment (LCA) is therefore necessary to evaluate opportunities and trade-offs across the value chain, from feedstock production to disposal or reintegration strategies. End-of-life options such as mechanical recycling, chemical recycling, industrial composting, anaerobic digestion, and energy recovery can lead to different environmental outcomes and do not occupy the same position in the circular value hierarchy (Spierling et al., 2020; Van Roijen & Miller, 2022).

The success of bioplastics consequently depends not only on technical properties but also on product design, waste-management infrastructure, public policies, clear labeling, and consumer behavior (Parveen et al., 2024; Rosenboom et al., 2022). In view of these considerations, this research aimed to critically analyze the life-cycle-related environmental potential of bioplastics and their technical, economic, and regulatory limitations within the circular economy.

2 THEORETICAL FRAMEWORK

2.1 Circular economy: foundations, principles, and transition from the linear model

The circular economy has gained prominence by proposing an economic model that minimizes waste generation, reduces dependence on virgin resources, circulates products and materials at their highest feasible value, and regenerates natural systems (Ellen MacArthur Foundation, 2013; Geissdoerfer et al., 2017). It challenges the linear logic of extraction, production, consumption, and disposal by treating waste prevention and value retention as design and management requirements rather than only as end-of-pipe actions.

Although definitions vary, the literature converges on the idea of closing, slowing, and narrowing resource loops through systemic changes in production and consumption (Kirchherr et al., 2017; Korhonen et al., 2018). Closing loops concerns the reintegration of secondary materials; slowing loops concerns extending product and component lifetimes; and narrowing loops concerns reducing material and energy inputs per unit of value delivered.

Circularity also distinguishes between technical and biological cycles. Durable materials should remain in technical cycles through maintenance, reuse, repair, refurbishment, remanufacturing, and recycling. Materials designed for biological cycles should return safely to natural systems under verified conditions, contributing nutrients without persistent or toxic residues (Braungart et al., 2007; Ellen MacArthur Foundation, 2013).

The hierarchy of resource-value-retention strategies is central to this approach. Strategies that avoid material demand, such as refuse, rethink, and reduce, generally retain more value than recycling or energy recovery. Reuse, repair, refurbishment, and remanufacturing preserve products, components, and embedded energy, while recycling recovers material after part of its value has already been lost. Energy recovery and disposal occupy lower positions in the hierarchy (Reike et al., 2018).

In organizational and supply-chain contexts, the circular economy therefore requires coordinated changes in product design, material selection, business models, reverse logistics, industrial processes, and consumer practices (Abdalla & Sampaio, 2018; Geissdoerfer et al., 2017). It also requires attention to rebound effects and burden shifting because a circular strategy can reduce one impact while increasing another, for example through additional energy use, land occupation, or infrastructure demand (Korhonen et al., 2018).

In this article, the circular economy is used as an analytical category through four criteria: reduction of virgin fossil inputs; retention of material and product value; compatibility with technical or biological cycles; and avoidance of environmental burden shifting identified through LCA. Under this lens, bioplastics are not considered circular by definition. Their circular contribution depends on the origin of the feedstock, product function, durability, collection system, recovery route, and environmental performance across the life cycle (Rosenboom et al., 2022; Spierling et al., 2020).

2.2 Conventional plastics and the problem of microplastics and nanoplastics

Plastic production has increased markedly since the mid-twentieth century, and the persistence of many polymers has made plastic waste a major environmental liability. Conventional petroplastics depend on non-renewable resources and generate impacts during extraction, refining, polymer production, use, and disposal (Barros et al., 2023; OECD, 2022).

After disposal, many plastics persist for long periods and progressively fragment into smaller particles rather than completely disappearing. This process generates microplastics and nanoplastics that can be transported across soils, water, air, and food chains (Bugatti et al., 2023; Wang et al., 2024).

Plastic pollution is intensified by high consumption volumes, short product lifetimes, and inadequate collection and treatment, especially for single-use products and packaging. Consequently, the environmental problem arises not only from the fossil origin of conventional plastics but also from material throughput, design choices, leakage, and fragmentation throughout the product life cycle (OECD, 2022).

Microplastics can alter soil properties and plant performance, while nanoplastics may interact with cells and biological processes. Evidence of human exposure has also expanded, although causal pathways and long-term health effects still require further investigation (Bugatti et al., 2023; de Souza Machado et al., 2019; Wang et al., 2024). These risks are relevant to bioplastics because bio-based origin does not prevent fragmentation, and biodegradability claims may not apply under uncontrolled environmental conditions.

2.3 Bioplastics: definition, classification, and production routes

Bioplastics have emerged as alternatives with potential to reduce dependence on fossil feedstocks and diversify material end-of-life options. However, the term includes heterogeneous polymers and should not be treated as synonymous with biodegradable plastic (Castro, 2019; Rosenboom et al., 2022).

InnProBio (2015) defines a bio-based product as one wholly or partly derived from biomass, including renewable raw materials such as wood, straw, sugar, corn, cassava, algae, and biological waste. In the plastics field, two distinct attributes must be separated: bio-based content, which concerns feedstock origin, and biodegradability, which concerns the capacity of a material to be converted by microorganisms under specified conditions into carbon dioxide, water, biomass, and mineral salts.

A polymer may therefore be bio-based and non-biodegradable, fossil-based and biodegradable, or both bio-based and biodegradable. Biodegradability does not guarantee rapid degradation in soil, freshwater, or marine environments, and compostability requires compliance with defined conditions of temperature, humidity, time, and disintegration (European Bioplastics, 2020; Van Roijen & Miller, 2022).

Common bio-based and biodegradable bioplastics include polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and thermoplastic starch (TPS). Processing routes include polymerization of bio-based monomers, modification of natural polymers, microbial synthesis, and adaptation of routes originally developed for fossil-based polymers (Parveen et al., 2024; Pooja et al., 2023).

Production from biogenic sources can reduce fossil carbon use, but environmental performance depends on crop type, agricultural inputs, land-use change, energy demand, allocation methods, and end-of-life assumptions. Agricultural residues and other non-food feedstocks can reduce some pressures, although their availability, logistics, and competing uses must also be considered (Bishop et al., 2021; Pooja et al., 2023; Rosenboom et al., 2022).

Market expansion has been accompanied by technological advances and increased interest in renewable materials (Amorim, 2019; Castro, 2019). Nevertheless, production costs, scale, raw-material availability, competition with food production, and insufficiently adapted collection and treatment systems remain barriers (Parveen et al., 2024).

2.4 Life cycle assessment applied to bioplastics

LCA is essential to compare bioplastics and conventional plastics because it evaluates impacts across interconnected stages rather than focusing on a single attribute. The results are influenced by the functional unit, system boundaries, electricity mix, feedstock production, transport, product performance, allocation of co-products, and end-of-life scenarios (Bishop et al., 2021; Rosenboom et al., 2022).

Biogenic carbon accounting requires particular care. Some scenario-based studies may report net greenhouse gas reductions greater than 100% relative to a fossil reference when carbon uptake during biomass cultivation is credited and favorable storage or end-of-life assumptions are adopted. Such results do not represent a literal efficiency improvement above 100%; they indicate a net-negative balance within a specific system boundary and are highly sensitive to carbon accounting, land-use change, time horizon, and allocation choices (Bishop et al., 2021; Rosenboom et al., 2022).

End-of-life assumptions are equally decisive. Mechanical recycling can preserve material value but may be constrained by contamination and polymer degradation. Chemical recycling may recover monomers but can require substantial energy. Industrial composting is appropriate only for certified compostable materials and suitable organic-waste systems, while energy recovery is lower in the circular hierarchy because it destroys material value (Spierling et al., 2020; Van Roijen & Miller, 2022).

Therefore, LCA findings should be interpreted as scenario-dependent rather than as universal evidence that a specific bioplastic is environmentally preferable. Comparative assessments should use equivalent functions and explicitly disclose assumptions about durability, collection rates, recycling yields, biodegradation conditions, and avoided products or energy (Bishop et al., 2021; Spierling et al., 2020).

2.5 Bioplastics and circular economy: convergences and trade-offs

Bioplastics converge with the circular economy when they reduce fossil feedstock use, are designed for long and repeated use, circulate through technically viable recovery systems, or safely return to a biological cycle under verified conditions. Their contribution is strongest when material choice is integrated with product design, reverse logistics, labeling, and local treatment infrastructure (Parveen et al., 2024; Rosenboom et al., 2022).

Trade-offs arise when renewable feedstocks increase land, water, fertilizer, or biodiversity pressures; when biodegradable plastics contaminate mechanical recycling streams; when compostable products are sent to landfills; or when short-lived applications increase total material throughput. In these situations, replacing fossil carbon with biogenic carbon does not necessarily retain material value or reduce total environmental impact (Bishop et al., 2021; Korhonen et al., 2018; Van Roijen & Miller, 2022).

End-of-life routes also differ in circular value. Reuse and high-quality mechanical recycling generally retain more embedded value than composting or energy recovery. Composting can be justified when the product is contaminated with food residues and the material is certified for industrial composting, while anaerobic digestion or energy recovery may be considered only under compatible technical and regulatory conditions (Spierling et al., 2020).

Accordingly, the analytical question is not whether bioplastics are inherently sustainable, but under which combinations of feedstock, function, design, infrastructure, policy, and consumer behavior they generate net environmental benefits and support circular value retention.

3 METHOD

3.1 Research design and scope

This study is exploratory and qualitative and adopts a narrative bibliographic and documentary review. The review was designed to integrate evidence from different disciplines and document types concerning circular economy, life cycle assessment, bioplastics, microplastics, waste management, and environmental regulation. It does not claim the exhaustive coverage or statistical synthesis expected of a systematic review.

3.2 Search strategy and eligibility criteria

The bibliographic survey was conducted in public scholarly search environments, specifically Google Scholar and SciELO, and was complemented by searches on publisher platforms and in institutional repositories. Documentary sources included publications from OECD, the United Nations, European

Bioplastics, industry associations, companies, and Brazilian legislative repositories. The main search combinations were: ("bioplastic*" OR "bio-based plastic*" OR "biodegradable plastic*") AND ("circular econom*" OR "life cycle assessment" OR LCA); ("bioplastic*" AND ("recycling" OR "composting" OR "end of life" OR "waste management")); ("microplastic*" OR "nanoplastic*") AND ("bioplastic*" OR "biodegradable plastic*"); and ("bioplastic*" OR "bio-based plastic*" OR "biodegradable plastic*") AND ("regulation" OR "policy" OR "legislation" OR "extended producer responsibility" OR "public procurement"). Equivalent terms in Portuguese were also used.

The main publication period was 2015 to 2025, while earlier seminal works were retained when necessary for conceptual and historical grounding. English- and Portuguese-language publications were considered. Inclusion criteria were direct relevance to the research objective, availability of sufficient bibliographic information or full text, scientific or institutional authority, and contribution to at least one stage of the bioplastics life cycle. Duplicates, opinion pieces without an identifiable evidence base, materials unrelated to life-cycle or circular-economy questions, and sources superseded by more complete primary documents were excluded.

The initial search was iterative and was not originally recorded as a systematic-review screening log. Consequently, exact database-level counts of retrieved and excluded records could not be reconstructed without artificial precision. The final analytical corpus comprised 39 documents listed in the references, after removal of duplicates, secondary repository links when primary sources were available, and sources that did not support the claims made in the text.

Table 1. Search and analysis protocol

DIMENSION	PROTOCOL ADOPTED
Review design	Exploratory narrative bibliographic and documentary review with a structured and transparent search protocol.
Search environments	Google Scholar; SciELO; publisher platforms; institutional and legislative repositories.
Main descriptors	Bioplastic*, bio-based plastic*, biodegradable plastic*, circular econom*, life cycle assessment, LCA, microplastic*, nanoplastic*, recycling, composting, end of life, waste management, regulation, policy, legislation, extended producer responsibility, public procurement.
Time and language	Main emphasis on 2015–2025; earlier seminal publications retained. English and Portuguese.
Inclusion criteria	Direct relevance to the objective; adequate bibliographic information or full text; scientific or institutional authority; contribution to production, use, end-of-life, environmental impact, or regulation.
Exclusion criteria	Duplicates; unsupported opinion pieces; sources unrelated to life-cycle or circular-economy analysis; secondary repository links when primary sources were available.
Analytical corpus	39 documents included in the final reference list. Exact initial hit counts were not retrospectively reconstructable because the original review was narrative and iterative.
Analysis	Deductive-inductive thematic coding followed by integrative synthesis across five analytical axes.

Source: Authors (2026).

Table 1 consolidates the main parameters adopted in the review and clarifies the scope, eligibility criteria, and composition of the analytical corpus. Based on this protocol, the selected materials were subsequently subjected to thematic coding and integrative synthesis, as detailed in the following subsection.

3.3 Thematic analysis and synthesis

The material was analyzed through thematic coding informed by the procedures proposed by Braun and Clarke (2006). A hybrid deductive-inductive strategy was used. Initial codes were derived from the objective and from circular-economy and LCA constructs, including feedstock origin, value retention, technical and biological cycles, environmental trade-offs, and end-of-life compatibility. During full-text reading, additional codes emerged from the evidence and were incorporated into the coding framework.

The codes were reviewed and consolidated into five analytical axes: overview of bioplastics production and use; environmental and socioeconomic advantages; technological and market challenges; microplastics and environmental regulation; and opportunities for the circular economy. The axes were therefore partly defined a priori and partly refined from the material. The methodological path is summarized in Figure 1.

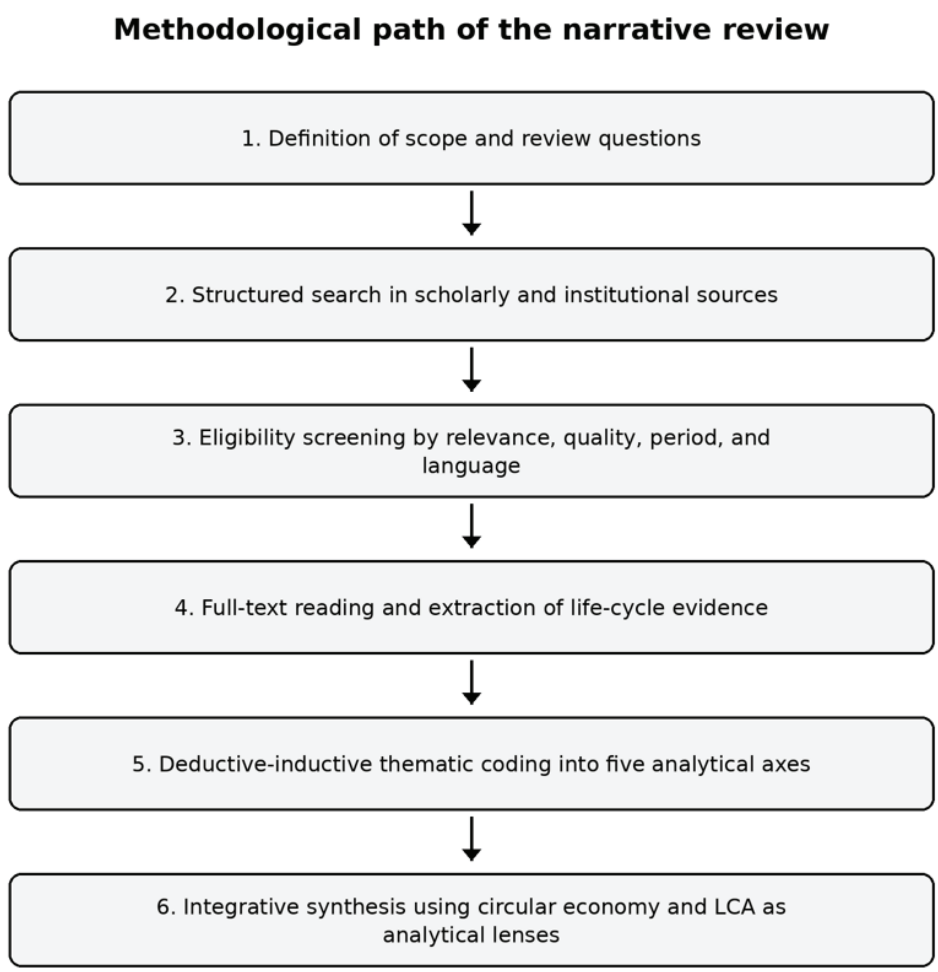

Figure 1. Methodological path of the narrative review

Source: Authors (2026).

Figure 1 summarizes the methodological sequence adopted, from the definition of scope and search procedures to thematic coding and integrative synthesis. Based on this process, the findings are presented and discussed in the following section according to the five analytical axes established in the review.

4 RESULTS AND DISCUSSION

4.1 Overview of the production and use of bioplastics in the context of the circular economy

Understanding the role of bioplastics in the circular economy requires a clear distinction between two central attributes: the origin of the raw material and the material's biodegradability. This distinction is important because the term "bioplastic" encompasses different types of polymers with distinct environmental performances, production routes, and end-of-life possibilities.

Figure 2 summarizes the classification of bioplastics by raw material origin and biodegradability, based on the material coordinate system proposed by European Bioplastics (2020). This distinction is central to avoiding generalizations, since bio-based materials may not be biodegradable, whereas some fossil-based polymers may be biodegradable under specific conditions (Castro, 2019; European Bioplastics, 2016).

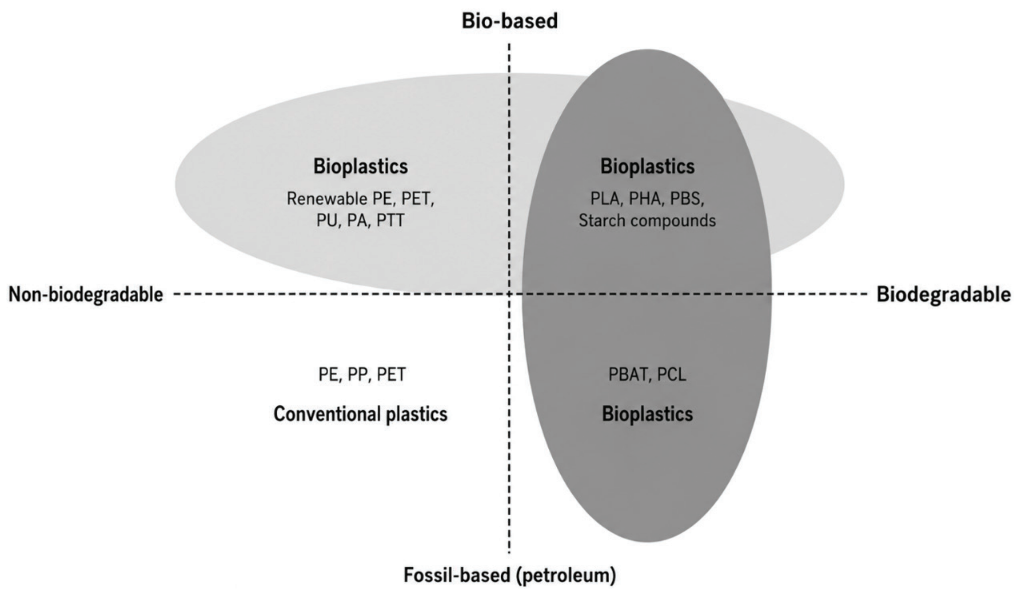

Figure 2. Bioplastics according to their characteristics

Source: Adapted from European Bioplastics (2020).

The first group consists of polymers produced from renewable sources but not biodegradable, such as polyethylene (PE), poly(ethylene terephthalate) (PET), polyurethane (PU), polyamide (PA), and poly(trimethylene terephthalate) (PTT). The second group includes bioplastics that are both renewable and biodegradable, including poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), poly(butylene succinate) (PBS), and starch-based materials. The third group is composed of fossil-derived polymers that are biodegradable under specified conditions, such as poly(butylene adipate-co-terephthalate) (PBAT) and polycaprolactone (PCL) (Castro, 2019; European Bioplastics, 2020).

Bioplastics still account for a small share of global plastic production, but technical and market assessments indicate substantial potential for expansion and substitution in selected applications. These estimates should be interpreted as scenarios rather than forecasts because actual adoption depends on cost, product performance, feedstock availability, regulation, and end-of-life infrastructure (Parveen et al., 2024; Van Roijen & Miller, 2022).

Industry reports compiled in the reviewed literature project growth in global bioplastics production capacity and market value over the current decade (Parveen et al., 2024). The expansion reflects technological development and demand for lower-fossil-carbon materials, but it does not by itself demonstrate improved environmental performance.

In Brazil, Braskem's I'm green™ bio-based polyethylene illustrates a commercial route based on sugarcane ethanol. The company reports that the material retains the performance and recyclability of conventional polyethylene and presents a favorable cradle-to-gate carbon balance because biogenic carbon uptake is included in the calculation (Braskem, n.d.). Such company-reported values should be interpreted within their declared system boundaries and verified against application-specific LCA assumptions.

The versatility of plastics does not automatically ensure alignment with circular-economy principles. Circular performance depends on product design, duration of use, collection, sorting, reuse, recycling, and the prevention of leakage. These conditions also relate to Sustainable Development Goal 12 on responsible consumption and production (ABIPLAST, 2023; United Nations, 2015).

Historical studies show that conventional polymers became central to mass production and consumption during the twentieth century, while interest in biodegradable and bio-based polymers expanded with concerns about fossil resources, waste accumulation, and climate change (Schaulet et al., 2024).

Research on biodegradable polymers includes PHAs, cellulose-based materials, starch compounds, and other polymers produced through fermentation or chemical conversion. Brazil has relevant feedstock conditions for sugarcane-based production, although land use, water demand, and competing uses of biomass must be evaluated (Castro, 2019; Schaulet et al., 2024).

Biodegradable polymers may degrade more rapidly than conventional plastics only when the required environmental or industrial conditions are present. Consequently, biodegradation is a potential end-of-life route, not an intrinsic guarantee of harmless or rapid disappearance in any environment (European Bioplastics, 2020; Van Roijen & Miller, 2022).

4.2 Environmental and socioeconomic advantages of bioplastics

Gross and Kalra (2002) highlight that renewable raw materials may reduce dependence on fossil carbon. Recent reviews also indicate that bio-based materials can reduce climate impacts across their life cycle, provided that biomass production, energy use, and end-of-life management are appropriately controlled (Bishop et al., 2021; Rosenboom et al., 2022; Spierling et al., 2020).

For PLA, the literature identifies potential energy and greenhouse gas advantages over some conventional plastics. However, these benefits depend on feedstock, electricity mix, agricultural management, product performance, and disposal route. Biodegradation should not be assumed generically because it depends on polymer type, additives, temperature, humidity, microbial activity, and treatment conditions (Parveen et al., 2024; Rosenboom et al., 2022; Van Roijen & Miller, 2022).

The expansion of bio-based plastics has been led in part by durable, non-biodegradable polymers such as bio-based polyethylene and polyurethane. This distinction is important because renewable origin can reduce fossil feedstock use while the material remains in a technical cycle and requires conventional collection and recycling systems (Castro, 2019).

Production-capacity data compiled by Castro (2019) show the historical prominence of polyurethane, bio-based PET, starch compounds, PLA, and bio-based polyethylene. These figures demonstrate the diversity of the market, but older capacity data should be treated as historical evidence rather than as a description of the current market.

The environmental and socioeconomic advantages of bioplastics therefore include potential fossil-resource substitution, technological innovation, diversification of agricultural and waste-derived feedstocks, and new industrial opportunities. Their realization depends on avoiding land-use conflict, maintaining product performance, and creating collection and recovery systems that preserve material value.

4.3 Technological and market challenges

The bioplastics market is influenced by the cost and availability of raw materials, production and distribution costs, consumer demand, crude-oil prices, product-performance requirements, and regional restrictions on conventional plastics (Parveen et al., 2024).

Biodegradable bioplastics can remain more expensive than conventional polymers, especially at limited production scales. Localizing feedstock supply and production may reduce import exposure and logistics costs, but economic viability also depends on stable demand, quality control, and infrastructure investments.

While economies of scale and technological advances may reduce costs, the initial investment required to transition from conventional plastics to bioplastics can discourage companies and consumers. Agricultural feedstocks also require land, water, and inputs that may compete with food production or habitat conservation (Bishop et al., 2021; Parveen et al., 2024).

The properties of bioplastics are frequently misinterpreted, leading to the misconception that all are environmentally preferable or fully biodegradable. This confusion can favor greenwashing when environmental benefits are communicated without corresponding evidence across the life cycle (Parveen et al., 2024; Rosenboom et al., 2022; Van Roijen & Miller, 2022).

Techno-economic barriers extend to end-of-life management. Bioplastics do not have a single post-consumer route; management depends on polymer type, biodegradability, recyclability, contamination, and local collection, sorting, and treatment infrastructure (Spierling et al., 2020; Van Roijen & Miller, 2022).

Source separation and sorting are decisive because incorrect disposal can contaminate mechanical recycling or organic-waste streams. Standardized labeling and consumer education are therefore necessary to direct materials to compatible systems (Parveen et al., 2024; Van Roijen & Miller, 2022).

Mechanical recycling is often the preferred value-retention route for durable bio-based polymers when a sufficiently pure stream exists. Composting applies only to certified compostable materials under controlled conditions and does not recover the polymer as a material. Chemical recycling can recover monomers but may involve high energy and process requirements (Parveen et al., 2024; Spierling et al., 2020).

Anaerobic digestion may represent an additional biological treatment route for compatible certified biodegradable materials within organic-waste systems. Its feasibility is polymer- and process-specific and depends on biodegradation rates, methane recovery, digestate quality, and the availability of suitable industrial infrastructure (Spierling et al., 2020).

Energy recovery may be considered for non-recyclable materials where regulated facilities exist, but it is lower in the waste hierarchy because material value is lost. Landfilling and uncontrolled disposal provide the least circular outcomes and may result in persistence, methane generation, or fragmentation depending on the polymer and environmental conditions (Spierling et al., 2020).

The life cycle of bioplastics begins with biomass selection, which directly influences land, water, biodiversity, and climate outcomes. It continues through production and use and ends in a route that may retain material value, return biological nutrients under controlled conditions, recover energy, or lose the material entirely. Integrated planning is therefore required across feedstock policy, product design, reverse logistics, infrastructure, and environmental education (Bishop et al., 2021; Rosenboom et al., 2022).

Improperly managed plastics, including non-biodegradable bio-based plastics and some materials marketed as biodegradable, can fragment and affect soil and aquatic systems. Microplastics can alter soil properties and plant performance, while additives or sorbed contaminants may also be released (de Souza Machado et al., 2019).

Bioplastics can also contaminate conventional plastic or organic recycling streams when they are incorrectly sorted. The consequences include increased separation costs, lower process yields, and reduced quality of recycled or composted outputs (Parveen et al., 2024; Van Roijen & Miller, 2022).

4.4 Microplastics and environmental regulation

Microplastics and nanoplastics are found in seawater, freshwater, soils, food, and air. Human exposure may occur through ingestion and inhalation, while environmental effects depend on particle size, shape, polymer, additives, concentration, and exposure conditions (Bugatti et al., 2023; Wang et al., 2024).

Primary microplastics are intentionally manufactured at microscopic size, whereas secondary microplastics result from fragmentation and abrasion of larger products. Microplastics are commonly defined as particles smaller than 5 mm, while nanoplastic definitions vary and often include particles below 1 μm (Bugatti et al., 2023).

Microplastics have been detected in human tissues and biological samples, including placenta and breast milk. These findings demonstrate exposure, but they should not be interpreted as conclusive evidence of specific clinical outcomes. The literature emphasizes the need for standardized analytical methods and longitudinal research to clarify dose-response relationships and long-term risks (Bugatti et al., 2023; Wang et al., 2024).

The scale of plastic pollution requires technological, behavioral, and regulatory responses. The international process for a legally binding instrument on plastic pollution was initiated in 2022 and addresses the full plastics life cycle, including production, design, and disposal. The fifth session continued through INC-5.2 in August 2025. INC-5.3 was held on 7 February 2026 for organizational and administrative purposes, including the election of officers, and no substantive negotiations were held. Preparatory activities for INC-5.4 are ongoing, while differences regarding scope, production controls, financing, and implementation remain central to the process (United Nations Environment Programme, 2026).

Without additional policies, global plastic production and waste are projected to increase substantially by 2060, reinforcing the need for instruments that act across the life cycle rather than only at disposal (OECD, 2022).

In Brazil, legislative initiatives have sought to restrict single-use plastics and encourage reusable, recyclable, or biodegradable alternatives. Bill No. 1,228/2020 proposed national restrictions on selected single-use plastic products, while São Paulo State Law No. 17,110/2019 prohibited the supply of plastic straws in specified establishments and required alternatives (Brazil, Chamber of Deputies, 2020; São Paulo [State], 2019).

For the bioplastics sector, regulation should combine clear definitions, certification, labeling, extended producer responsibility, public procurement, collection standards, and investment in recycling and composting infrastructure. Climate policies can create indirect incentives for lower-carbon materials, but renewable feedstock alone is insufficient without verified life-cycle performance and compatible end-of-life systems (Fortuna, 2020; OECD, 2013; Parveen et al., 2024).

4.5 Opportunities for the circular economy

The accumulation of plastic waste has strengthened interest in closed-loop systems. However, circularity should prioritize prevention, reuse, and value retention before considering material recovery. For bioplastics, this means selecting applications in which the material provides functional value and has a realistic post-consumer route.

Bioplastics can contribute to circular strategies by reducing fossil feedstock use, enabling repeated technical cycles for durable bio-based polymers, or enabling controlled biological treatment for certified compostable materials. Their incorporation into production systems should be linked to reuse, repair, recycling, remanufacturing, or appropriate organic-waste management rather than to a generic substitution narrative.

Packaging is one of the principal application segments for bioplastics, reflecting demand for alternatives in food and consumer-goods chains (Fortuna, 2020). Because food packaging must protect products against chemical and microbiological agents, circular design must balance material reduction, food-waste prevention, product safety, recyclability, and compostability.

Novel materials and products, including seaweed- and starch-based applications, demonstrate innovation potential, but environmental claims require evidence regarding sourcing, durability, decomposition conditions, and post-consumer management (Fortuna, 2020).

Incorporating bioplastics into the production chain can support more sustainable material strategies when it reduces fossil-resource dependence and is combined with value-retention systems. Their strategic role therefore depends on application-specific LCA, circular design, credible labeling, and coordination among industry, government, consumers, and waste-management actors.

5 FINAL CONSIDERATIONS

5.1 Synthesis of findings

Bioplastics represent a potentially important alternative to conventional plastics, but their environmental performance cannot be assumed from the terms “bio-based,” “biodegradable,” or “compostable” alone. The reviewed evidence indicates that benefits depend on feedstock, production technology, energy matrix, land-use effects, product function, collection, sorting, and end-of-life treatment.

The circular-economy analysis shows that bioplastics contribute most when they reduce virgin fossil inputs and retain value through long use, reuse, or high-quality recycling, or when certified materials safely enter a compatible biological cycle. Composting, chemical recycling, energy recovery, and disposal present different trade-offs and should not be treated as equivalent circular strategies.

The study also identified persistent barriers, including higher production costs, competition for biomass and land, insufficient post-consumer infrastructure, inconsistent labeling, consumer confusion, contamination of waste streams, and greenwashing. Public policy, ecodesign, standards, environmental education, and infrastructure investment are therefore as important as material innovation.

5.2 Study limitations

This study is a narrative and exploratory review rather than a systematic review or meta-analysis. The original bibliographic collection was iterative and did not generate a complete screening log; therefore, exact counts of initial records and exclusions could not be reconstructed. This limits reproducibility compared with protocols such as PRISMA and may introduce selection bias.

The review also combines heterogeneous evidence, including peer-reviewed articles, academic works, institutional reports, company information, and legal documents. Differences in functional units, system boundaries, geographic contexts, technologies, and end-of-life assumptions restrict direct comparison among LCA results and prevent statistical generalization.

Finally, the rapid evolution of bioplastics markets, regulations, and waste-management technologies means that production data and policy status can become outdated. The findings should therefore be interpreted as an integrative synthesis of the available corpus rather than as a definitive ranking of polymers or end-of-life routes.

5.3 Future research agenda

Future studies should conduct comparative LCAs for Brazilian conditions using consistent functional units and transparent assumptions about electricity, agriculture, land-use change, transport, collection rates, recycling yields, composting infrastructure, and biogenic carbon. Longitudinal and real-world studies are needed to compare laboratory biodegradation claims with actual waste-management performance.

Research should also evaluate the effectiveness of Brazilian regulatory instruments, certification and labeling systems, extended producer responsibility, public procurement, and incentives for recycling and industrial composting. Studies on consumer understanding and disposal behavior could clarify how labels influence contamination of recycling and organic-waste streams.

Additional priorities include ecodesign for disassembly and recyclability, development of non-food and residue-based feedstocks, assessment of chemical recycling and anaerobic digestion, monitoring of microplastic formation from biodegradable and bio-based polymers, and business models that prioritize reduction, reuse, and material value retention. Collaboration among universities, industry, public authorities, and waste-management organizations will be essential to translate technical potential into effective circular outcomes.

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