

Review

Bioplastics Beyond Materials: A Review on Regulatory, Economic, and Circular Pathways Toward Sustainable Food Packaging

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Abstract

The transition from fossil-based plastics to bioplastics in food packaging requires not only technological advances but also coherent regulatory frameworks and economic support mechanisms. This review examines how policies, production costs, and industrial initiatives shape the large-scale adoption of biopolymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based materials. The regulatory comparison indicates substantial differences in legal scope and implementation across jurisdictions, while also showing that the existence of binding legislation does not by itself demonstrate bioplastic-specific circular-performance outcomes. Although the high production cost of bioplastics remains a major barrier to widespread implementation, strategies including agricultural residue valorization and green fiscal instruments may contribute to improving competitiveness. Overall, the evidence reviewed suggests that the transition toward sustainable food packaging depends on the combined development of material performance, regulatory coherence, industrial integration, and life-cycle accountability, highlighting the need for greater coordination across these dimensions.

Keywords: bioplastics; circular economy; compostability; regulatory frameworks; policy harmonization; sustainability; food packaging



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1. Introduction

Since their commercial introduction in the early twentieth century, low-density polyethylene (LDPE) and high-density polyethylene (HDPE) have become widely used in packaging systems and consumer goods. LDPE, first synthesized in the 1930s, offered flexibility and chemical resistance, facilitating its widespread adoption in films, bags, and coatings. By the 1950s, HDPE emerged as a robust alternative for rigid containers and bottles due to its superior mechanical strength and durability [1]. The widespread use of these fossil-based polymers contributed to major changes in modern manufacturing and distribution systems. Their versatility, low production cost, and favorable performance characteristics contributed to the rapid growth of plastic production throughout

the latter half of the twentieth century and to changes in the preservation, transportation, and consumption of food and consumer products worldwide.

Consequently, LDPE and HDPE became widely used materials in global production and consumption systems. Their dominance persists today, as these polymers continue to constitute a substantial proportion of plastic packaging waste streams. In Europe, LDPE and HDPE collectively account for nearly half of post-consumer plastic packaging waste [2].

The properties that contributed to the widespread use of LDPE and HDPE, particularly durability and chemical resistance, also contributed to their environmental persistence. Due to their high molecular stability and resistance to biodegradation, these polymers can persist in natural environments for decades to centuries, accumulating in landfills, terrestrial ecosystems, and aquatic systems.

Increasing evidence indicates that the fragmentation of plastic packaging leads to the formation of micro- and nanoplastics, which pose significant risks to ecosystems and human health [3,4]. These particles have been detected across multiple food matrices and drinking water sources, suggesting continuous human exposure through ingestion pathways, with current estimates indicating that individuals may ingest thousands of microplastic particles annually through food and water consumption [5]. Beyond their physical presence, microplastics can also act as vectors for toxic organic pollutants and heavy metals, facilitating the transfer of hazardous substances across trophic levels and amplifying potential toxicological impacts on both marine organisms and human health [4].

The environmental footprint of conventional plastics is now recognized not only in terms of visible waste accumulation, but also in their role as persistent and mobile contaminants. Additionally, the production and widespread use of fossil-based plastics are associated with significant climate impacts and the intensive consumption of non-renewable fossil resources. This growing body of evidence has led organizations such as the United Nations Environment Programme (UNEP) to recognize plastic pollution as a major global environmental challenge and to call for actions to reduce plastic leakage and promote more sustainable materials and packaging systems. In response to these environmental challenges, increasing attention has been directed toward the development of bioplastics that are bio-based, biodegradable, or both, as a strategy to mitigate the long-term persistence of conventional plastics in the environment, particularly fossil-based polymers such as low-density polyethylene (LDPE) and high-density polyethylene (HDPE). Bioplastics offer a promising pathway to reduce environmental accumulation, provided that their production systems and end-of-life management are properly addressed. Thus, the production of biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) from renewable resources represents an alternative pathway toward more sustainable food packaging materials [6].

According to European Bioplastics, the term “bioplastics” encompasses a diverse family of materials that may be bio-based, biodegradable, or both [7]. These two attributes represent distinct classification criteria: bio-based refers to feedstock origin, indicating that a material is wholly or partly derived from biomass, whereas biodegradability is related to the chemical structure of the material and its capacity to undergo microbial degradation under defined environmental conditions. As illustrated in Figure 1, combining these two criteria allows plastics to be differentiated into four groups. Bio-based materials may be biodegradable, such as PLA, PHA/PHB, and starch-based materials, or non-biodegradable, such as bio-PE, bio-PP, and bio-PET. Conversely, biodegradable plastics may also originate from fossil-based feedstocks, as illustrated by PBAT, whereas conventional PE, PP, and PET are fossil-based and non-biodegradable. This classification emphasizes that feedstock origin and biodegradability are independent attributes; therefore, bio-based origin does

not necessarily imply biodegradability, and biodegradability does not necessarily imply bio-based origin.

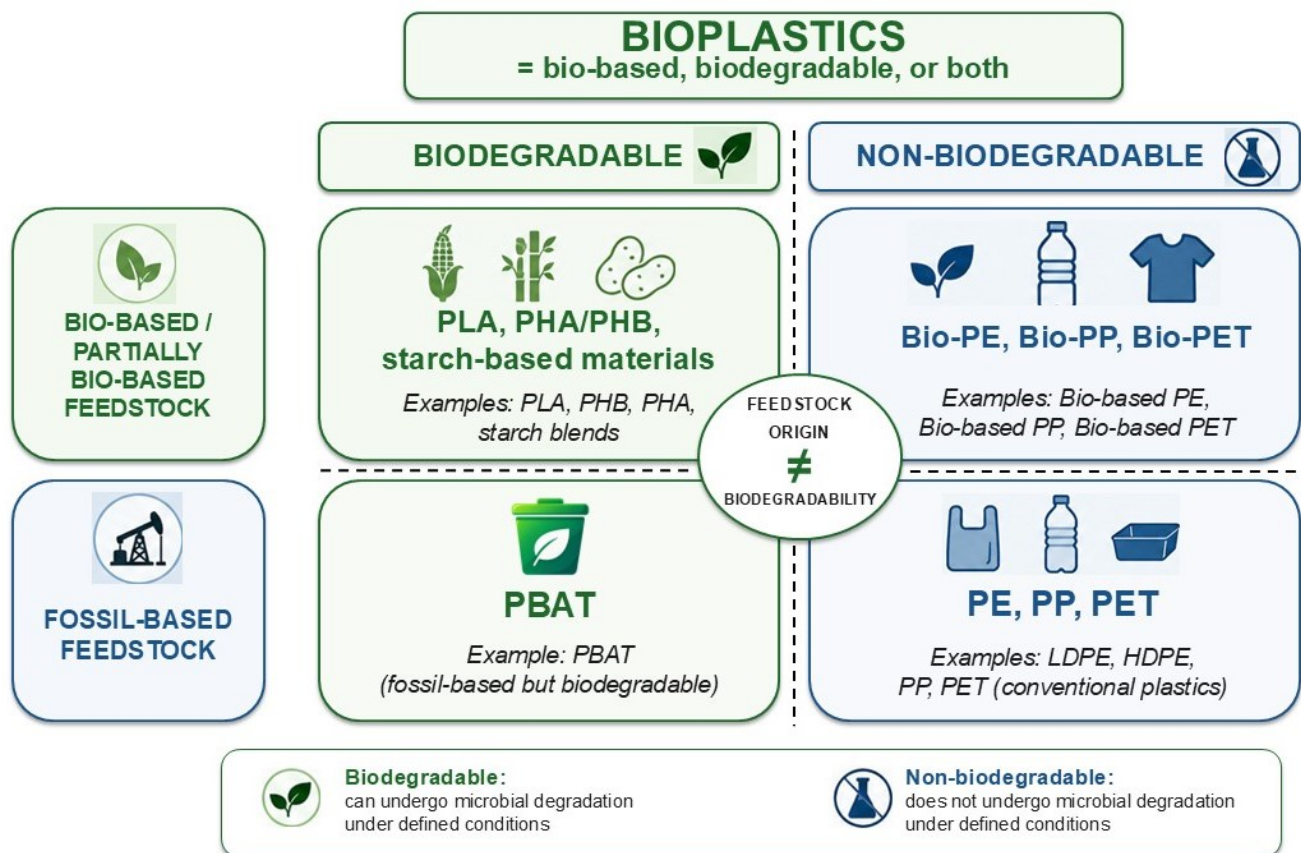


Figure 1. Classification of plastics according to feedstock origin and biodegradability. Source: Adapted conceptually from European Bioplastics [7].

Although promising, recent assessments highlight that the environmental sustainability of bio-based materials is context-dependent. Life-cycle studies indicate that, while bio-based polymers may reduce fossil resource dependence and greenhouse gas emissions, they can in some cases present higher impacts in categories such as eutrophication potential and water consumption, depending on agricultural practices, feedstock production, and processing conditions [8]. Therefore, the integration of renewable feedstocks into bioplastic manufacturing can contribute to circular economy strategies aimed at reducing the environmental impacts of plastics.

Despite their environmental potential, the large-scale adoption of bioplastics remains uneven across regions and markets. This observation highlights the need to move beyond purely technical assessments and adopt a multidisciplinary perspective that integrates policy analysis, economic evaluation, and industrial dynamics. In this context, the present review provides a comprehensive synthesis of the regulatory, economic, and corporate factors that may influence the global transition from fossil-based plastics to bioplastics in the food packaging sector. By critically examining how legislative frameworks, market incentives, and industry strategies converge—or diverge—across different regions, this article seeks to identify the key pathways and persistent barriers shaping the adoption of sustainable packaging solutions. In this review, regulatory analysis is limited to instruments that materially affect the market introduction, certification, collection, recovery, recycling, composting, or other end-of-life pathways of bioplastic food packaging, even when those instruments regulate plastic packaging more broadly rather than bioplastics

specifically. This analysis can support informed decision-making by policymakers and industry stakeholders.

2. Review Methodology

This review followed a narrative approach to examine the scientific, environmental, economic, and regulatory aspects of bioplastics for food packaging. Relevant literature was identified primarily through Google Scholar and ScienceDirect, together with peer-reviewed publications from scientific publishers including Elsevier, Springer Nature, MDPI, ACS Publications, the Royal Society of Chemistry (RSC), and Wiley. Institutional and regulatory information was obtained from official and recognized sources, including ISO, ASTM International, CEN, the European Commission, OECD, UNEP, FAO, European Bioplastics, and national governmental agencies. Search terms included combinations of “bioplastics”, “bio-based plastics”, “biodegradable polymers”, “food packaging”, “PLA”, “PHA”, “PHB”, “PBAT”, “thermoplastic starch”, “life cycle assessment”, “carbon footprint”, “circular economy”, “production costs”, “regulation”, “legislation”, and “waste management”.

Sources were selected according to their relevance to the main topics addressed in the review, particularly material properties, environmental performance, production costs, circular economy, industrial implementation, and regulatory frameworks. Recent publications were prioritized, while earlier studies were retained when they provided foundational concepts, original experimental evidence, or primary life-cycle inventory data. The literature included in the review spans 1999–2026. The materials discussed were selected to represent different technological pathways relevant to sustainable food packaging, considering the availability of evidence across the main dimensions examined in this review. Particular attention was given to PLA, PHA/PHB, PBAT, and starch-based materials, including TPS, as these materials represent different feedstock origins, biodegradation characteristics, technological properties, and food-packaging applications. PBAT was also considered because of its relevance to flexible films and biodegradable blend systems, particularly PLA/PBAT blends, where its flexibility can help compensate for the comparatively brittle behavior of PLA [9,10]. Its inclusion also illustrates that biodegradability does not necessarily imply a bio-based origin. LDPE and HDPE were retained as conventional fossil-based reference polymers for comparative purposes. Table 1 summarizes the rationale for selecting these representative materials and their relevance to research and industrial food-packaging applications.

Countries and companies were included as illustrative cases rather than as an exhaustive global sample. Countries were selected to represent different geographical regions, regulatory contexts, policy implementation stages, circular-economy integration, and waste-management infrastructure. For the regulatory comparison, priority was given to legislative and policy instruments with a direct operational connection to plastic and bioplastic packaging, particularly those establishing restrictions or phase-outs, quantitative waste-reduction, collection, recovery or recycling targets, recycled-content requirements, extended producer responsibility (EPR) obligations, reuse or refill requirements, deposit-return systems, or other relevant end-of-life provisions. Similarly, companies were selected based on their documented involvement in bioplastic production or food-packaging applications and their relevance to different technological and regional contexts. Because the reviewed studies differ in feedstocks, production conditions, geographical scope, and assessment methods, quantitative results were interpreted with these methodological differences in mind. Accordingly, the study should be considered a narrative review rather than a systematic review or meta-analysis.

Table 1. Rationale and relevance of the main bioplastics considered in this review.

Material	Origin/Classification	Relevance to Food Packaging	Research and Industrial Relevance	Role in this Review
PLA	Mainly bio-based polyester; industrially compostable under appropriate conditions	Rigid and thermoformed packaging, trays, containers and films	Extensively investigated and commercially implemented in packaging; substantial evidence on processing, mechanical properties and LCA	Represents a commercially developed bio-based polyester
PHA/PHB	Microbially produced, bio-based and biodegradable polyesters	Films, coatings, trays, containers and other biodegradable packaging systems	Extensive academic research on production, properties and biodegradation, with growing industrial development	Represents biologically produced biodegradable polyesters
PBAT	Mainly fossil-based biodegradable polyester	Particularly relevant to flexible films and biodegradable blends including PLA/PBAT systems	Widely investigated in blends because of its flexibility and film-forming properties; documented food-packaging applications	Represents a flexible biodegradable polyester and illustrates that biodegradable does not necessarily mean bio-based
Starch/TPS	Renewable polysaccharide-based material	Films, coatings, blends and single-use packaging alternatives	Extensively investigated because of renewability, availability and biodegradability; frequently combined with other polymers to improve performance	Represents renewable polysaccharide-based packaging systems

Note: This table provides a qualitative synthesis; no High/Medium/Low ranking is assigned because no harmonized bibliometric or production-volume comparison was performed.

3. Conceptual Framework: Definitions and Classification

The development of polymer science and alternative packaging materials has introduced terms such as “bioplastics”, “bio-based”, “biodegradable”, and “compostable”, which are often used interchangeably in academic and industrial contexts. A lack of clear definitions and standardized criteria has contributed to confusion among scientists, policymakers, and end users. For this reason, a clear conceptual framework is needed to distinguish between these categories, ensure scientific accuracy, guide regulatory compliance, inform policy development, and support transparent communication with consumers. Internationally recognized standards and definitions provide a basis for discussing the sustainability and adoption of alternative packaging materials.

3.1. Bioplastics

The term bioplastics refers to a heterogeneous group of polymeric materials defined according to two independent criteria: feedstock origin and biodegradability. In this framework, a bioplastic may be classified as bio-based, meaning that it is fully or partially derived from renewable resources such as starch, cellulose, or microbial biomass, or as biodegradable, meaning that it can be decomposed by microbial activity under specific conditions, as defined by international standards [11].

Importantly, these criteria are not interchangeable. A material can be bio-based without being biodegradable, as exemplified by polyethylene produced from sugarcane feedstocks, which is chemically identical to fossil-based polyethylene. Conversely, some polymers synthesized from fossil resources, such as polybutylene adipate terephthalate (PBAT), are fully biodegradable. This classification provides a conceptual basis for current regulatory and standardization frameworks and supports consistent material identification across scientific, industrial, and policy contexts.

3.2. Biodegradable vs. Compostable

While biodegradability refers broadly to the capacity of a material to undergo microbial decomposition under natural or managed environments, compostability represents a more restrictive and operational concept. Compostable materials are designed to biodegrade only under controlled composting conditions, where temperature, moisture, aeration, and microbial activity are regulated to ensure predictable and complete transformation.

In practical terms, material may be biodegradable without being compostable, as degradation can occur slowly, incompletely, or under conditions that do not align with waste management infrastructures. By contrast, compostable plastics must meet defined performance thresholds, including complete disintegration, absence of toxic residues, and conversion into stable compost within a specified timeframe.

For this reason, compostability is assessed through standardized certification schemes rather than inferred from material composition alone. In Europe and North America, standards such as EN 13432 [11] and ASTM D6400 [12] establish the technical criteria required for materials to be labeled as compostable, providing a clear distinction between environmental degradability and compliance with industrial composting systems.

3.3. Scientific Implication

Clear differentiation between bio-based, biodegradable, and compostable plastics is important for scientific classification, regulatory clarity, market transparency, and consumer trust. In the absence of precise and harmonized terminology, sustainability claims may be interpreted inconsistently across jurisdictions, creating opportunities for misleading environmental labeling and greenwashing practices.

From a regulatory perspective, the lack of shared definitions can complicate the mutual recognition of certifications between regions, potentially affecting international trade and confidence in sustainable packaging solutions. This challenge has prompted standardization bodies such as the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) to prioritize the development of unified testing methodologies and labeling criteria that clearly distinguish material origin from end-of-life performance [11,13].

Clear terminology is therefore necessary for effective policy design, market surveillance, and the implementation of circular economy strategies, and can help ensure that environmental claims associated with bioplastics are scientifically verifiable, legally supported, and internationally comparable.

4. Properties and Barriers

Processing technologies shape the structural and textural attributes required for specific packaging applications. In practice, selecting a processing route is closely linked to the desired material performance. Different technologies impose distinct thermal, mechanical, and deformation histories that influence film morphology, mechanical response, and surface texture. Extrusion and thermoforming remain the dominant technologies for the manufacture of films and trays because they enable the production of materials with homogeneous thickness, smooth surfaces, and reproducible mechanical behavior (Table 2). These characteristics are useful for large-scale packaging applications that require dimensional stability, flexibility, and consistent handling performance. The continuous nature of these processes supports high productivity and cost efficiency and contributes to their widespread industrial adoption. However, the elevated temperatures and shear stresses involved may restrict formulation flexibility and can negatively affect texture uniformity when incorporating thermally sensitive components or heterogeneous bio-based fillers [14]. By contrast, batch-based or semi-continuous techniques such as thermocom-

pression and compression molding allow greater control over material consolidation and internal structure (Table 2). This can result in stiffer textures, higher density, or improved barrier performance, depending on processing conditions and formulation. While such attributes may be desirable for specific applications, the reduced throughput and higher operational costs associated with these methods limit their suitability for large-volume packaging production.

Table 2. Comparison of bioplastic production and processing techniques: materials, operating conditions, advantages, and disadvantages.

Production/Processing Method	Processed Materials	Process Parameters	Advantages	Disadvantages	References
Extrusion	Starch, PLA, PHA, blends with plasticizers	• Temperature: 120–180 °C • Pressure: medium • Variable screw speed	• Continuous and large-scale production • Good dispersion of additives • Improved mechanical properties	• Sensitive to moisture • Limited for certain polymers such as TPS	[15–17]
Thermoforming	PLA films, thermoplastic starch (TPS)	• Temperature: 110–140 °C (above T_g of PLA) • Pressure: low to moderate • Forming mechanism: vacuum or air pressure	• Low mold cost • Ideal for large parts • Fast process	• Less dimensional accuracy • May generate more waste due to trimming	[18,19]
Thermocompression	PHB, PLA, TPS powders or granules	• Temperature: 150–200 °C • Pressure: high (up to 100 bar)	• Allows thickness and shape control • Suitable for structural parts	• Slow and costly process • High energy requirements	[20]
Compression molding	Homogeneous starch and protein blends	• Temperature: 140–180 °C • Pressure: high • Pressing time: 5–10 min.	• Improves homogeneity • Suitable for thin biofilms • Good thermal control	• Requires compatibilization • Greater sensitivity to temperature and time	[21–24]
Electrospinning	Polymer solutions (PLA, PCL, proteins)	• Voltage: 15–30 kV • Collector distance: 10–20 cm • Flow rate: 0.5–1 mL/h	• High surface/volume ratio • Fibers with superior mechanical properties	• High cost • Limited scalability	[25–28]
Microbial synthesis of biopolymers	Agro-industrial wastes converted to PHA	• Fermentation: 30–37 °C • pH controlled • Substrate: glucose, oils	• 100% biodegradable • Use of organic wastes • High environmental compatibility	• High initial costs • Requires genetic engineering of strains	[14,22,29–31]

Electrospinning represents an alternative approach in which processing conditions enable the formation of highly structured micro- and nanofibrous networks (Table 2). These architectures can provide specific textural and functional properties, such as increased surface area or tailored permeability. However, limited scalability and energy demand currently restrict the process mainly to specialized or high-value applications rather than mainstream food packaging.

Microbial synthesis routes differ fundamentally from thermoplastic processing because material properties are largely defined during biosynthesis rather than during subsequent shaping processes (Table 2). Although these pathways offer advantages in terms of biodegradability and the valorization of agro-industrial residues, controlling texture and mechanical consistency at scale remains challenging due to variability in polymer composition and downstream processing requirements.

Overall, these observations indicate that barriers to the large-scale adoption of bioplastics are influenced by processing-related structural and textural outcomes, in addition to economic and regulatory constraints. Differences in process-induced texture, mechanical behavior, and surface characteristics help explain why certain technologies remain industrially dominant, while others are confined to niche applications or developmental stages.

For food-packaging applications, the relevance of bioplastics depends not only on their origin or end-of-life behavior but also on whether their mechanical performance meets functional requirements. Because packaging materials are subjected to stretching, sealing, stacking, and handling, stiffness, strength, and extensibility are important criteria for their practical use. Mechanical performance therefore provides a link between material characteristics and industrial applicability. Bioplastic systems typically show distinct

mechanical characteristics (Figure 2). For instance, PLA presents high stiffness (expressed as Young's modulus) and average tensile strength compared with the other materials or composites shown, while its limited elongation indicates a brittle mechanical response (left-side bars, Figure 2). Such behavior constrains its use in flexible packaging while making it more suitable for rigid applications where dimensional stability is prioritized over deformability. PHB shows a similar mechanical profile, suggesting greater suitability for rigid packaging formats than for applications requiring high mechanical compliance (center-left bars, Figure 2).

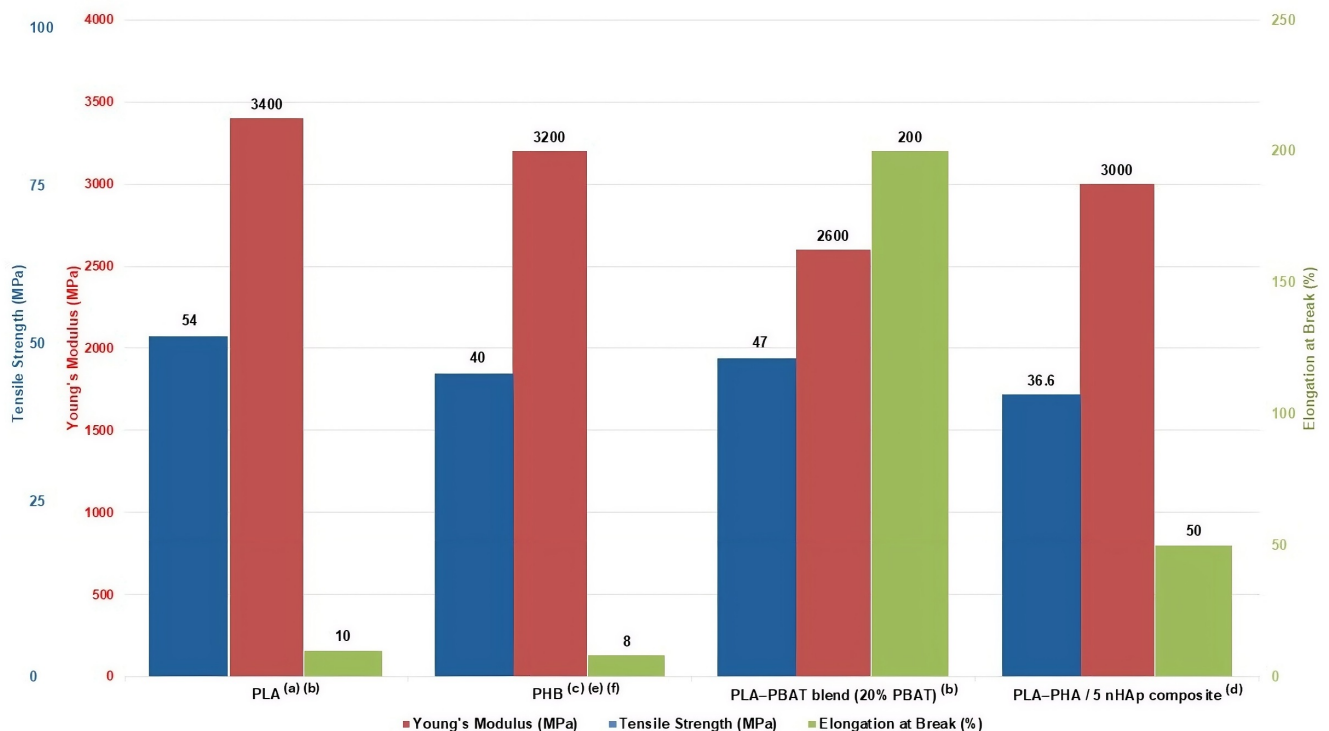


Figure 2. Comparative Mechanical Performance of Selected Bioplastics for Packaging Applications (PLA, polylactic acid; PHB, polyhydroxybutyrate; PBAT, poly (butylene adipate-co-terephthalate); PHA, polyhydroxyalkanoates; nHAp, nano-hydroxyapatite). Source: Data compiled from (a) [18]; (b) [32]; (c) [33]; (d) [34]; (e) [35]; and (f) [36].

By contrast, blended and hybrid systems show a different mechanical response. Materials combining PLA with flexible components, such as PBAT or PHA-based phases, show higher elongation at break than the single-polymer systems presented (center-right and right-side bars, Figure 2). This higher ductility can improve the ability of these materials to accommodate deformation, which is relevant for films, bags, and other flexible packaging formats subjected to mechanical stress during processing and use. The data presented in Figure 2 suggest that these compositional strategies can help balance stiffness and flexibility in bioplastic systems.

Overall, these trends indicate that achieving high stiffness, strength, and extensibility simultaneously remains challenging for individual biopolymer systems. Mechanical performance can therefore be adjusted through controlled blending, hybridization, or structural modification, supported by appropriate processing routes. Material composition and processing conditions should therefore be considered together when targeting mechanical properties suitable for packaging applications and performance closer to that of conventional fossil-based plastics. However, mechanical performance represents only one component of packaging functionality. For direct food-packaging applications, barrier properties, thermal behavior, sealability, moisture resistance, and food-contact safety are also important because they affect product protection, processability, package integrity,

and regulatory compliance. These complementary requirements are discussed in the following subsection.

Food-Packaging Functional Performance

Beyond mechanical properties, the suitability of bioplastics for food packaging also depends on barrier performance, thermal behavior, sensitivity, moisture sensitivity, and food-contact safety, as summarized in Table 3. These properties vary considerably among polymer systems. PLA provides useful barrier performance and heat-sealing capability, although its thermal resistance can limit some applications [18]. PHA/PHB shows promising barrier performance, but its processing can be constrained by thermal stability and brittleness [37]. PBAT and PLA/PBAT blends are relevant for flexible packaging, although their gas and water-vapor barrier properties remain strongly dependent on formulation and modification [9,10]. Starch-based materials and TPS are especially sensitive to moisture, which can affect their barrier and mechanical performance [38].

Table 3. Key functional properties of bioplastics for food-packaging applications.

Material	Oxygen Barrier	Water-Vapor Barrier	Thermal Performance	Sealability	Moisture Sensitivity	Food-Contact Safety	Main Technical Implication	References
PLA	Moderate; strongly influenced by crystallinity, film structure and formulation	Moderate; may be insufficient for applications requiring high moisture protection	Relatively low Tg limits prolonged high-temperature applications; thermal behavior depends on crystallinity and formulation	Heat-sealable, but the sealing window must be controlled to avoid deformation or shrinkage	Lower than starch/TPS, although humidity and hydrolysis can affect long-term performance	Food-contact suitability must be evaluated according to formulation, residual substances, additives and applicable migration requirements	Suitable for rigid, semi-rigid and selected film applications; modification or blending may be required for demanding barrier and thermal applications	[18,39]
PHA/PHB	Promising gas-barrier performance; strongly dependent on PHA type, crystallinity and formulation	Variable according to polymer composition, crystallinity and modification strategy	Narrow thermal-processing window and brittleness can restrict processing; strongly composition-dependent	Application- and formulation-dependent; less comprehensively documented than PLA/PBAT systems	Generally less moisture-sensitive than TPS because of its more hydrophobic character	Commercial food-contact PHA grades exist, but compliance must be established for each formulation and intended use	Promising for biodegradable films, coatings and rigid packaging although thermal processing and brittleness remain important constraints	[37]
PBAT/PLA-PBAT	Neat PBAT presents limited gas-barrier performance compared with conventional petrochemical packaging; barrier properties can be improved by blending and fillers	Neat PBAT has relatively limited water-vapor resistance; performance can be substantially modified through blends, fillers and nanocomposites	PBAT provides flexibility but has limited thermal resistance; PLA/PBAT performance depends strongly on blend composition and modification	Particularly relevant for flexible films; PLA/PBAT formulations can provide improved processing and sealing-related performance	Lower intrinsic sensitivity than TPS, but moisture response becomes formulation-dependent, especially in starch-containing blends	Food-contact safety cannot be assumed from biodegradability; PBAT/starch systems may release oligomers and other migrants and therefore require migration assessment	Particularly attractive for flexible food packaging when barrier, thermal and migration performance are optimized through formulation	[9–11]
Starch/TPS	Can provide useful oxygen-barrier performance under dry conditions, but performance deteriorates with increasing humidity	Generally poor because of the hydrophilic nature of starch	Strongly influenced by moisture, plasticizer content and processing temperature	Highly formulation-dependent; blending with thermoplastic polyesters can improve practical film-processing and sealing behavior	High; water absorption can plasticize the matrix and alter mechanical and barrier properties	Plasticizers, additives, blend components and potential migrants must be considered; biodegradability does not demonstrate food-contact safety	Highly renewable and biodegradable, but generally requires blending, coatings or multilayer structures for high-moisture food applications	[23,38–41]

Food-contact safety must also be evaluated independently of biodegradability. The final formulation, including additives and other blend components, must meet applicable migration requirements [39]. This is particularly relevant for modified and active packaging systems, as shown for a PBAT/starch-based material in which formulation-specific migration required further safety assessment [40]. Overall, the selection of a bioplastic should therefore be matched to the protection, processing, storage, and food-contact requirements of the intended application.

5. Economic and Corporate Analysis

The economic and corporate dimensions of bioplastics adoption represent a central component of this review, focusing on the interaction between cost structures, market incentives, and industrial strategies in the transition from conventional plastics to bioplastics. In this sense, the viability of bioplastics is influenced by their price competitiveness, access to subsidies, and technical properties. Economic barriers and drivers, including raw material costs, manufacturing scalability, and fiscal policies, can influence the pace and scope of market integration. Recent research has increasingly considered business models, regional investment trends, and the role of multinational corporations alongside technical analyses of sustainable packaging [7,42,43].

5.1. Cost and Subsidy Barriers

The higher production cost of many bioplastics remains one of the major barriers to their widespread adoption. A comparison of global production costs shows that biodegradable polymers—particularly PLA, PHB, and starch-based blends—remain significantly more expensive than conventional LDPE or HDPE, with typical production costs ranging from approximately 2.3–2.5 USD/kg compared with 1.0–1.5 USD/kg for fossil-based polymers (Table 4). This persistent gap reflects structural factors such as limited industrial scale, catalyst costs, and energy requirements associated with fermentation and polymerization processes. However, in integrated biorefinery systems, part of the energy demand can be offset through the valorization of by-products and biomass residues for energy generation, which may partially improve process efficiency. Nevertheless, current industrial deployment remains limited, and these techno-economic constraints continue to restrict the financial competitiveness of bio-based materials. Beyond price itself, feedstock dependence is an important contributor to production costs. As shown in Table 4, the reliance on primary agricultural crops, which can account for up to 40% of total production expenses, helps explain why bioplastics remain vulnerable to commodity price volatility and ongoing food security debates. By contrast, countries investing in residue-based feedstocks, particularly in Latin America and parts of Asia, tend to exhibit reductions of approximately 20–30% in production costs. These trends suggest that circular-economy strategies based on feedstock valorization can offer not only environmental benefits, but also economic advantages.

Regarding capital intensity, the requirement of up to €40,000 per ton of annual production capacity may help explain why bioplastic manufacturing remains largely concentrated in high-income regions (Table 4). In this context, cost reduction appears closely linked to policy intervention rather than technological maturity alone. The European Union has developed support mechanisms including R&D funding and technology transfer [44,45], whereas Latin America and Africa continue to rely more heavily on private or international funding [44,46]. This asymmetry indicates that disparities in production capacity are shaped not only by technological access, but also by the availability and continuity of public financing mechanisms.

Table 4. Economic Cost Gap and Policy Instruments Shaping the Global Competitiveness of Bioplastics.

Aspect/Parameter	Key Findings and Quantitative Data	Representative Regions/Policies	Implementation or Support Mechanism	Reference(s)
Average production cost (USD/kg)	Conventional LDPE/HDPE: 1.0–1.5 USD/kg vs. bioplastics (PLA, PHB, starch blends): 2.3–2.5 USD/kg.	Global (baseline comparison).	Low economies of scale; high energy and catalyst costs.	[42]
Feedstock contribution to total cost	Agricultural feedstocks (e.g., maize and sugarcane) represent a substantial share of bioplastic production costs, with economic performance strongly influenced by feedstock availability and market fluctuations.	EU, Brazil, USA (PLA feedstocks).	High agricultural input prices; competition with food sector.	[42]
Alternative biomass/waste valorization	Agro-industrial residues (cassava bagasse, corn husks, etc.) can reduce production cost by 20–30 %.	Latin America, Asia.	Use of by-products for lactic acid/PHA synthesis; circular economy.	[42,47]
Capital expenditure (CapEx)	€5000–40,000 per ton · year ^{−1} of installed capacity for biobased plants.	Europe, USA, Japan.	High investment threshold for fermentation/polymerization equipment.	[48]
Market share	Bioplastics < 1 % of global plastics output.	Global.	Limited infrastructure; early-stage market.	[42,49]
Oil-price sensitivity	Profitability is strongly affected by low crude-oil prices that keep fossil polymers cheap.	Global.	Price volatility discourages long-term investment.	[42,49]
Public subsidies/incentives	EU “Circular Biobased Europe JU”, “European Plastics Strategy” fund R&D and pilot plants.	EU (Germany, France, Netherlands).	R&D funding; tax credits; technology transfer.	[44,45]
Need in developing regions	Lack of subsidy schemes limits competitiveness and scaling.	Latin America, Africa.	Reliance on private or international funding.	[44,46]

Reducing the existing cost gap is therefore likely to require coordinated fiscal action alongside technological diversification. Bioplastics are more likely to achieve sustained market competitiveness when feedstock valorization, industrial scaling, and long-term policy support converge within coherent regulatory frameworks. From this perspective, economic sustainability is an important condition for the effective implementation of circular economy models.

5.2. Carbon Footprint and Environmental Sustainability

The carbon footprint of fossil-based and bio-based polymers varies considerably depending on feedstock origin, production technology, energy requirements, geographical context, system boundaries, life-cycle inventory databases, impact assessment methods, and the treatment of biogenic carbon. As shown in Figure 3, the cradle-to-gate carbon footprints reported for virgin fossil-based low-density polyethylene (LDPE) and high-density polyethylene (HDPE) are 1.87 and 1.80 kg CO₂-eq/kg polymer, respectively [50]. Based on these values, an average fossil-based benchmark of 1.84 kg CO₂-eq/kg polymer was calculated for the comparative analysis presented in Figure 3. This benchmark should therefore be interpreted as a reference derived from the two fossil-based polymers considered in this review rather than as a universal threshold for fossil-based plastics.

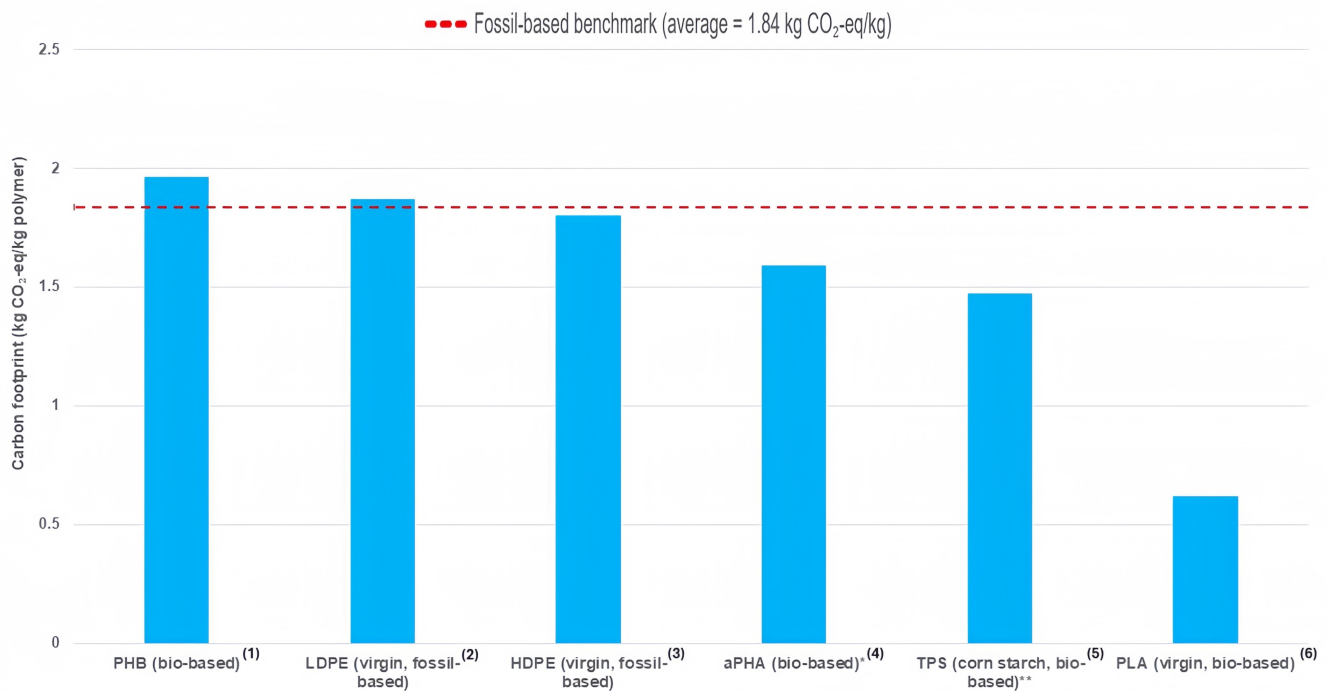


Figure 3. Comparative cradle-to-gate carbon footprint (kg CO₂-eq/kg polymer) of selected fossil-based and bio-based polymers relevant to food packaging (LDPE, low-density polyethylene; HDPE, high-density polyethylene; PLA, polylactic acid; aPHA amorphous polyhydroxyalkanoate; PHB, polyhydroxybutyrate; TPS, thermoplastic starch). Source: Data compiled from (1) [51]; (2) [50]; (3) [50]; (4) [52]; (5) [53]; and (6) [54]. * aPHA: amorphous polyhydroxyalkanoate; bio-based: derived from renewable biological resources. ** TPS: thermoplastic starch; GPCS: glycerol-plasticized corn starch (75 wt.% corn starch and 25 wt.% glycerol).

Among the bio-based polymers considered, substantial differences in carbon footprint are observed. The reported cradle-to-gate carbon footprint of polylactic acid (PLA) is 0.62 kg CO₂-eq/kg polymer [54], whereas amorphous polyhydroxyalkanoate (aPHA) exhibits a value of 1.59 kg CO₂-eq/kg polymer [52]. The comparatively low value reported for PLA is associated with a specific industrial Ingeo production system and includes biogenic carbon uptake; consequently, it should not be interpreted as a universal carbon footprint for all PLA production systems. Likewise, the aPHA value represents the specific feedstock and production configuration evaluated in the corresponding primary LCA study rather than the entire PHA family.

Thermoplastic starch (TPS) produced from glycerol-plasticized corn starch exhibits a cradle-to-gate carbon footprint of 1.47 kg CO₂-eq/kg polymer [53]. This value specifically corresponds to glycerol-plasticized corn starch (GPCS) containing 75 wt.% corn starch and 25 wt.% glycerol and should therefore not be generalized to all starch-based bioplastics. In contrast, polyhydroxybutyrate (PHB) shows a carbon footprint of 1.96 kg CO₂-eq/kg polymer [51], slightly exceeding both virgin LDPE and HDPE values considered in Figure 3. The PHB assessment is based on a biologically derived production route involving fermentation, recovery, purification, and drying, for which energy requirements, particularly steam and electricity consumption, contribute substantially to the environmental burden.

These results indicate that a bio-based origin does not inherently guarantee a lower carbon footprint than fossil-based polymers. Within the systems considered in Figure 3, PLA, TPS, and aPHA exhibit lower reported cradle-to-gate GWP values than the calculated fossil-based benchmark of 1.84 kg CO₂-eq/kg polymer, whereas PHB exhibits a slightly higher value. Nevertheless, these numerical differences should be interpreted cautiously because the underlying LCA/LCI studies are not fully harmonized. Differences in feedstocks,

geographical boundaries, electricity mixes, production scales, background databases, life-cycle impact assessment methods, allocation procedures, and biogenic-carbon accounting can substantially influence the reported GWP values. Accordingly, Figure 3 provides an indicative comparison of values reported in the cited LCA/LCI studies and technical inventory sources.

Moreover, production-stage carbon footprint represents only one component of the overall environmental performance of packaging materials. The sustainability of bio-based polymers also depends on feedstock cultivation and land-use implications, energy sources, material functionality, product lifetime, and end-of-life pathways, including recycling, industrial composting, anaerobic digestion, incineration, and landfill. Consequently, favorable cradle-to-gate GWP values do not necessarily translate into superior cradle-to-grave environmental performance when appropriate collection and treatment infrastructure is unavailable [44,46].

Therefore, sustainability claims for bio-based and biodegradable packaging should be supported by transparent and context-specific life-cycle assessment rather than by feedstock origin or biodegradability alone. Harmonization of functional units, system boundaries, biogenic-carbon accounting, allocation procedures, background inventories, and end-of-life assumptions is particularly important when comparing fossil-based and bio-based polymers. Such methodological transparency can help avoid misleading environmental claims and support evidence-based material selection, certification, and policy development [55,56].

5.3. Environmental Trade-Offs in Life Cycle Assessment of Bio-Based Polymers

Although carbon footprint (CFP) is often used as the primary indicator to assess the environmental performance of bio-based polymers, relying solely on greenhouse gas emissions may provide an incomplete picture of sustainability. Life cycle assessment (LCA) studies indicate that the environmental profile of bioplastics must also consider other impact categories, including eutrophication, land use, and water consumption.

For example, biomass production for bio-based pathways can involve substantial water requirements, with water footprints varying considerably depending on crop type, geographical location, climatic conditions, and agricultural practices [57]. These differences highlight the importance of considering agricultural water demand when evaluating the environmental implications of biomass-derived feedstocks. For the 2014 Ingeo production system, a cradle-to-gate global warming potential of 0.62 kg CO₂-eq/kg polymer was reported, substantially lower than the values reported for several fossil-based polymers considered in the study. However, the authors emphasize that environmental performance also depends on factors such as agricultural feedstock production, land use, water consumption, and other regional impact categories, whose interpretation is sensitive to local conditions and LCA methodology [54]. These findings indicate that the sustainability of bio-based polymers should be evaluated through life cycle assessments that consider both environmental benefits and trade-offs across multiple impact categories.

5.4. Integration of Bioplastics into Existing Recycling Systems

The integration of bioplastics into existing recycling systems depends strongly on their chemical structure rather than solely on their renewable origin or biodegradability. In this context, an important distinction exists between drop-in bio-based polymers and chemically novel bioplastics. Drop-in polymers such as bio-based polyethylene (bio-PE) and bio-based polyethylene terephthalate (bio-PET) have the same chemical structure and material properties as their fossil-based counterparts and can therefore follow the same downstream processes, including established end-of-life treatment pathways. In contrast, chemically

novel bioplastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) have no direct fossil-based equivalents and generally cannot be incorporated into existing material-conserving recycling streams without polymer-specific end-of-life strategies. Consequently, the integration of bioplastics into current recycling infrastructure cannot be addressed as a single pathway but must account for polymer identity and compatibility with established waste-management streams [58].

Effective sorting and separation are therefore critical for integrating chemically distinct bioplastics into existing recycling systems. This is particularly relevant for PLA and PET packaging, which can be difficult to distinguish visually and may enter the same collection stream [59]. Near-infrared (NIR) sorting technologies can discriminate PLA from PET, with reported separation efficiencies varying according to the sorting configuration and operating conditions; however, incomplete separation may still allow residual PLA to enter the PET recycling stream [59]. Moreover, density-based separation is not necessarily sufficient because both PLA and PET can sink during conventional float–sink separation [59]. Consequently, the integration of bioplastics requires material identification together with appropriate source separation, sorting, and pre-processing strategies capable of delivering sufficient homogeneous and low-contamination feedstocks for subsequent recycling operations [58,59].

Mechanical recycling represents an important material-recovery pathway for thermoplastic bioplastics, but its feasibility depends on both the purity of the recovered stream and the ability of the polymer to withstand repeated thermal and mechanical processing. These requirements are particularly relevant for PHA-based materials, whose reprocessing can be affected by thermal and hydrolytic degradation, potentially leading to chain scission and changes in material properties. Nevertheless, experimental evidence for PHBV indicates that its mechanical properties can be retained over several extrusion cycles under controlled processing conditions, suggesting that dedicated mechanical recycling may be technically feasible when sufficiently pure material streams are available. From an environmental perspective, mechanical recycling has also been identified as a favorable end-of-life scenario for PHBV; however, its environmental benefits depend on the quality of the recovered material and its capacity to substitute virgin polymer. Therefore, mechanical recycling of bioplastics should not be considered universally applicable, but rather as a polymer- and stream-specific strategy whose effectiveness depends on sorting efficiency, recycle quality, and the preservation of material properties during reprocessing [37,58,60].

Chemical recycling provides a complementary pathway for bioplastic waste that cannot be effectively recovered through mechanical recycling, particularly when material degradation, contamination, or complex waste streams limit direct reprocessing. Unlike mechanical recycling, these processes convert polymers into lower-molecular-weight compounds while potentially preserving or recovering valuable chemical functionality. For PLA, several routes have been investigated, including hydrolysis, solvolysis, catalytic depolymerization, and pyrolysis, enabling the recovery of lactic acid, lactide, or other value-added intermediates depending on the process conditions [58]. Chemical recycling has also been investigated for PHA-based materials, including PHB, through hydrolysis, catalytic depolymerization, and pyrolysis, although the available evidence is less extensive than for PLA [37,58]. Despite these technical opportunities, chemical recycling should not be considered a universally preferable alternative to mechanical recycling, because process performance depends on polymer composition, feedstock quality, energy and reagent requirements, product selectivity, and the feasibility of recovering useful products. Moreover, many chemical recycling technologies for bioplastics remain at laboratory, early-development, or pilot stages, and their broader implementation requires demonstrated

environmental benefits, process reliability, economic feasibility, and adequate recycling infrastructure [37,58].

A major barrier to the integration of bioplastics into existing recycling systems is the mismatch between increasing material diversity and waste-management infrastructure originally designed for established conventional polymer streams. When chemically distinct bioplastics are not adequately identified and separated, they may enter incompatible recycling streams and affect processing efficiency or recycle quality. PLA in PET recycling provides a relevant example, as residual PLA remaining after sorting can interfere with PET reprocessing, highlighting that even technically sortable materials require sufficiently effective separation to maintain stream quality. At the same time, establishing dedicated collection and recycling routes for emerging bioplastics can be constrained by low or geographically dispersed waste volumes, additional sorting and pre-processing requirements, and the limited availability of specialized recycling infrastructure. Similar limitations apply to chemical recycling, for which many bioplastic-specific technologies remain in laboratory, early-development, or pilot stages rather than being broadly integrated into existing waste-management systems. Therefore, infrastructure development should be aligned with the expected composition and volume of bioplastic waste streams, while maintaining adequate material identification, separation, and feedstock quality to avoid transferring contamination or inefficiency from one end-of-life pathway to another [58,59].

Taken together, the available evidence suggests that the integration of bioplastics into existing recycling systems should follow differentiated pathways according to polymer chemistry, waste-stream purity, and infrastructure availability. First, drop-in bio-based polymers that are chemically equivalent to their fossil-derived counterparts, such as bio-PE and bio-PET, can generally be integrated into the corresponding established polymer-specific recycling streams. Second, chemically distinct thermoplastic bioplastics may be directed toward dedicated sorting and mechanical recycling when sufficiently pure and homogeneous waste streams can be collected and when material properties can be adequately retained during reprocessing. Third, chemical recycling may complement mechanical recycling for selected bioplastic streams that cannot meet the purity or material-quality requirements for direct mechanical recovery, provided that the specific conversion route offers technically viable product recovery and demonstrable environmental and economic benefits. Where neither material-recycling pathway is technically or environmentally justified, alternative end-of-life routes should be selected according to polymer characteristics and locally available waste-management infrastructure. Thus, effective circular integration requires a polymer-specific rather than a universal end-of-life strategy, supported by appropriate collection, sorting, recycling capacity, and assessment of technical, environmental, and economic feasibility [37,59,60].

5.5. Regional Corporate Strategies

Regional corporate strategies in the bioplastics sector reflect how companies adapt technological choices to distinct regulatory, economic, and resource contexts (Table 5). Rather than following a uniform development pathway, firms across regions prioritize different production routes, material formulations, and market segments in response to local constraints and opportunities.

In South America, corporate strategies tend to emphasize the valorization of agro-industrial residues and the use of locally available feedstocks (Table 5). This orientation favors formulations that integrate PLA with starches or natural fibers to reduce costs and respond to emerging environmental regulations and agricultural side-stream management. These approaches are typically aligned with regional needs for affordability and resource efficiency rather than high-performance specialization.

Table 5. Regional comparison of leading companies developing bioplastics for food packaging.

Region	Company(ies)	Products & Applications	Technology Used	Regulatory Context	Strategy/Notable Features	References
South America	BioElements	Compostable bags, utensils; food retail packaging	PLA + corn starch	Emerging policies	Made from renewable sources	[21,22]
South America	Greenplast	Biodegradable fruit trays; fresh produce packaging	Biopolymers + vegetable fibers	Emerging policies	Reuses agro-industrial side streams	[21,22,38]
North America	NatureWorks	Ingeo PLA resins; bottles, food trays, flexible films	Fermentation of plant sugars	Compostability certification	High-performance PLA	[38]
Europe	Novamont, Total Corbion	Mater-Bi bioplastics; bags, trays, flexible packaging	Starch-based blends with PCL	EU SUP Directive	Widely certified, compostable	[6,11,29]
Asia	Kaneka, Mitsubishi	PHBH, PHA biopolymers; films, trays, containers, utensils	Fermentation of plant-derived oils	Extended Producer Laws	Biodegradable in seawater, tech innovation & export	[22,61]

By contrast, companies operating in North America generally focus on standardized, high-performance PLA-based materials aimed at large-scale flexible packaging markets (Table 5). This strategy is associated with a regulatory environment that prioritizes certification, traceability, and market consistency and supports the development of resins optimized for industrial processing and broad commercial deployment. In Europe, corporate strategies are influenced by harmonized regulatory frameworks and binding directives that encourage compliance-oriented innovation (Table 5). Firms therefore tend to focus on compostable materials that meet certification criteria within a market characterized by regulatory alignment and continued technological development.

Asian corporate strategies show a different emphasis, prioritizing technological differentiation through advanced biopolymer synthesis, particularly in PHA- and PHBH-based materials (Table 5). These pathways reflect an orientation toward export competitiveness and specific end-of-life performance targets, including biodegradability under diverse environmental conditions.

Taken together, these regional patterns illustrate that corporate strategies in the bioplastics sector are shaped by the interaction between material performance, regulatory scope, regulatory implementation status, and resource availability at the regional level. Differences in regulatory ambition, whether incremental, directive-driven, or responsibility-based—shape both the technological trajectories firms pursue and the markets they target. Consequently, cross-regional alignment and dialogue can help reduce fragmentation and support the broader deployment of sustainable packaging solutions.

6. Global and Regional Legislative Framework

The global and regional legislative framework governing bioplastics provides a basis for understanding the opportunities and structural constraints affecting the development of sustainable food packaging. Regulatory coherence or its absence appears to play a significant role in influencing investment flows, technological prioritization, and the speed of market adoption across jurisdictions. Consequently, examining international, continental, and national policy instruments helps clarify how legal definitions, certification schemes, and compliance mechanisms affect the positioning of bioplastics within the packaging sector.

Over the past decade, several international organizations have emphasized the importance of greater alignment in standards and certification systems. For instance, the EUBP has highlighted the need for clear labeling frameworks to avoid consumer confusion and greenwashing [62]. Similarly, the Organization for Economic Co-operation and Development (OECD) has underscored that policy fragmentation may hinder cross-border

trade and slow the scaling of circular materials [44]. The United Nations Environment Programme (UNEP) has also advocated for coordinated global approaches to plastics governance, particularly in the context of life-cycle assessment, waste management infrastructure, and international regulatory dialogue [46].

While regulatory harmonization can facilitate the adoption of bioplastics, current reports suggest that harmonization alone cannot fully resolve existing market barriers. Greater regulatory convergence could reduce uncertainty for producers and facilitate certification recognition across markets. The development of robust and interoperable standards may contribute to building consumer trust and supporting more predictable investment environments. A proposed Codex Vasorum (Code of Containers), analogous to the Codex Alimentarius, could provide a global framework for the regulatory assessment of food and non-food packaging, including safety standards and sustainability requirements. Thus far, implementation remains uneven, reflecting differences in economic capacity, infrastructure maturity, and political priorities across regions.

6.1. Global Overview

At the macro level, the governance of bioplastics is increasingly shaped by the coordinated action of international organizations and standard-setting bodies that aim to harmonize definitions, certification criteria, and sustainability targets across borders. The United Nations (UN) and UNEP have contributed to global efforts to address plastic pollution through life-cycle approaches, waste prevention, circularity, and improved end-of-life management [46]. The Food and Agriculture Organization (FAO) has further contributed to this agenda by highlighting the risks and opportunities of bioplastics in food systems, recommending robust risk assessments and the development of science-based policies to ensure safety and environmental compatibility [63].

The International Organization for Standardization (ISO) has established technical standards that support the environmental assessment and certification of bioplastics. Key frameworks include ISO 17088:2021 [13] for specifications of compostable plastics and the ISO 14040:2006 [55] and ISO 14044:2006 [64] standards, which define the principles, framework, requirements, and methodological guidelines for life-cycle assessment (LCA). In addition, ISO 14067:2018 [65] provides specific guidance for quantifying and reporting the carbon footprint of products (CFP) based on LCA methodology.

Together, these standards provide common terminology and methodological guidance for evaluating environmental impacts in the bioplastics sector. As noted in recent studies [66,67], unified standards and definitions can help prevent greenwashing, facilitate international trade, and support transparent sustainability claims in both established and emerging economies.

Global initiatives increasingly promote circular-economy approaches that prioritize material recovery, resource efficiency, and reduced environmental impacts over the traditional “take-make-dispose” model. The OECD’s 2022 Global Plastics Outlook and the EU Circular Economy Action Plan identify bioplastics within broader strategies aimed at closing material loops, reducing greenhouse gas emissions, and supporting innovation in sustainable packaging [44,68].

International cooperation and cross-sectoral alignment supported by organizations such as the UN, UNEP, FAO, ISO, and OECD contribute to policy development related to bioplastics. Continued dialogue among scientists, regulators, and industry stakeholders can support the development of environmentally credible and scalable packaging solutions.

6.2. Regional and National Legislation

Regional and national legislation relevant to bioplastics differs in regulatory scope, implementation, and policy objectives across jurisdictions. Table 6 summarizes selected legal frameworks, quantitative targets, implementation evidence, and evidence limitations relevant to the market introduction and end-of-life management of bioplastic food packaging in the jurisdictions considered. Importantly, the instruments included in this comparison are not necessarily bioplastics-specific laws; rather, they were considered when their provisions directly affect the conditions under which bioplastic packaging may be introduced, collected, recovered, recycled, composted, or otherwise managed at end of life. This comparison illustrates how different regulatory models address the transition toward sustainable packaging.

For the comparative analysis presented in Table 6, regulatory instruments were selected according to their direct relevance to the use, market introduction, and end-of-life management of bioplastics and bioplastic-related packaging. Priority was given to binding legislation and policy instruments that establish restrictions or phase-outs, quantitative waste-reduction, collection, recovery or recycling targets, recycled-content requirements, extended producer responsibility (EPR) obligations, reuse or refill requirements, deposit-return systems, or other compliance requirements affecting plastic packaging and, consequently, the regulatory conditions applicable to bioplastic packaging. Their relevance to bioplastics therefore arises when these requirements influence regulatory acceptance, waste-management compatibility, or the intended end-of-life pathway of bioplastic food packaging. Broader environmental or waste-management policies without a clear operational connection to these aspects were not prioritized. This scope was adopted to enable a consistent comparison of regulatory barriers, obligations, quantitative targets, and implementation progress rather than an exhaustive compilation of national environmental legislation.

The regulatory frameworks summarized in Table 6 reveal substantial differences not only in regulatory scope, but also in implementation status across jurisdictions. Binding measures addressing packaging waste, extended producer responsibility (EPR), single-use plastics, recycling, recycled content, and resource circulation are present across several regions, although their implementation pathways and demonstrated outcomes differ considerably. These differences indicate that regulatory development should be assessed not only according to the existence of binding legislation, but also according to the extent to which implementation mechanisms and measurable outcomes can be documented. Accordingly, the existence of a binding legal instrument should not, by itself, be interpreted as evidence of demonstrated implementation or measurable circular performance.

Within Europe, the regulatory framework affecting plastic and bioplastic packaging extends beyond material-specific requirements to encompass waste prevention, extended producer responsibility (EPR), separate collection, recycling, recycled-content requirements, reuse and refill, and deposit-return systems. At the EU level, the Waste Framework Directive (2008/98/EC) [69], the Single-Use Plastics Directive (EU) 2019/904 [68], and Regulation (EU) 2025/40 [45] on Packaging and Packaging Waste (PPWR) collectively establish an integrated framework for packaging and packaging-waste management. The PPWR further introduces progressive packaging-waste reduction targets, recyclability and recycled-content requirements, reuse and refill provisions, and deposit-return obligations for specific beverage containers (Table 6) [45,70]. Germany complements these EU-level requirements through its national Packaging Law Implementation Act (VerpackDG) and the established Pfand deposit-return system, linking producer responsibility and packaging-waste management with a mandatory deposit for eligible single-use beverage containers [71,72].

Table 6. Selected packaging policy frameworks and their relevance to bioplastic food packaging.

Jurisdiction	Instrument and Year	Instrument Type and Scope	Main Provisions and Targets	Relevance to Bioplastic Food Packaging	Implementation Evidence	Evidence Limitations	References
European Union	Packaging and Packaging Waste Regulation (EU) 2025/40 [45].	Binding regulation on packaging design, market placement and waste management.	Packaging-waste reduction targets of 5% by 2030, 10% by 2035 and 15% by 2040 relative to 2018. Articles 8 and 9 address biobased feedstock and compostable packaging, respectively.	Explicitly distinguishes biobased content from compostability. Specified packaging formats must meet compostability requirements, whereas other biodegradable packaging must generally be designed for material recycling, subject to stated exceptions.	General application from August 2026, with provision-specific transitions. Key compostability requirements apply from February 2028.	Application dates and targets do not demonstrate achieved circularity or justify composting all bioplastic packaging.	[45]
Germany	Packaging Law Implementation Act (VerpackDG, 2026); established beverage-container deposit system.	Binding packaging producer-responsibility and deposit-return framework.	Producer registration, system participation and take-back obligations; minimum EUR 0.25 deposit for covered single-use beverage containers.	Provides collection and financing conditions relevant to bioplastic beverage packaging. Feedstock substitution alone does not establish compatibility with existing sorting and recycling systems.	DPG reports a return rate exceeding 96% for deposit-bearing single-use beverage containers.	The rate concerns the overall deposit system, not bioplastics separately, and cannot be attributed to the 2026 law alone.	[71,72]
Brazil	Decree No. 12,688/2025, implementing the National Solid Waste Policy.	Binding reverse-logistics framework for plastic packaging and equivalent products within its scope.	Recovery targets increase from 32% in 2026 to 50% in 2040; recycled-content targets increase from 22% to 40%. Packaging subject to specific regulation, including food packaging, is excluded from the recycled-content targets under Article 33(3).	Connects packaging design with recovery and traceability. Bioplastic food-packaging applications require assessment alongside food-specific regulation; bio-based content is distinct from recycled content.	The decree establishes phased obligations, reporting and verification mechanisms, with recycled-content obligations beginning in 2026 according to company size.	Targets are not measured outcomes. The food-packaging exception prevents generalizing recycled-content requirements to all food-contact applications.	[73]
Uruguay	Ministerial Resolutions No. 271/021 and No. 1391/024.	Binding post-consumer packaging recovery and specified recycled-content requirements.	Recovery and territorial-coverage obligations; 40% recycled content for specified plastic beverage packaging. Resolution No. 1391/024 revises implementation deadlines.	Establishes recovery conditions relevant to alternative food and beverage packaging. Bioplastic substitution requires compatibility with the applicable packaging-management system.	Resolution No. 1391/024 documents preparatory progress under Plan Vale and extends implementation deadlines.	Preparatory progress does not demonstrate target attainment. The cited evidence does not establish separate recovery outcomes for bioplastic food packaging.	[74]
Chile	Law No. 20,920 (2016); Supreme Decree No. 12/2020.	Binding extended producer responsibility framework for packaging collection and recovery.	Material-specific collection and recovery obligations, producer management systems, reporting and enforcement.	Makes packaging classification and recovery arrangements relevant to bioplastic design. Alternative materials require assessment against the applicable category and available treatment route.	Collection and recovery obligations became applicable following the decree's 30-month transition after publication in March 2021.	Legal commencement does not demonstrate recovery performance or the availability of collection and composting systems for biodegradable packaging.	[75,76]
Peru	Law No. 30884 (2018); Supreme Decree No. 006-2019-MINAM (2019).	Binding restrictions on specified single-use plastics and expanded-polystyrene food and beverage packaging.	Progressive product restrictions; provisions concerning reuse, recovery and degradation without microplastic or hazardous-substance pollution; specified food-safety and hygiene exceptions.	Directly addresses food-service articles and requirements relevant to replacement products. Renewable feedstock alone does not demonstrate that a bioplastic alternative meets these requirements.	The law and its implementing regulation establish phased prohibitions and mechanisms for technical regulation and information collection.	The legal framework does not quantify bioplastic adoption or end-of-life performance. Product restrictions alone do not demonstrate successful substitution.	[77,78]
Colombia	Law No. 2232 (2022).	Binding framework for gradual reduction and substitution of specified single-use plastic products.	Product-specific phase-out periods and provisions concerning sustainable alternatives, biodegradability, recycling and producer responsibility.	Establishes conditions for alternative products, including provisions concerning degradation in natural environmental conditions. Generic bioplastic or industrial-compostability claims do not establish eligibility.	The law establishes a staged transition and provides for technical requirements governing alternative products.	Recognition of alternatives does not demonstrate actual degradation, collection or adoption. Product conformity requires assessment of applicable implementing requirements.	[79]

Table 6. Cont.

Jurisdiction	Instrument and Year	Instrument Type and Scope	Main Provisions and Targets	Relevance to Bioplastic Food Packaging	Implementation Evidence	Evidence Limitations	References
United States	EPA National Strategy to Prevent Plastic Pollution (2024).	Federal strategy rather than a uniform binding packaging-compliance regime.	Strategic actions addressing plastic reduction, recovery and pollution prevention across the materials lifecycle.	Provides policy context for alternative packaging systems. The strategy itself does not authorize bioplastic food-contact materials or establish nationwide acceptance of compostable packaging.	Published in 2024; the EPA webpage updated in June 2026 states that the strategy is under review.	Publication does not demonstrate implementation or bioplastic-specific outcomes. Review status limits conclusions about the future policy direction.	[80,81]
Japan	Resource Circulation Strategy for Plastics (2019); Act on Promotion of Resource Circulation for Plastics (2021; effective 2022).	National strategy and binding lifecycle resource-circulation framework.	Strategic milestones include 60% reuse/recycling of plastic containers and packaging and approximately 2 million tonnes of biomass plastics introduced by 2030.	Explicitly includes biomass plastics alongside reduction, reuse and recycling. Food-packaging applications still require assessment of functional suitability and their intended recovery route.	The act took effect in April 2022, establishing lifecycle measures for plastic products.	The biomass-plastics milestone extends beyond food packaging. Strategic milestones and legal commencement do not demonstrate achieved bioplastic recovery.	[82,83]
China	Opinions on Further Strengthening Plastic Pollution Control (2020).	National policy framework with phased product restrictions and measures promoting alternatives.	Restrictions on non-degradable bags and specified food-service articles; a 2025 target to reduce non-degradable disposable-tableware consumption intensity in takeaway services in prefecture-level cities by 30%.	Identifies food-service applications relevant to material substitution. Suitability of alternatives must be assessed separately from degradation under actual waste-management conditions.	The instrument specifies phased milestones for 2020, 2022 and 2025.	Milestones describe intended implementation rather than verified attainment. They do not quantify bioplastic substitution or end-of-life outcomes.	[84]
South Africa	Amendments to the Plastic Carrier Bags and Plastic Flat Bags Regulations (2021).	Binding product-specific requirements for covered carrier and flat bags.	Minimum post-consumer recycled content of 50% from 2023, 75% from 2025 and 100% from 2027, with an exemption mechanism for the final requirement.	Relevant to alternative bags used in food retail. Biobased origin alone does not satisfy a requirement for post-consumer recycled content.	The regulation specifies dated minimum-content obligations and enforcement provisions.	Required percentages are not measured compliance rates. Bag-specific requirements cannot be generalized to all food packaging or used as evidence of bioplastic circularity.	[85]
Australia	National Plastics Plan (2021); packaging-regulation reform process.	National policy plan and regulatory-reform process.	The plan records 2025 targets of 100% reusable, recyclable or compostable packaging and 70% recycling or composting of plastic packaging.	Recognizes compostable packaging as an option whose practical suitability depends on collection and treatment. Compostability does not establish acceptance in a particular waste-management system.	Official documents record the targets and subsequent reform consultation. Use of the proposed recyclability-grading framework remains subject to a decision.	Targets do not demonstrate achievement. Reform proposals are distinct from enacted requirements, and aggregate indicators do not establish bioplastic-specific performance.	[86,87]

Implementation evidence also varies substantially across the jurisdictions considered. Germany provides an example of demonstrated implementation through its long-established Pfand deposit-return system, for which return rates exceeding 96% have been reported for deposit-bearing single-use beverage containers [72]. By contrast, the European Union, Brazil, Uruguay, Chile, Peru, Colombia, Japan, China, and South Africa have binding frameworks or requirements for which quantitative outcomes, infrastructure, compliance mechanisms, or bioplastic-specific end-of-life performance remain under implementation or are not yet sufficiently documented to demonstrate comparable circular-performance outcomes (Table 6; Figure 4). The United States and Australia are treated separately as strategic/partial cases because their national frameworks do not provide the same combination of binding requirements and demonstrated implementation identified for Germany. These differences support a distinction between regulatory adoption and demonstrated implementation rather than a comparison based solely on the existence or number of regulatory instruments (Figure 4).

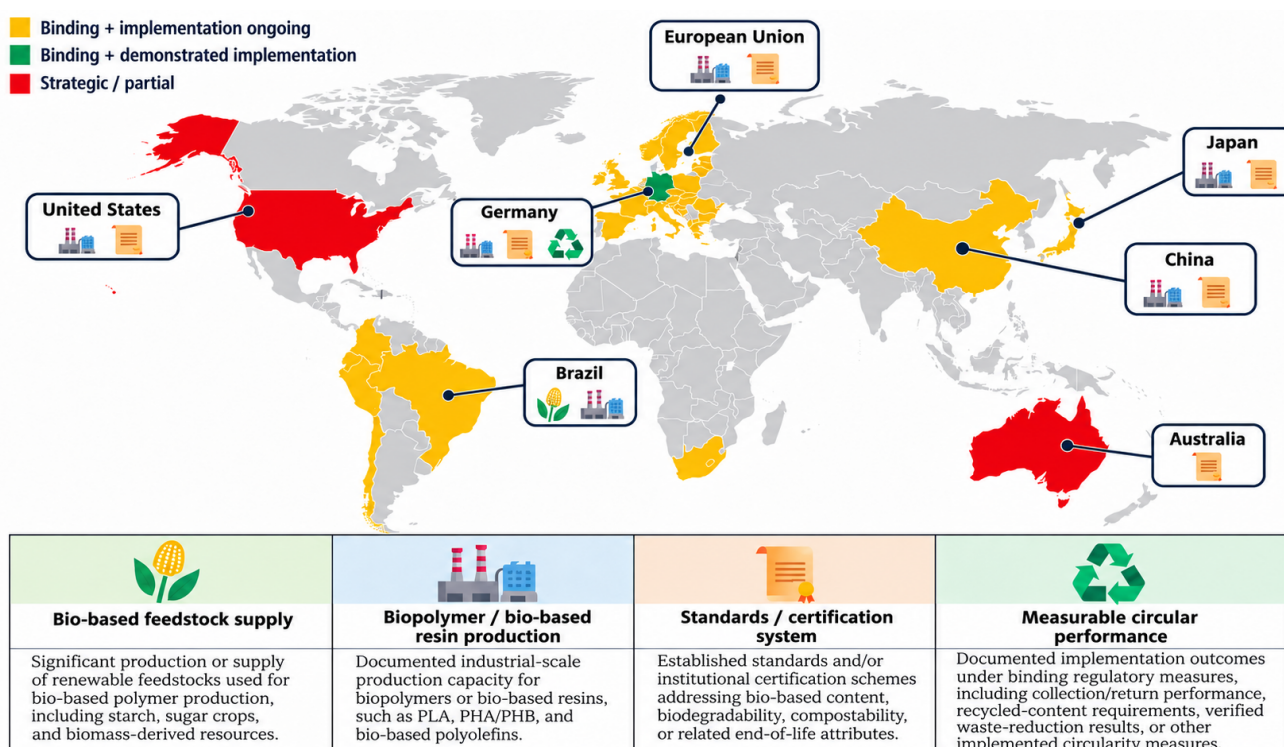


Figure 4. Global regulatory maturity and strategic positioning in the bioplastics value chain. Source: Authors' elaboration based on the regulatory frameworks and implementation evidence summarized in Table 6, complemented by institutional and industry sources on bio-based feedstock supply, biopolymer production, standards and certification systems, and circular-economy implementation [88–96].

Effective legislative design, supported by harmonized standards, measurable targets, and binding regulatory instruments, can contribute to translating policy ambition into tangible sustainability outcomes. In addition, coherent policy frameworks, financial support mechanisms, and political commitment can support the large-scale adoption of sustainable materials. However, the effectiveness of these frameworks ultimately depends on implementation conditions, including infrastructure availability, institutional capacity, enforcement mechanisms, and stakeholder participation. Consequently, the relevance of these regulatory frameworks to bioplastics lies not only in whether they explicitly mention bioplastics, but also in whether their provisions materially affect the market introduction,

certification, collection, recovery, recycling, composting, or other end-of-life pathways of bioplastic food packaging.

6.3. Regulatory Maturity and Circular Performance in the Global Bio-Based Economy

Regulatory frameworks relevant to bioplastics differ across jurisdictions (Figure 4), and three implementation categories were identified: (i) binding + demonstrated implementation; (ii) binding + implementation ongoing; and (iii) strategic/partial.

The binding + demonstrated implementation category is represented by Germany (Table 6; Figure 4). Germany provides documented implementation through its long-established Pfand deposit-return system, with return rates exceeding 96% reported for deposit-bearing single-use beverage containers [72]. However, this return rate refers to the overall deposit system and should not be interpreted as a bioplastic-specific performance indicator or as an outcome attributable solely to the current Packaging Law Implementation Act. Within this review, Germany is therefore considered an example of demonstrated implementation of a packaging circularity mechanism relevant to the regulatory and end-of-life conditions under which bioplastic beverage packaging would need to operate.

The evidence therefore supports a conservative interpretation of “demonstrated implementation”, distinguishing documented operation or measurable outcomes from regulatory targets, legal entry into force, or phased obligations that have not yet been demonstrated through comparable performance evidence. Accordingly, the classification used here describes the implementation status supported by the available evidence and should not be interpreted as a ranking of the overall regulatory quality of the jurisdictions considered.

The binding + implementation ongoing category comprises the European Union, Brazil, Uruguay, Chile, Peru, Colombia, Japan, China, and South Africa (Table 6; Figure 4). These jurisdictions have established binding regulatory frameworks or requirements addressing areas such as packaging waste, extended producer responsibility, single-use plastics, recovery and recycling, recycled content, or resource circulation, while important quantitative targets, infrastructure requirements, implementation outcomes, or compliance mechanisms remain under progressive implementation or are not yet sufficiently documented. The European Union, for example, is progressively implementing the PPWR requirements through 2030–2040 [45,70], while Brazil has introduced national recovery and recycled-content targets for plastic packaging extending to 2040 [73]. Peru, Japan, and South Africa are also included in this category because binding measures are in place, but the available evidence does not establish comparable bioplastic-specific circular-performance outcomes. Peru’s Law No. 30884 and its implementing regulation, Supreme Decree No. 006-2019-MINAM, establish binding restrictions and phased implementation requirements [77,78]; Japan’s resource-circulation framework has been in force since 2022, although its strategic biomass-plastics milestones do not by themselves demonstrate achieved bioplastic recovery [82,83,97]; and South Africa has established binding recycled-content and extended producer responsibility requirements, although the prescribed percentages should not be interpreted as measured compliance rates or evidence of bioplastic-specific circularity [85,98]. Uruguay, Chile, Colombia, and China similarly combine binding measures with phased targets, implementation schedules, or ongoing development of collection, recovery, substitution, and compliance mechanisms [74–76,79,84,99–102].

The strategic/partial category comprises the United States and Australia (Table 6; Figure 4). At the federal level, the U.S. National Strategy to Prevent Plastic Pollution establishes a strategic objective of eliminating releases of plastic waste from land- and sea-based sources by 2040, while implementation remains distributed across federal, state, local, and Tribal levels [80]. In parallel, standards such as ASTM D6400 provide technical criteria for labeling plastics designed for aerobic composting in municipal or industrial facil-

ities [88]. Australia's National Plastics Plan establishes national packaging objectives, while the subsequent packaging-regulation reform process remains under development [86,87]. The broader Australian packaging framework also includes the National Environment Protection (Used Packaging Materials) Measure 2011 [103]. The available evidence documents policy targets, existing packaging measures, and reform initiatives but does not demonstrate bioplastic-specific circular-performance outcomes. These cases therefore represent important strategic, standardization, and regulatory-reform initiatives, but do not provide the same combination of binding requirements and demonstrated implementation identified for Germany.

Beyond implementation status, Figure 4 also highlights differences in strategic positioning within the bioplastics value chain. Biopolymer or bio-based resin production and standards or certification systems represent complementary dimensions of this positioning. Standards or certification systems are identified in the European Union, Germany, the United States, Japan, China, and Australia [88–96]. These dimensions complement the regulatory classification by showing that industrial capacity, standardization, and regulatory implementation do not necessarily develop at the same pace across jurisdictions.

Latin American jurisdictions also show differences between regulatory implementation and strategic positioning. Brazil and Peru illustrate different regulatory implementation pathways, although both are classified within the binding + implementation ongoing category (Table 6; Figure 4). Brazil combines phased recovery and recycled-content targets with reporting and verification mechanisms [73], whereas Peru applies binding restrictions and progressive requirements under Law No. 30884, while bioplastic-specific adoption and end-of-life performance remain insufficiently documented [77]. Uruguay, Chile, and Colombia have binding frameworks whose implementation continues through phased recovery, EPR, substitution, or compliance mechanisms. These differences reinforce the need to distinguish regulatory status from implementation progress and measurable circular performance when comparing national regulatory frameworks relevant to bioplastics (Table 6; Figure 4).

7. Conclusions

Although advances in material science have improved the performance and applicability of bioplastics for food packaging, their large-scale adoption remains constrained by a combination of material performance, processing requirements, production costs, regulatory coherence, and end-of-life management.

The regulatory comparison indicates that the existence of binding legislation should not be interpreted as evidence of demonstrated implementation or measurable circular performance. Across the jurisdictions examined, regulatory targets, implementation schedules, and legal requirements do not necessarily correspond to verified bioplastic-specific outcomes. Germany provides an example of demonstrated implementation through its long-established Pfand deposit-return system, for which return rates exceeding 96% have been reported for deposit-bearing single-use beverage containers. However, this rate refers to the overall deposit system and should not be interpreted as a bioplastic-specific performance indicator. These findings highlight the importance of distinguishing regulatory adoption, implementation progress, and documented performance when assessing the relevance of policy frameworks to bioplastic food packaging.

The economic competitiveness of bioplastics is influenced by coordinated policy instruments, feedstock diversification, and industrial scaling. Fiscal incentives, residue valorization strategies, and infrastructure investment may help reduce cost disparities with fossil-based plastics and support the broader adoption of bioplastics.

From an environmental perspective, the sustainability advantages of bio-based polymers cannot be assessed solely through carbon footprint reductions. Life cycle assessment

studies indicate that while materials such as PLA may achieve substantial reductions in greenhouse gas emissions compared with fossil-based plastics, other environmental indicators, including water consumption, land use, and eutrophication, may increase depending on feedstock origin, agricultural practices, and production pathways.

Therefore, future bioplastic strategies should incorporate life-cycle assessment frameworks that consider environmental trade-offs across multiple impact categories. Integrating low-impact feedstocks, sustainable agricultural practices, renewable energy inputs, and efficient end-of-life management systems could help improve the environmental performance of bioplastics within circular food-packaging systems.

Greater international coordination linking regulatory enforcement, industrial integration, and life-cycle accountability could support the broader integration of bioplastics into circular food-packaging systems. In this context, established supranational frameworks such as Codex Alimentarius could provide a reference model for developing greater international alignment of packaging sustainability criteria.

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Abbreviations

The following abbreviations are used in this manuscript:

FFs	fossil fuel-based materials
NFFs	non-fossil fuel-based materials
HDPE	high-density polyethylene
LDPE	low-density polyethylene
PLA	polylactic acid
PHB	polyhydroxybutyrate
PHA	polyhydroxyalkanoates
PBAT	polybutylene adipate terephthalate
ISO	International Organization for Standardization
CEN	European Committee for Standardization
UNEP	United Nations Environment Programme
EUBP	European Bioplastics Association
EPR	Extended Producer Responsibility
LCA	Life cycle assessment

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