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Biodegradable Polymers and Green Chemistry in Packaging: A Narrative Review

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ABSTRACT

Plastic packaging is used briefly and discarded in very large quantities, and biodegradable polymers are widely promoted as a solution. This narrative review examines what green chemistry can and cannot deliver for packaging. Of about 6,300 million tonnes of plastic waste generated up to 2015, only 9% was recycled and 79% accumulated in landfills or the natural environment. Bioplastics are growing quickly but remain about 0.5% of the roughly 414 million tonnes of plastics produced, with global capacity of 2.47 million tonnes in 2024 forecast to reach 5.73 million tonnes by 2029; packaging is their largest application (45%). We describe the main families, poly(lactic acid) (PLA), polyhydroxyalkanoates (PHAs), starch and other polysaccharides, and fossil-based biodegradable polyesters, together with the chemistry of their synthesis (including ring-opening polymerisation of lactide) and degradation, and we map the twelve principles of green chemistry onto packaging polymers. The central finding is that biodegradability depends on conditions, not on the polymer alone. In a study of 15 plastics and blends, PLA was not home compostable, a PLA/polycaprolactone blend was, only PHB and thermoplastic starch broke down completely in all soil and water conditions tested, and most materials failed standard soil and water tests. Policy is moving: India banned identified single-use plastics in 2022 and exempts certified compostable plastics, the EU packaging regulation applies from August 2026, while the global plastics treaty talks have not reached agreement. We conclude that biodegradable polymers are useful for specific applications with matching waste infrastructure, but are not a general substitute for reducing, reusing and recycling packaging, and that chemically recyclable polymers offer a complementary route.

Key words: biodegradable polymers; green chemistry; packaging; poly(lactic acid); polyhydroxyalkanoates; compostability; circular economy; India.

1. Introduction

Plastic packaging is cheap, light and protective, but it is also used for a short time and discarded in large quantities. A global analysis estimated that 8,300 million tonnes (Mt) of virgin plastics had been produced by 2015, generating about 6,300 Mt of waste, of which 9% had been recycled, 12% incinerated and 79% had accumulated in landfills or the natural environment [1]. Replacing persistent fossil-based polymers with biodegradable ones is an attractive idea, and green chemistry, which aims to reduce hazards and waste across the life cycle of chemical products, supplies a framework for judging such replacements [2].

This review asks what biodegradable polymers can realistically achieve in packaging. It covers the terminology, the main polymer families and their chemistry, the evidence on biodegradation in real conditions, the application of green chemistry principles, and the policy landscape in India, the European Union and internationally. It is a narrative review without a systematic search; sources were selected by the author from major reviews, experimental studies, standards and official documents.

2. Terminology and Market

Two properties are often confused. A polymer is bio-based if it is made from renewable feedstock, and biodegradable if microorganisms can break it down into water, carbon dioxide (or methane) and biomass under defined conditions. The two properties are independent (Figure 1): PLA and PHAs are both bio-based and biodegradable, bio-based polyethylene is bio-based but not biodegradable, and

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fossil-based polybutylene adipate terephthalate (PBAT) and polycaprolactone (PCL) are biodegradable though petrochemical [3–5].

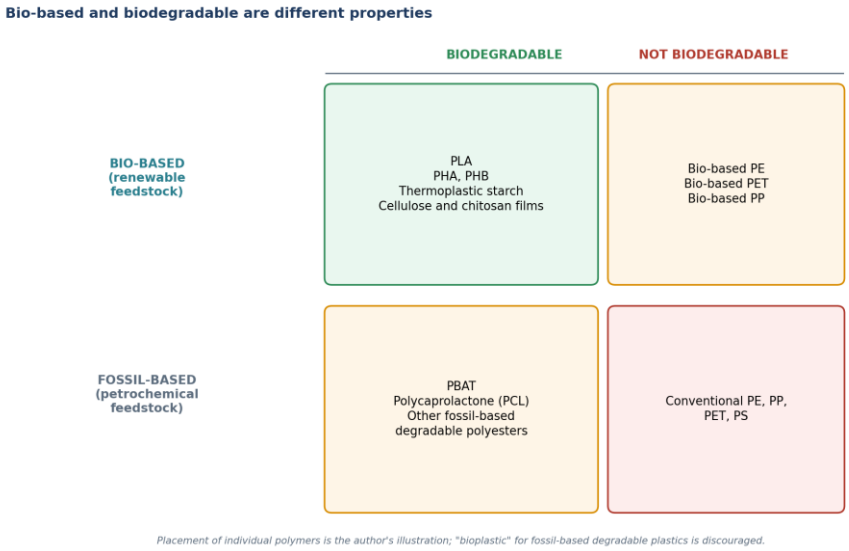

Figure 1. Classification of packaging polymers by feedstock and biodegradability [3–5].

Bioplastics are a small but growing market. Global bioplastics capacity was 2.47 Mt in 2024, about 0.5% of roughly 414 Mt of plastics, and is forecast to reach 5.73 Mt by 2029; packaging is the largest application at 45% (1.12 Mt) [6]. PLA held the largest capacity share (37.1%) in 2024, forecast to rise to 42.3% by 2029, while PHAs are expected to reach about 17% [7] (Figure 2).

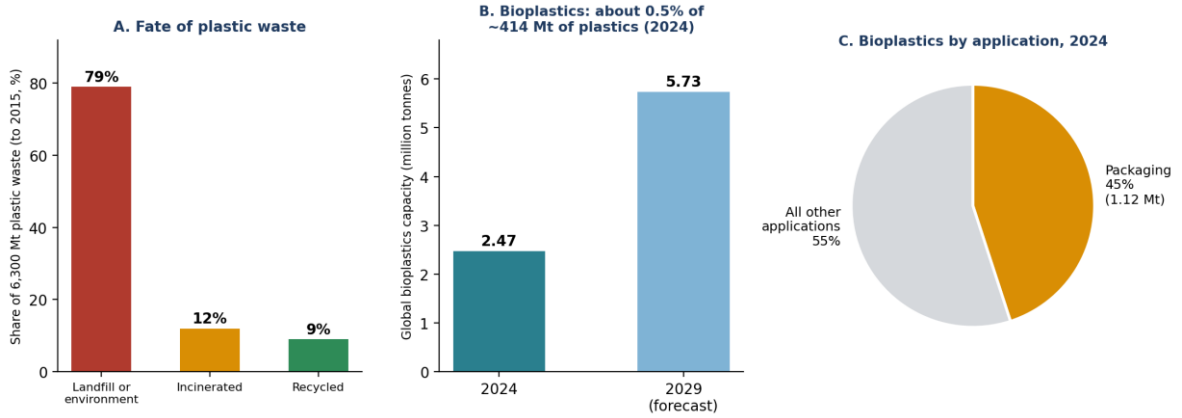

Figure 2. Context for biodegradable packaging: (A). Fate of plastic waste generated up to 2015 [1]; (B). Global bioplastics production capacity [6]; (C). Share of bioplastics by application, 2024 [6]. Graphs prepared from published values.

3. Main Polymer Families and Their Chemistry

3.1 Poly(lactic acid)

PLA is the leading bio-based biodegradable polyester. Lactic acid is made by fermentation of sugars, converted to the cyclic dimer lactide, and polymerised by ring-opening polymerisation (ROP) with metal or organic catalysts and an initiator (Figure 3A). The controlled ROP of lactide and glycolide has been reviewed extensively [8]. PLA combines high mechanical strength, good processability, biocompatibility and biodegradability, which explains its use in films, trays and cups [9]. Its drawback is end-of-life behaviour: it breaks down at the high temperatures of industrial composters but was not home compostable in a systematic comparison [5].

3.2 Polyhydroxyalkanoates

PHAs are polyesters stored by bacteria, with poly(3-hydroxybutyrate) (PHB) the best known (Figure 3B). They are produced by microbial fermentation, and a PHA-based bio- and materials industry has been developing [10]. In a systematic test of 15 plastics and blends, PHB was one of only two materials that broke down completely under all the soil and water conditions studied [5], which makes PHAs the most environmentally forgiving of the polymers discussed here, but they currently represent a modest part of bioplastics capacity [7].

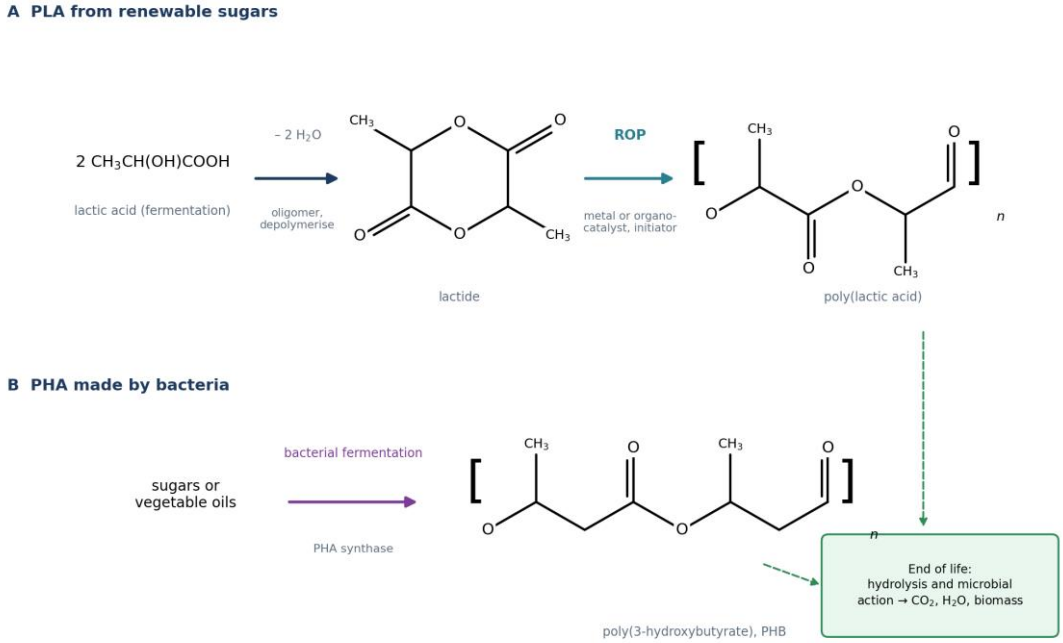

Figure 3. Synthesis and fate of biodegradable packaging polyesters. (A) PLA: fermentation-derived lactic acid is converted to lactide, which undergoes ring-opening polymerisation [8,9]. (B) PHB, a polyhydroxyalkanoate made by bacteria [10]. Both polyesters degrade by hydrolysis and microbial action [5].

3.3 Starch and other polysaccharides

Thermoplastic starch (TPS) was the other material that broke down completely under all soil and water conditions tested [5]. Polysaccharides such as starch, cellulose and chitosan can be formed into films and coatings; these generally offer good barriers to oxygen and carbon dioxide, and the tensile strength of films from high-amylose starch or chitosan is comparable to that of high-density polyethylene [11]. Hydrophilicity and sensitivity to moisture remain practical limits, so these materials are often blended or coated.

3.4 Fossil-based biodegradable polyesters and blends

PBAT and PCL are petrochemical but biodegradable, and are used to improve the flexibility and toughness of materials such as PLA. Blending can also change end-of-life behaviour: a PLA/PCL blend was home compostable at around 28 °C, unlike PLA alone [5]. Table 1 summarises the families.

Table 1. Main biodegradable polymer families for packaging.

Polymer	Origin and route	Strengths	Limitations	Ref.
PLA	Bio-based; fermentation → lactic acid → lactide → ROP	High strength, processability, biocompatibility	Not home compostable; needs industrial composting	[5,8,9]
PHA / PHB	Bio-based; bacterial fermentation	Broke down fully in all soil and water conditions tested	Small share of capacity; production still developing	[5,7,10]
Thermoplastic starch	Bio-based; processed starch	Broke down fully in soil and water tests	Moisture sensitivity; usually blended	[5,11]
Polysaccharide films (starch, chitosan, cellulose)	Bio-based; cast or coated films	Good O_2 and CO_2 barrier; strength comparable to HDPE for some films	Water sensitivity; processing on packaging lines	[11]
PBAT, PCL and blends	Fossil-based biodegradable polyesters	Flexibility; PLA/PCL blend home compostable	Petrochemical feedstock	[3,5]

4. Biodegradability: Conditions Matter

The word biodegradable has no meaning without specifying conditions. The European standard EN 13432 defines packaging as compostable in industrial composting if at least 90% biodegrades within 6 months and at least 90% disintegrates into fragments smaller than 2 mm within 12 weeks, with no adverse effect on the compost [12]. Compostability of bioplastic packaging has been reviewed in detail [13]. India's rules refer to the Indian standard IS/ISO 17088 for compostable plastics [14,15].

Real-world performance is more complicated. In a systematic study of 15 plastics and blends in industrial and home composting, anaerobic digestion, soil and freshwater and marine conditions, only PHB and TPS broke down completely in all soil and water conditions; the majority of materials failed to degrade to the standards required in soil and water; and anaerobic digestion degraded most materials but took 3–6 times longer than the typical retention time in a plant [5]. The authors concluded that biodegradable plastic blends create new options for end-of-life management but are not a panacea for plastic pollution [5]. Reviews of the impact of biodegradable polymers likewise caution that they should not be treated as a licence to litter [4]. Table 2 sets out the main conditions.

Table 2. Biodegradation routes and what the evidence shows.

Route	Requirement or standard	Evidence for packaging polymers	Ref.
Industrial composting	EN 13432: 90% biodegradation in 6 months; 90% disintegration (< 2 mm) in 12 weeks	PLA degrades at high temperature but is not home compostable	[5,12]
Home composting	Lower, variable temperatures (about 28 °C in the study)	PLA/PCL blend home compostable; PLA is not	[5]
Anaerobic digestion	Digester retention time of the plant	Most tested materials degrade but 3–6 times slower than retention time	[5]
Soil and water	ISO and ASTM tests	Only PHB and TPS broke down completely; majority failed	[5]
Compostable plastics in India	IS/ISO 17088 and certification under the PWM Rules	Exempted from the single-use ban if certified	[14,15]

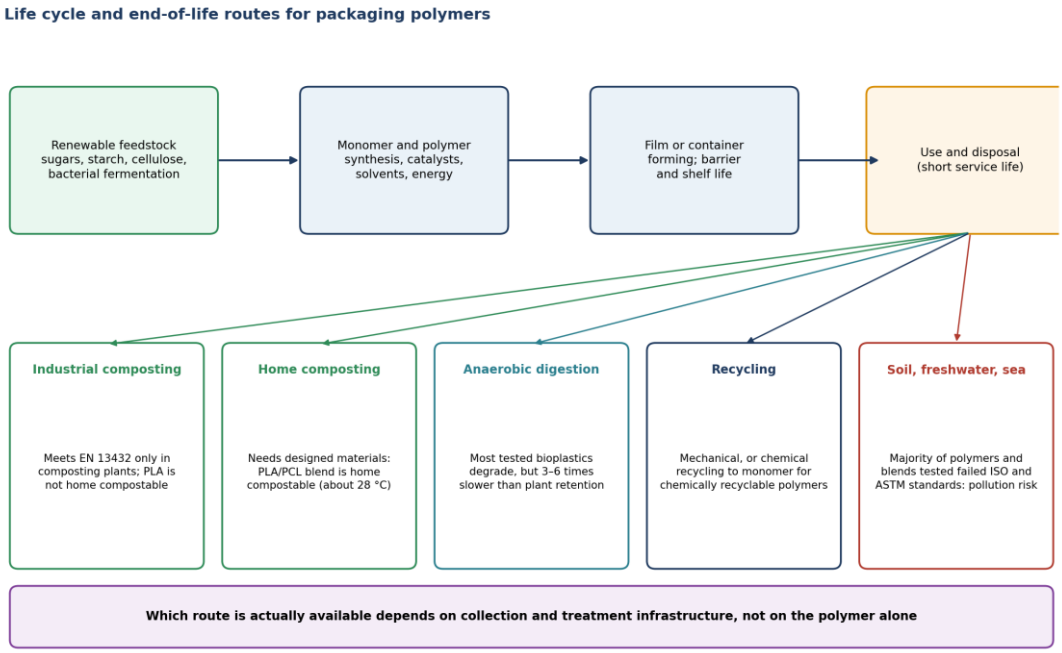

Figure 4. Life cycle and end-of-life routes for biodegradable packaging polymers, with the main caveats from refs [5,12,16].

5. Green Chemistry Principles Applied to Packaging Polymers

Anastas and Warner's twelve principles provide a checklist [2]. Table 3 maps them onto packaging polymers, showing where the biodegradable polymers perform well and where gaps remain. The mapping is the author's synthesis; the supporting evidence for individual points is cited where available. Use of renewable feedstocks is the clearest advantage: lactic acid, starch and microbial fermentation substrates all come from biomass [9,10]. Catalysis matters in synthesis, since controlled ROP of lactide relies on metal or organic catalysts [8]. Design for degradation is only a real benefit if the degradation route exists, as the compost and soil data show [5].

Table 3. Green chemistry principles and their relevance to packaging polymers.

Principle	Application to packaging polymers	Status	Ref.
Waste prevention	Plastic waste ends in landfill or the environment in 79% of cases; reduction and reuse come before material substitution	Priority	[1]
Renewable feedstocks	PLA from fermentation sugars; PHAs from bacterial fermentation; starch and cellulose films	Strength	[9–11]
Catalysis	Controlled ring-opening polymerisation of lactide with metal or organic catalysts	Used	[8]
Design for degradation	Compostable under defined conditions; most materials fail in soil and water	Conditional	[5,12]
Safer chemicals and design for function	Blends improve toughness and processing but change end-of-life behaviour	Trade-off	[5,11]
Design for circularity	Chemically recyclable polymers that depolymerise to monomer offer closed-loop recycling	Emerging	[16]
Evaluation across the life cycle	Mass-based metrics must be complemented by life-cycle assessment and system analysis	Needed	[3]

A complementary approach is design for chemical recycling. Chemically recyclable polymers can be depolymerised back to monomer and repolymerised, supporting a circular economy without relying on biodegradation [16]. This is a reminder that biodegradation is one end-of-life strategy among several, and that bio-based and recyclable polymers are not alternatives to each other.

6. Policy and Regulation

India's Plastic Waste Management (Amendment) Rules, 2021 prohibited identified single-use plastic items from 1 July 2022 and increased the minimum thickness of plastic carry bags to 75 microns from September 2021 and 120 microns from 31 December 2022; compostable plastics that meet the specified standards and are certified are exempt, and extended producer responsibility guidelines followed in February 2022 [14,15]. In the European Union, Regulation (EU) 2025/40 on packaging and packaging waste entered into force on 11 February 2025 and applies from 12 August 2026. From February 2028, permeable tea and coffee bags and labels on fruit and vegetables must be industrially compostable, and packaging is to be recyclable by 2030 [17]. At the international level, negotiations for a global plastics treaty ended in Geneva in August 2025 without agreement, and the resumed session on 7 February 2026 only elected a new chair, with no substantive negotiation [18] (Figure 5, Table 4).

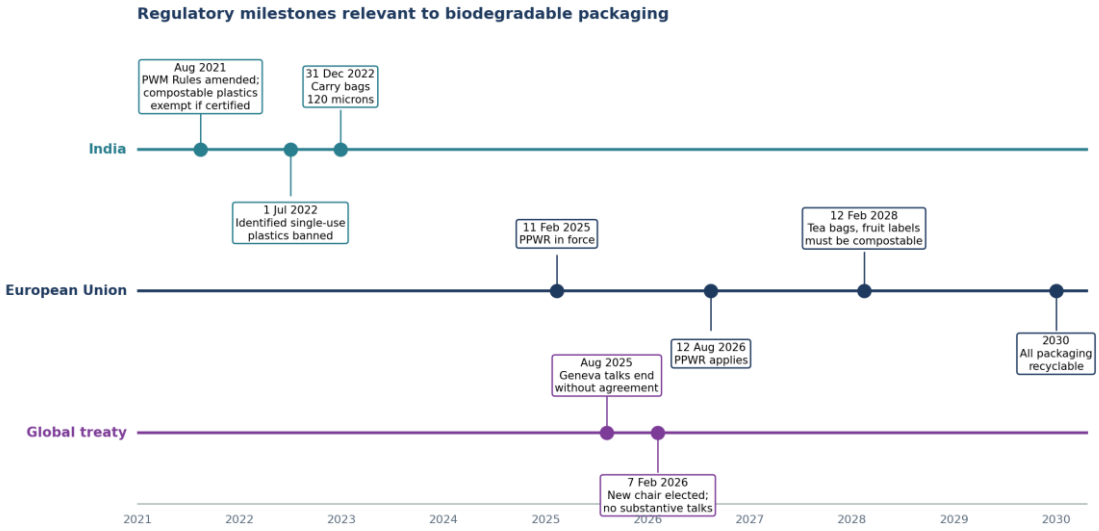

Figure 5. Regulatory milestones relevant to biodegradable packaging in India, the European Union and the global treaty process [14,17,18].

Table 4. Policy landscape for biodegradable packaging.

Jurisdiction	Measures	Relevance to biodegradable polymers	Ref.
India	Single-use plastic ban (1 July 2022); carry-bag thickness 75 then 120 microns; EPR guidelines (February 2022)	Certified compostable plastics exempt; IS/ISO 17088	[14,15]
European Union	Regulation (EU) 2025/40: applies from 12 August 2026; compostable tea bags and fruit labels from February 2028; recyclability by 2030	Compostability required for defined items; recyclability emphasised	[17]
Global	Treaty talks: Geneva August 2025 ended without agreement; 7 February 2026 session elected a new chair	No binding international rules yet	[18]

7. A Framework for Choosing Packaging Polymers

The evidence suggests five questions for packaging designers and policymakers (Figure 6). First, is the packaging needed at all, and can it be reduced or reused? Second, can the polymer be made from renewable or waste feedstocks with less hazardous catalysts and solvents [2,8]? Third, does it meet the barrier, strength and shelf-life needs of the product, perhaps through blends or composites [11]? Fourth, is there a real end-of-life route, such as industrial composting, recycling or chemical recycling, where the product will be used [5,16]? Fifth, are claims verified under realistic conditions and communicated clearly [5,12]? Biodegradable polymers make most sense where collection and composting are practical; the evidence reviewed here supports this as a design logic rather than as an established recommendation.

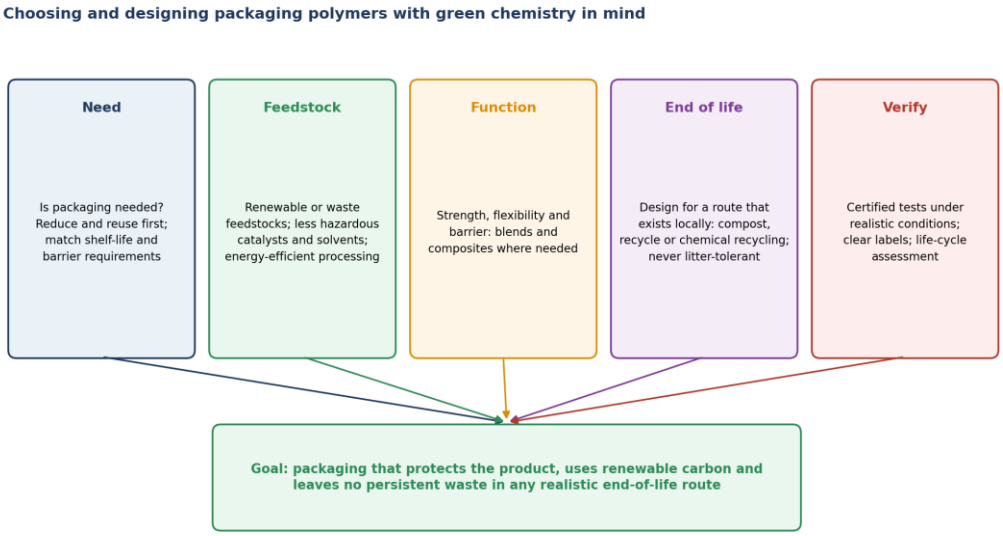

Figure 6. Framework for choosing and designing packaging polymers with green chemistry in mind. Based on refs [2,5,11,16].

8. Challenges and Future Directions

Several challenges remain. Standards and labels must reflect real conditions, since the study of 15 materials shows that laboratory compostability does not guarantee breakdown in soil, water or home compost [5]. Collection and treatment infrastructure is a prerequisite for compostable packaging, and is uneven across and within countries. Performance gaps, such as the limited flexibility and barrier properties of some biodegradable polymers, call for new blends and composites, but blending changes biodegradation behaviour [5,11]. Production costs and feedstock choices must be assessed with life-cycle methods rather than assumed to be sustainable [3]. Finally, chemically recyclable polymers and improved recycling may complement or compete with biodegradable polymers, and should be developed together [16].

9. Conclusions

Biodegradable polymers offer real chemistry-led advantages: Renewable feed stocks, controlled synthesis and the possibility of composting. But biodegradability depends on conditions, most materials do not degrade in soil or water to accepted standards, and bioplastics remain about 0.5% of global plastics. Policy is tightening in India and the EU while international agreement is pending. The most defensible position is that biodegradable polymers are a useful tool for specific applications with matching waste infrastructure, to be used alongside reduction, reuse, recycling and chemically recyclable polymers, and not a general solution to plastic pollution.

Declaration, Conflict of interest and funding

The content presented in this Narrative Review is developed using AI tools, and is meant to help Researchers who are working world wide in the fields of Green and Sustainable Chemistry.

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References

1. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv. 2017;3(7):e1700782. doi:10.1126/sciadv.1700782
2. Anastas PT, Warner JC. Green chemistry: Theory and practice. Oxford: Oxford University Press; 1998.
3. Rosenboom JG, Langer R, Traverso G. Bioplastics for a circular economy. Nat Rev Mater. 2022;7(2):117–137.
4. Haider TP, Völker C, Kramm J, Landfester K, Wurm FR. Plastics of the future? The impact of biodegradable polymers on the environment and on society. Angew Chem Int Ed. 2019;58(1):50–62.
5. Narancic T, Verstichel S, Reddy Chaganti S, et al. Biodegradable plastic blends create new possibilities for end-of-life management of plastics but they are not a panacea for plastic pollution. Environ Sci Technol. 2018;52(18):10441–10452.
6. European Bioplastics. Bioplastics market development update 2024: global production capacities of bioplastics 2024–2029. Berlin: European Bioplastics; December 2024.
7. nova-Institute. Bio-based building blocks and polymers: global capacities, production and trends 2024–2029. Hürth: nova-Institute; 2024.
8. Dechy-Cabaret O, Martin-Vaca B, Bourissou D. Controlled ring-opening polymerization of lactide and glycolide. Chem Rev. 2004;104(12):6147–6176.
9. Auras R, Harte B, Selke S. An overview of polylactides as packaging materials. Macromol Biosci. 2004;4(9):835–864.
10. Chen GQ. A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry. Chem Soc Rev. 2009;38(8):2434–2446.
11. Cazón P, Velazquez G, Ramírez JA, Vázquez M. Polysaccharide-based films and coatings for food packaging: a review. Food Hydrocoll. 2017;68:136–148.
12. European Committee for Standardization. EN 13432:2000. Packaging – requirements for packaging recoverable through composting and biodegradation – test scheme and evaluation criteria for the final acceptance of packaging. Brussels: CEN; 2000.
13. Kale G, Kijchavengkul T, Auras R, Rubino M, Selke SE, Singh SP. Compostability of bioplastic packaging materials: an overview. Macromol Biosci. 2007;7(3):255–277.
14. Ministry of Environment, Forest and Climate Change, Government of India. Plastic Waste Management (Amendment) Rules, 2021 (Gazette notification, 12 August 2021) and Plastic Waste Management (Amendment) Rules, 2022 (extended producer responsibility guidelines, February 2022). New Delhi.
15. Bureau of Indian Standards. IS/ISO 17088: Specifications for compostable plastics. New Delhi: BIS.
16. Hong M, Chen EYX. Chemically recyclable polymers: a circular economy approach to sustainability. Green Chem. 2017;19(16):3692–3706.
17. European Parliament and Council of the European Union. Regulation (EU) 2025/40 on packaging and packaging waste. Official Journal of the European Union; 2025.
18. United Nations Environment Programme. Intergovernmental Negotiating Committee on plastic pollution: fifth session (parts 5.2 and 5.3). Nairobi: UNEP; 2025.