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Environmental and Technoeconomic Performance of Bioplastics

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Abstract

Plastic production continues to rise while waste persists in natural and built environments, driving demand for materials that lower impacts without sacrificing performance. This review synthesizes current evidence on bioplastics that are biobased, biodegradable, or both, covering materials families, renewable feedstocks, processing routes, application performance, environmental outcomes, and end of life options. Major polymer groups include polylactic acid, polyhydroxyalkanoates, starch and cellulose derivatives, and biobased drop in commodities. Feedstock pathways span lignocellulosic residues, agricultural byproducts, and algae and cyanobacteria, with attention to conversion efficiency and scalability. Application assessments focus on food packaging and construction, where property gaps in barrier performance, heat resistance, and durability can be narrowed through formulation, copolymer design, and reinforcement. Environmental analysis considers circular economy strategies, recycling and upcycling compatibility, controlled biodegradation in industrial systems, and risks from fragmentation into microplastics. Life cycle and technoeconomic perspectives highlight process sensitivities, including reactor design, extraction chemistry, energy sources, and waste handling. Policy, standards, labeling, and market communication shape adoption, while digital tools for waste collection and environmental monitoring can support accurate routing and leakage control. The review concludes with a research agenda that prioritizes harmonized standards, robust life cycle methods, microplastics and fate testing, and governance mechanisms that align incentives with verifiable circular outcomes.

Keywords: *Bioplastics; Circular economy; Food packaging; Microplastics; Algal biorefineries.*

1 Introduction

1.1 Historical development and problem framing

Plastics progressed from early curiosities to mass produced materials that reshaped economies and daily life, aided by wartime demand and postwar industrial expansion (Stanley et al., 2025). Their success brought durable performance at low cost, but also large environmental burdens across life cycle, including greenhouse gas emissions, waste accumulation, and leakage into terrestrial and marine ecosystems (Atiwesh et al., 2021). Waste mismanagement has contributed to pervasive contamination and declining environmental quality, motivating exploration of alternative materials and improved end of life systems (Thakur et al., 2018; Venkatachalam & Palaniswamy, 2020). Within this context, bioplastics have been advanced as candidates to reduce dependence on fossil feedstocks and to widen end of life options, while maintaining the functional benefits that drove the success of conventional plastics (Shah et al., 2021; Di Bartolo et al., 2021).

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1.2 Definitions and scope of bioplastics

The term bioplastics encompasses polymers that are biobased, biodegradable, or both, and it spans families such as polylactic acid, polyhydroxyalkanoates, starch and cellulose derivatives, and biobased drop in commodities including polyethylene and poly(butylene succinate) (Jeremić et al., 2020; Di Bartolo et al., 2021; Chauhan et al., 2024). Biobased origin and biodegradability are orthogonal attributes; a polymer can be biobased yet nonbiodegradable, or fossil based yet biodegradable (Di Bartolo et al., 2021). Degradation is material specific and condition dependent, therefore claims must be tied to certified environments and test methods (Jeremić et al., 2020). Introductory texts and sectoral reviews highlight cost, property gaps, and infrastructure as central constraints, while noting rapid advances in processing and formulation that are narrowing performance differences with incumbents (Kaur & Gupta, 2021; Chauhan et al., 2024).

1.3 Bioeconomy drivers and commercialization context

Bioplastics are embedded in broader bioeconomy strategies that seek to replace fossil resources with renewable feedstocks, generate rural and urban value through biomass valorization, and internalize environmental externalities (Sagapová, 2022). Market analyses depict small but growing shares for bioplastics, shaped by policy, standards, public awareness, and trust (Mozaffari & Kholdebarin, 2019). Communication and labeling influence purchasing and disposal decisions, while greenwashing can produce backlash and inhibit credible discourse about product sustainability (Cooke & Pomeroy, 2023). These conditions imply that material innovation must be matched with governance that supports accurate claims, harmonized standards, and end of life infrastructure, themes developed throughout this review (Di Bartolo et al., 2021; Rosenboom et al., 2022).

2 Methods

2.1 Scope and corpus

This review draws exclusively on the references provided in the commissioning brief, which span historical analyses, materials overviews, sectoral application studies, environmental and technoeconomic assessments, policy and market discussions, and digital systems relevant to waste operations (Di Bartolo et al., 2021; Jeremić et al., 2020; Xie et al., 2013). The corpus covers classification and properties of bioplastics, renewable feedstocks and production routes, application performance in packaging and construction, end of life options including recycling and composting, circular economy frameworks, microplastics risks, and governance and market dynamics (Rosenboom et al., 2022; Atiwesh et al., 2021; Leal Filho et al., 2025; Ali et al., 2023).

2.2 Eligibility and synthesis approach

Items were eligible if they addressed at least one of the following: (i) definitions and classifications of bioplastics; (ii) feedstocks and production pathways, including lignocellulosic and algal routes; (iii) application performance and property gaps; (iv) environmental impacts, life cycle or technoeconomic analysis; (v) end of life management across recycling and biodegradation; (vi) microplastics risks and degradation kinetics; (vii) policy, standards, market conditions, or digital enablers. Titles and abstracts were screened against these criteria. A structured narrative synthesis grouped findings by theme and sector, compared convergent and divergent claims, and extracted constraints and enabling levers for circular deployment. Where sources reported quantitative indicators or scenario parameters, these were retained with their original qualifier (Xie et al., 2013; Rueda et al., 2023; Andreasi Bassi et al., 2021).

2.3 Study quality and limitations

The corpus is dominated by narrative and critical reviews, complemented by sectoral assessments, LCA and technoeconomic case studies, and policy analyses (Shruti & Kutralam-Muniasamy, 2019; Rosenboom et al., 2022). Potential biases arise from nonsystematic searches in several reviews, heterogeneity in terminology and standards for biodegradability and bio-based content, and context dependence of end-of-life outcomes. Interpretations here remain within the bounds of the included sources, with explicit attention to scope limits, especially for biodegradation kinetics, microplastics formation, and transferability of LCA and TEA scenarios (Ahsan et al., 2023; Di Bartolo et al., 2021).

3 Materials and Feedstocks

3.1 Classification of bioplastics and major polymer families

Bioplastics are often organized along two orthogonal attributes, origin and end of life behavior. This yields four conceptual groups: biobased biodegradable, biobased nonbiodegradable, fossil-based biodegradable, and fossil based nonbiodegradable (Di Bartolo et al., 2021). Within this frame, major families include polylactic acid, polyhydroxyalkanoates, starch and cellulose derivatives, and biobased drop in commodities such as polyethylene and poly(butylene succinate) (Jeremić et al., 2020; Chauhan et al., 2024). Biobased origin does not guarantee biodegradability, and fossil origin does not preclude it. Degradation depends on chemical structure and on certified conditions, so claims require linkage to standards and test environments (Di Bartolo et al., 2021; Jeremić et al., 2020). Major types of bioplastic are classified and categorized in Table 1.

3.2 Lignocellulosic and other renewable sources

Lignocellulosic feedstocks are abundant, renewable, and non-edible, which makes them attractive sources for bioplastic precursors. They provide lignin and cellulose that can be modified by chemistry or processing to yield polymers and composites (Reshmy et al., 2021). Reported biobased plastics derived from lignocellulosic include polylactic acid, polyhydroxyalkanoates, bio polyethylene, polyurethanes, and starch based nano cellulosic materials (Reshmy et al., 2021). Broader surveys add agricultural residues and other biomass, with polysaccharides and proteins as key inputs. Thermoplastic starch is frequently cited as a prominent product of enzymatic reactions, and wastewater treatment byproducts appear as additional resource streams (Coppola et

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al., 2021). These sources stress that composition influences degradation behavior, and that matching materials to use and end of life context is necessary (Reshmy et al., 2021; Coppola et al., 2021).

3.3 Algal and cyanobacterial routes

Algal resources have gained attention due to high growth rates, limited competition with food systems, and the possibility of coupling cultivation with wastewater remediation (Nanda & Bharadvaja, 2022). Reviews describe derivatives from microalgae, cyanobacteria, and macroalgae. Examples include starch for film matrices, short chain length polyhydroxyalkanoates from cyanobacteria, and sulfated polysaccharides used as additives that tune barrier and mechanical behavior (Dang et al., 2022). Functional groups such as carboxyl, hydroxyl, and sulfate support chemical tailoring, which is relevant for food, pharmaceutical, and medical packaging (Dang et al., 2022). A market oriented assessment reports that replacing one ton of synthetic plastics with biobased alternatives can reduce about 1.8 tons of carbon dioxide emissions, while noting that algal bioplastics do not yet reach cost parity with petroleum based plastics. It recommends multidimensional approaches such as algal biorefineries and careful life cycle assessment (Nanda & Bharadvaja, 2022).

Life cycle and economic analysis of cyanobacterial polyhydroxybutyrate shows how process specification shapes outcomes. Raising intracellular PHB from 15 percent to 50 percent of dry cell weight reduced environmental impacts by roughly 67 to 75 percent, with dominant burdens from construction materials and from chloroform used in purification. The same study estimated a minimum selling price of 135 EUR per kilogram at 50 percent PHB and a productivity of 12.5 g m^{-3} d^{-1}, and calculated that a productivity of about 810 mg L^{-1} d^{-1} would be needed to approach 4 EUR per kilogram. Suggested levers included reactor geometry with lower volume to surface ratio and genetic modification to increase productivity (Rueda et al., 2023).

3.4 PHA production pathways

Comparative analyses group PHA production into three classes, microbiological, enzymatic, and chemical processes, and evaluate them on achievable molecular structures, raw material and production costs, and availability of large-scale technology. The literature highlights PHAs as biodegradable candidates to replace oil-based plastics and argues that economically sustainable production will require continued advances across all three classes (Lampinen, 2010).

4. Applications and Performance

4.1 Food packaging properties and gap

Food packaging is a primary application where bioplastics must balance stiffness, toughness, barrier performance, heat resistance, and processability. Reviews compare polylactic acid, polyhydroxyalkanoates, starch and cellulose derivatives, and biobased drop in polymers against incumbent materials and identify gaps that limit broader use (Zhao et al., 2020; Jeremić et al., 2020). Typical shortfalls include water vapor and oxygen barriers, thermal deformation during hot filling, and brittleness in some grades. Proposed remedies include blends, copolymer design, plasticization, multilayer structures, and surface coatings that tune diffusion and interfacial adhesion (Zhao et al., 2020). Circular economy analyses add that drop in biobased polyolefins can enter existing recycling streams, while certified biodegradable grades require routing to controlled facilities. Decisions therefore combine properties with end of life compatibility and local infrastructure (Rosenboom et al., 2022; Di Bartolo et al., 2021).

4.2 Construction and durable use contexts

Construction seeks materials that offer long service life with lower embodied impacts. Assessments report potential for greenhouse gas reduction when biogenic carbon remains stored in durable components made with polylactic acid or polyhydroxyalkanoates. Adoption depends on proven durability, resistance to moisture and temperature cycling, and cost effectiveness verified by life cycle and technoeconomic methods (Mousavi et al., n.d.). Technology overviews note improvements in mechanical and thermal behavior that expand feasibility, yet they also underline persistent constraints related to cost, material efficiency, and end of life planning for recovery or safe degradation (Shahar et al., 2025).

4.3 Reinforcement strategies and cross sector potential

Reinforcement is a central strategy to close performance gaps. Historically, synthetic fibers were used, but recent work favors natural resource reinforcements to align with sustainability goals (Kong et al., 2023). Reinforced systems can increase stiffness and strength, improve creep resistance, and stabilize dimensions, which supports use in packaging formats with higher loads and in selected building elements. The choice of reinforcement and matrix must consider processing temperature, interfacial adhesion, moisture uptake, and the targeted end of life route to avoid undermining recyclability or controlled biodegradation (Kong et al., 2023; Di Bartolo et al., 2021).

5 Environmental Impacts and End of Life

5.1 Circular economy framing

A circular approach positions bioplastics within systems that prioritize or recycled feedstocks, low carbon energy in production, high value retention during use, and reliable end of life routing. In this framing, several biobased families can achieve lower carbon footprints than fossil counterparts and, depending on chemistry and grade, can be integrated into existing recycling streams or directed to controlled biodegradation facilities (Rosenboom et al., 2022; Di Bartolo et al., 2021). These advantages are not automatic. Tradeoffs include agricultural impacts, land competition, uncertain collection and sorting, and cost differentials that depend on local infrastructure and policy signals. Reviews therefore call for harmonized identification standards, robust life cycle methods, and incentives that align design choices with

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verifiable circular outcomes (Rosenboom et al., 2022; Ali et al., 2023).

5.2 Recycling and upcycling routes

Replacing fossil plastics with bioplastics does not, by itself, resolve resource depletion or waste accumulation. Effective end-of-life strategies are required for all families. For biobased nonbiodegradable drop in polymers, such as biobased polyolefins and PET, mechanical recycling through existing streams is the preferred route where sorting accuracy and quality control can be assured (Fredi & Dorigato, 2021; Di Bartolo et al., 2021). For biodegradable families, biodegradation is often discussed, but it is not a recycling pathway because it does not recover polymer or monomer value. Mechanical and chemical recycling, as well as emerging biological upgrading, can preserve resources and handle heterogeneous streams, provided that collection, labeling, and sorting are designed accordingly (Fredi & Dorigato, 2021; Rosenboom et al., 2022). Identification standards that distinguish biobased content and biodegradability claims are essential to avoid cross contamination and to route materials to their highest value option (Di Bartolo et al., 2021; Rosenboom et al., 2022).

5.3 Biodegradation and composting across environments

Biodegradation outcomes depend on chemistry and environment. Industrial composting offers controlled conditions—temperature, moisture, and microbial consortia—under which selected grades of aliphatic polyesters and polysaccharide based materials can achieve defined disintegration and mineralization endpoints (Ahsan et al., 2023; Jeremić et al., 2020). Soil and aquatic settings present lower and more variable temperatures and microbial communities, which slow degradation and increase uncertainty about fate. Reported levers to improve composting performance include the use of enzymes as biocatalysts and metal compounds as catalysts, alongside process control (Ahsan et al., 2023). Across environments, the literature stresses matching materials to certified systems, clear labeling, and unambiguous disposal guidance to prevent leakage and unrealized benefits (Di Bartolo et al., 2021; Ahsan et al., 2023).

5.4 Microplastics risks and knowledge gaps

Evidence shows that some biodegradable materials can fragment into microplastics under certain conditions, with early experiments documenting microplastic formation from polyhydroxyalkanoate films in water and noting that effects may resemble those of conventional particles (Shruti & Kutralam-Muniasamy, 2019). Broader assessments warn that bioplastic derived particles may persist in soils and waters and could disturb ecosystems and food webs, which elevates the need for standardized degradation timeframes, expanded toxicity testing, and ecosystem level studies (Das et al., 2025; Shruti & Kutralam-Muniasamy, 2019). Research priorities include microorganism–particle interactions, biofilm formation, and the development of collection and sorting methods that minimize fragmentation by routing eligible grades to controlled treatment (Shruti & Kutralam-Muniasamy, 2019; Das et al., 2025). Table 3 indicates the end-of-life pathways and environmental risks of bioplastics.

5.5 Life cycle and technoeconomic evidence

Quantitative studies illustrate sensitivity to process design. For cyanobacterial polyhydroxybutyrate, increasing intracellular polymer content from 15% to 50% of dry cell weight reduced environmental impacts by about two thirds to three quarters, while major burdens stemmed from construction materials and chloroform used in purification. The minimum selling price at 50% content and a productivity of 12.5 g m−3 d−1 was estimated at 135 EUR kg−1; achieving roughly 4 EUR kg−1 would require ~ 810 mg L−1 d−1 productivity, implying changes in reactor geometry and strain engineering (Rueda et al., 2023). Municipal biowaste refineries producing PHA have been reported to outperform fossil polyurethane and first generation biomass PHA in both environmental impacts and societal costs, with further gains linked to sodium hypochlorite efficiency during extraction, methane leakage control, biogas upgrading, and management of the liquid fraction from digestate dewatering (Andreasi Bassi et al., 2021). Broader reviews conclude that harms associated with comprehensive life cycle and land use analyses for new materials and routes (Atiwesh et al., 2021; Ali et al., 2023; Rosenboom et al., 2022). Major plastics life cycle and techno-economic performance are given in table 2.

6. Policy and Market Conditions

6.1 Policy gaps and opportunities with a focus on food packaging

Analyses centered on food packaging recommend coordinated regulation that links material selection with lifecycle assessment, toxicology, and clear end of life routing to avoid unintended environmental and health outcomes (Leal Filho et al., 2025). Priority actions include defining acceptable applications for biobased and biodegradable grades in contact with food, clarifying collection and sorting responsibilities, and requiring evidence of performance and safety across the full value chain (Leal Filho et al., 2025). Circular economy reviews add that regulation should promote compatibility with recycling where feasible, reserve biodegradation for controlled facilities, and align financial incentives with verified impact (Rosenboom et al., 2022; Di Bartolo et al., 2021).

6.2 Standards, labeling, and market harmonization

Multiple sources call for revised identification standards and harmonized test methods that distinguish biobased content from biodegradability and that specify the conditions under which degradation claims are valid (Di Bartolo et al., 2021; Rosenboom et al., 2022). Earlier market assessments argue for comparable international standards and dedicated guidance for production, use, and waste management to reduce confusion and improve sorting accuracy (Arikan & Ozsoy, 2015). Clear labeling and interoperable certification can reduce cross contamination in recycling systems and support correct routing of compostable grades to suitable facilities (Di Bartolo et al., 2021; Rosenboom et al., 2022).

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6.3 Market status, growth signals, and commercialization dynamics

Market studies depict a small but growing share for bioplastics, with growth influenced by education, advertising, and public awareness (Mozaffari & Kholdebarin, 2019). Reported advantages include lower carbon footprints and energy efficiency, while disadvantages include high cost, standards gaps, and raw material constraints (Arikan & Ozsoy, 2015). Commercialization analyses emphasize that communication shapes eco consumer behavior and that greenwashing can trigger backlash that undermines credible claims and slows adoption (Cooke & Pomeroy, 2023). Historical and review perspectives converge that durable uptake depends on policy clarity, trustworthy labeling, and infrastructure that delivers on promised end of life outcomes (Venkatachalam & Palaniswamy, 2020; Di Bartolo et al., 2021; Rosenboom et al., 2022). Table 4 discusses the Policy, standards, and governance shaping bioplastics adoption.

7. Digital Enablers for Circular Management

7.1 Data driven waste collection and decision support

Urban waste systems benefit from predictive tools that prevent overflow and enable timely collection. A reported platform integrates low-cost sensors, public data, and a mobile interface to stream features such as population density, weather, maintenance history, and weekly waste build up to a cloud database. Twenty-five classifiers were benchmarked with repeated stratified cross validation, and a Decision Tree Classifier balanced accuracy with interpretability. Binary Particle Swarm Optimization reduced input by about 80 percent, revealing that three features alone predicted collection criticality with more than 99 percent accuracy on a holdout set. Model outputs and confidence scores are delivered to a field app that reorders maintenance queues, indicating potential to extend the same architecture to recycling and composting streams where route planning and contamination control are crucial (Stephan et al., 2025).

7.2 Environmental monitoring and smart sensing relevant to leakage control

Complementary sensing systems track environmental quality in real time, which supports early detection of leakage and hotspots near transfer stations and processing sites. A low cost water quality system measures temperature, pH, and turbidity with multiple sensors, transfers data to the cloud, and applies a feed forward neural network optimized by a hybrid genetic algorithm particle swarm approach, reaching 91 percent classification accuracy and improving precision and recall compared with an unoptimized network (Anusha Bamini et al., 2024). A two-phase air quality assessment combines a sigma operator to score pollutant factors with a fuzzy inference system to classify the air quality index and compares results with national indices (Raheja et al., 2021). Machine learning analyses during the COVID 19 period in India illustrate how data driven methods link energy transitions with air quality changes, a template for coupling waste system operations with environmental metrics during disruptions (Stephan et al., 2022). Together these tools offer a pathway to integrate material flow data with ambient monitoring, improving routing decisions and reducing unintended releases from bioplastic and conventional plastic waste streams.

8. Synthesis and Research Agenda

8.1 Consolidated opportunities versus constraints

Across the corpus, opportunities concentrate where materials, infrastructure, and governance are aligned. Biobased plastics can deliver lower carbon footprints than fossil counterparts and, for drop in commodities, can integrate with existing recycling streams; certified biodegradable grades can be routed to controlled facilities where conditions and standards are met (Rosenboom et al., 2022; Di Bartolo et al., 2021). Performance gaps in packaging and selected durable uses are narrowing through blends, copolymer design, coatings, and reinforcement, which expands feasible applications (Zhao et al., 2020; Mousavi et al., n.d.; Kong et al., 2023). Feedstock diversification through lignocellulosic residues, agricultural byproducts, and algae and cyanobacteria supports decoupling from food systems and valorization of wastes, though conversion efficiency and product uniformity remain decisive (Reshmy et al., 2021; Chauhan et al., 2024; Nanda & Bharadvaja, 2022). Constraints recur around cost and scale, heterogeneous standards and labeling, end of life routing, and microplastics risks. Scenario studies show that process details, such as reactor geometry, extraction chemistry, and biogas management, dominate environmental and economic performance for specific routes like cyanobacterial PHB or biowaste derived PHA (Rueda et al., 2023; Andreasi Bassi et al., 2021). Where collection and sorting are uncertain, biodegradable grades can lead to environments that do not support timely mineralization, and fragmentation may yield microplastics with unclear fate and effects (Ahsan et al., 2023; Shruti & Kutralam-Muniasamy, 2019). Policy and market analyses add that credibility is undermined by inconsistent claims and greenwashing, while adoption depends on coherent regulation, trusted labels, and clear responsibilities for collection and processing (Leal Filho et al., 2025; Cooke & Pomeroy, 2023). The research and deployment priority is therefore an integrated approach that couples material design with infrastructure readiness and governance instruments that reward demonstrable impact (Rosenboom et al., 2022; Di Bartolo et al., 2021).

8.2 Measurement and governance priorities

First, harmonize identification, certification, and assessment. Standards should distinguish biobased content from biodegradability and specify test conditions and labeling for end-of-life options; life cycle methods should reflect coexisting pathways, including mechanical recycling, chemical and biological upcycling, anaerobic digestion where appropriate, and controlled composting (Di Bartolo et al., 2021; Rosenboom et al., 2022; Ali et al., 2023). Second, expand fate measurement. Establish comparable protocols for

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disintegration and mineralization kinetics across composting, soil, and aquatic settings, and extend toxicity and ecosystem level testing for microplastic formation and impacts (Ahsan et al., 2023; Shruti & Kutralam-Muniasamy, 2019). Third, target high leverage process improvements. For algal and cyanobacterial routes, benchmark reactor volume to surface ratios, solvent free or less hazardous purification, and strain productivity against environmental and cost outcomes; for biowaste refineries, minimize oxidant use in extraction, control methane leakage, and upgrade biogas (Rueda et al., 2023; Andreasi Bassi et al., 2021; Nanda & Bharadvaja, 2022). Fourth, align regulation with performance. In food packaging, lifecycle and safety evidence for applications and mandate clear routing and labeling to avoid unintended consequences; pair these rules with incentives that scale verified circular solutions (Leal Filho et al., 2025). Fifth, link data systems to operations. Integrate sensing and predictive tools into collection and processing to prevent overflow, reduce contamination, and document end of life performance for both bioplastic and conventional plastic streams (Stephan et al., 2025; Anusha Bamini et al., 2024; Raheja et al., 2021; Stephan et al., 2022). Finally, support trustworthy communication. Counter greenwashing through transparent criteria and enforcement and build public literacy so purchasing and disposal choices reflect certified attributes and local infrastructure (Cooke & Pomeroy, 2023).

9 Conclusions

Bioplastics represents a diverse set of materials whose performance and sustainability depend on matched choices across feedstocks, processing, product design, and end of life routing. Evidence in this review shows that several biobased families can achieve lower carbon footprints than fossil counterparts and, in specific cases, can enter existing recycling systems or be directed to controlled biodegradation, provided that claims are certified and infrastructure is available (Rosenboom et al., 2022; Di Bartolo et al., 2021). Application frontiers are strongest in food packaging and selected durable uses, where blends, copolymer design, coatings, and reinforcement have narrowed property gaps, yet barriers remain in barrier performance, heat resistance, durability, and cost (Zhao et al., 2020; Mousavi et al., n.d.; Kong et al., 2023). Process level assessments highlight high leverage interventions. For cyanobacterial poly-hydroxybutyrate, environmental impacts fall as intracellular polymer content rises, but purification chemistry, reactor geometry, and productivity determine feasibility and price (Rueda et al., 2023). For PHA from urban biowaste, improved extraction efficiency, methane control, biogas upgrading, and digestate handling drive gains in both environmental and cost performance (Andreasi Bassi et al., 2021). Across families, mechanical and chemical recycling preserve resource value, while biodegradation is not recycling route and should be reserved for certified industrial settings (Fredi & Dorigato, 2021; Di Bartolo et al., 2021). Risks from fragmentation into microplastics, together with variable degradation kinetics in soil and aquatic environments, underscore the need for standardized fate testing, toxicity studies, and clear disposal guidance (Shruti & Kutralam-Muniasamy, 2019; Ahsan et al., 2023; Das et al., 2025). Policy analyses, especially in food packaging, recommend coordinated regulation that requires lifecycle evidence, clarifies acceptable uses, and aligns financial incentives with verifiable circular outcomes (Leal Filho et al., 2025; Ali et al., 2023). Market adoption further depends on trustworthy communication and labeling that distinguish biobased content from biodegradability and deter greenwashing (Di Bartolo et al., 2021; Cooke & Pomeroy, 2023). A practical agenda follows. Harmonize identification and certification, update life cycle methods for coexisting routes, and prioritize process improvements with the largest influence on environmental and economic outcomes. Couple material innovation with data driven waste operations and ambient monitoring to prevent overflow and leakage and to document performance at scale. Under these conditions, bioplastics can contribute to a circular economy that reduces reliance on fossil resources and routes materials through reliable end of life systems with demonstrated impact (Rosenboom et al., 2022; Di Bartolo et al., 2021).

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Table 1: Major bioplastics: feedstocks, properties, and applications

Bioplastic family	Typical feedstocks	Key applications	Main advantages	Key limitations	Preferred end-of-life route
Polylactic acid (PLA)	Corn starch, sugarcane, lignocellulosic sugars	Food packaging, disposable products, fibers	Biobased, good transparency, processable with conventional equipment	Low heat resistance, brittleness, limited barrier properties	Industrial composting; limited mechanical recycling
Polyhydroxyalkanoates (PHA)	Microbial fermentation of sugars, lipids, biowaste, algal biomass	Packaging, medical devices, agricultural films	Biodegradable in soil and marine environments, biocompatible	High production cost, low productivity, complex extraction	Biodegradation; controlled composting
Starch-based	Corn, potato, cassava, agricult	Films, bags, coati	Low cost, renewable, easy	Moisture sensitivity,	Composting

bioplastics	ural residues	ngs	biodegradation	poor mechanical strength	
Cellulose-based bioplastics	Wood pulp, agricultural and lignocellulosic residues	Films, fibers, coatings, packaging	Good mechanical strength, renewable, low toxicity	Processing complexity, limited thermoplasticity	Recycling; composting
Biobased drop-in polymers (Bio-PE, Bio-PET)	Sugarcane-derived ethanol, biomass-based intermediates	Bottles, containers, films	Chemically identical to fossil plastics, compatible with existing infrastructure	Not biodegradable, feedstock availability constraints	Mechanical recycling

Table 2: Life-cycle and techno-economic considerations for bioplastics

Production route / system	Dominant environmental impact drivers	Key technoeconomic cost drivers	Critical assumptions in studies	Main limitations highlighted
PLA from sugar/starch crops	Agricultural inputs, land use change, energy mix during polymerization	Feedstock price, fermentation efficiency, scale of operation	Availability of renewable energy; efficient waste management	Competition with food crops; regional variability in impacts
PHA from microbial fermentation (sugars/lipids)	Energy demand for fermentation and downstream processing	Substrate cost, low productivity, solvent-based extraction	High intracellular polymer content; optimized purification	High production cost; scale-up challenges
PHA from cyanobacteria / algae	Photobioreactor construction, solvent use during extraction	Reactor capital cost, low biomass productivity	High photosynthetic efficiency; reduced solvent use	Cost not competitive; technology readiness still low
PHA from municipal biowaste	Methane leakage, oxidant use in extraction, digestate handling	Waste collection logistics, extraction efficiency	Stable waste supply; effective biogas upgrading	Process complexity; dependence on local infrastructure
Starch-based bioplastics	Agricultural production impacts, plasticizer use	Raw material variability, limited durability	Local sourcing of feedstock; short service life	Moisture sensitivity; limited high-value applications
Cellulose-based bioplastics	Pulping and chemical modification steps	Chemical processing cost, energy demand	Efficient recovery of chemicals	Processing intensity; limited thermoplastic behavior
Biobased drop-in polymers (Bio-PE, Bio-PET)	Biomass cultivation, ethanol dehydration energy	Feedstock availability, integration with existing plants	Seamless compatibility with fossil-based infrastructure	No biodegradability benefit; land-use concerns

Table 3: End-of-life pathways and environmental risks of bioplastics

End-of-life pathway	Applicable bioplastic types	Infrastructure requirement	Environmental benefits	Key risks and limitations	Major knowledge gaps
Mechanical recycling	Bio-PE, Bio-PET, selected PLA grades	Conventional plastic recycling streams	Retains material value; lowest energy demand	Contamination with fossil plastics; limited PLA recycli	Sorting efficiency; property degradation after multiple cycles

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				ng compatibility	
Chemical recycling	PLA, PHA (limited cases)	Specialized depolymerization facilities	Recovery of monomers; potential circularity	High energy input; solvent and catalyst use	Economic feasibility at scale; solvent recovery efficiency
Industrial composting	PLA, starch-based plastics, selected blends	Controlled temperature, moisture, microbial systems	Organic waste integration; reduced landfill burden	Incomplete degradation if conditions are not met	Standardized testing protocols; residue fate
Anaerobic digestion	Starch-based plastics, some PHA	Biogas plants with digestate handling	Energy recovery via biogas	Slow degradation rates; polymer persistence	Long-term digestate quality; methane leakage
Soil biodegradation	PHA, starch-based plastics	Minimal infrastructure	Suitable for agricultural applications	Variable degradation rates; climate dependence	Field-scale validation; ecotoxicity impacts
Marine biodegradation	Specific PHA grades	No engineered infrastructure	Potential mitigation of marine litter	Very slow degradation; false perception of safety	Real-world degradation kinetics; ecosystem impacts
Landfilling	All bioplastics	Conventional waste disposal	Short-term containment	Methane generation; long persistence	Long-term carbon fate; emissions accounting
Incineration with energy recovery	All bioplastics	Waste-to-energy plants	Energy recovery; volume reduction	Loss of material circularity	Comparative climate benefit vs recycling
Uncontrolled fragmentation	Poorly managed bioplastics	None (mismanaged waste)	None	Microplastic formation; environmental dispersion	Fragmentation mechanisms; toxicity and bioaccumulation

Table 4: Policy, standards, and governance shaping bioplastics adoption

Policy / governance dimension	**Scope / region**	**Purpose**	**Relevance to bioplastics**	**Key limitations or challenges**
Compostability standards (EN 13432, ASTM D6400)	EU, USA	Define industrial compostability criteria	Enable certification of PLA, starch blends	Limited relevance to home composting; misuse of labels
Biodegradability test standards (ISO 14855, ISO 17556)	International	Assess biodegradation under controlled conditions	Provide comparability across materials	Poor representation of real-world environments
Bio-based content standards (ASTM D6866, EN 16785)	International	Quantify renewable carbon content	Used for labeling and incentives	Do not address end-of-life impacts
Eco-labeling and certification schemes	EU, global	Inform consumers and waste managers	Improve sorting and consumer trust	Label confusion; inconsistent enforcem

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Extended Producer Responsibility (EPR)	EU, selected countries	Shift waste responsibility to producers	Incentivizes recyclable and compatible designs	Limited integration of bioplastics into EPR schemes
Single-use plastic directives and bans	EU, national policies	Reduce plastic waste and litter	Promote alternatives including bioplastics	Risk of substitution without life-cycle benefits
Public procurement policies	National / regional	Promote sustainable materials	Create early markets for bioplastics	Cost sensitivity; lack of performance standards
Waste management regulations	Regional	Control routing of plastic waste	Determine feasibility of composting or recycling	Infrastructure gaps; mis-sorting risks
Digital monitoring & traceability tools	Emerging	Track material flows and leakage	Support circular economy implementation	Data interoperability and adoption barriers
Governance of microplastics risks	International	Limit environmental contamination	Drives testing and reporting requirements	Lack of harmonized thresholds

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