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Biodegradable Polymers for Single-Use Plastics Replacement

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Abstract

The extensive use of petroleum-derived single-use plastics (SUPs) has resulted in persistent environmental pollution, microplastic accumulation, and adverse ecological and human health impacts (Jha et al., 2024; Environmental Sciences Europe, 2025). Biodegradable polymers have emerged as promising alternatives capable of degrading into environmentally benign products under controlled conditions (Agbogo et al., 2025; Science of the Total Environment, 2025). This chapter critically reviews biodegradable polymers used for SUP replacement, covering classification, degradation mechanisms, processing strategies, performance limitations, and environmental implications. Major biodegradable polymers including PLA, PHAs, TPS, PBS, and PBAT are systematically evaluated with comparative performance metrics. Recent advances in polymer blending, biocomposites, and nanofiller reinforcement are discussed to overcome mechanical and barrier limitations (Olonisakin et al., 2025; European Polymer Journal, 2025). Challenges related to composting infrastructure, cost, and real-world biodegradation are highlighted, concluding with future directions toward circular-economy integration.

Keywords: *Biodegradable polymers; single-use plastics; compostable plastics; polylactic acid; polyhydroxyalkanoates; polymer blends; biocomposites; environmental sustainability.*

Introduction

Single-use plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) dominate packaging, food service, and consumer goods due to their low cost, lightweight nature, and excellent mechanical properties. However, their resistance to degradation results in persistent environmental pollution (Jha et al., 2024; ScienceDirect, 2024). Conventional SUPs are estimated to constitute a significant portion of the >380 million tonnes of annual global plastic production, with a large fraction entering waste streams and ecosystems where they persist for decades or centuries. It is estimated that less than 10% of plastic waste is effectively recycled globally, while the remainder accumulates in landfills and natural ecosystems (Ugbetan et al., 2025; RSC Publishing, 2025).

Biodegradable polymers offer a sustainable alternative by undergoing microbial degradation into carbon dioxide, water, methane, and biomass (Agbogo et al., 2025; Bio-based plastics…, 2024). Their development aligns with global policies aimed at reducing plastic waste and promoting sustainable materials. However, not all biodegradable plastics perform equally, and their environmental benefits depend on proper disposal and composting conditions (Regulatory perspectives…, 2025). Therefore, a scientific comparison of biodegradable polymers with conventional plastics is essential (Science of the Total Environment, 2025). This chapter focuses on biodegradable polymers intended to replace SUPs, highlighting mechanisms of degradation, classifications, current applications, strengths, limitations, and future perspectives.

Classification of Biodegradable Polymers

Biodegradable polymers fall into two broad categories: bio-based (derived from renewable resources) and synthetic biodegradable (petroleum-derived but designed for enzymatic breakdown) (Polymers, 2025; CRC Press, 2024). They can include aliphatic polyesters (e.g., PLA, PHAs, PBS), carbohydrate-based polymers (e.g., starch, cellulose), and protein or polysaccharide derivatives (e.g., chitosan). Figure 1. represents the schematic classification of biodegradable polymers based on origin and chemical structure.

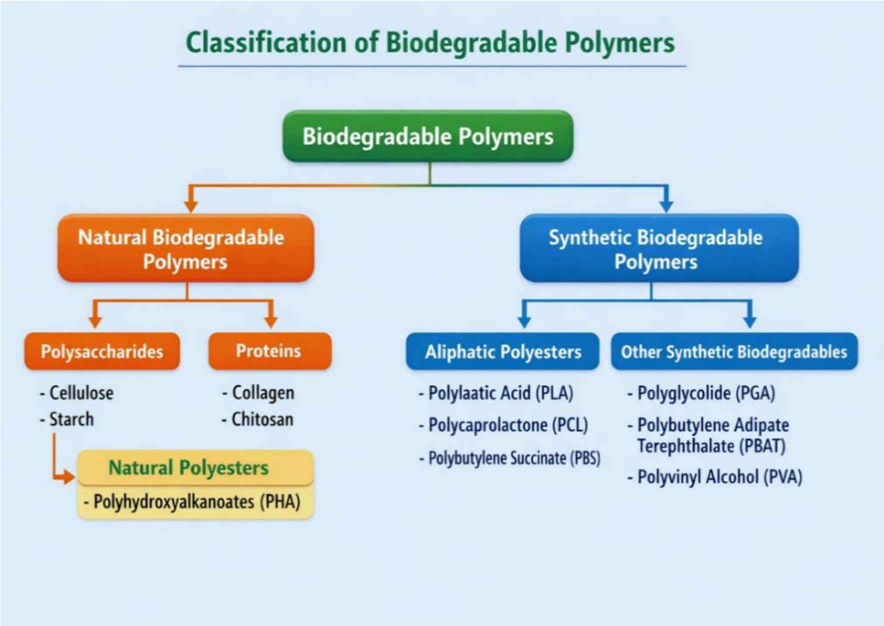

Figure 1. Classification of biodegradable polymers

Flow diagram showing two branches-bio-based (PLA, PHAs, TPS, cellulose) and synthetic biodegradable (PBS, PBAT, PCL). Biodegradable polymers can be broadly classified as bio-based or synthetic biodegradable polymers.

Bio-Based Biodegradable Polymers

1. **Polylactic Acid (PLA)**

PLA is produced from lactic acid obtained via fermentation of renewable feedstocks such as corn starch and sugarcane. Its mechanical properties-high modulus, clarity-make it suitable for rigit packaging, disposable utensils, cutlery, and films (Khandeparkar et al., 2024). Industrial composting can achieve >90% degradation within months at elevated temperatures (~58 °C), per ASTM D6400 standards (Bio-based plastics…, 2024). However, PLA's biodegradation is limited in ambient soil or aquatic environments, and it often remains intact without industrial composting conditions (Reddit discussions, Science of the Total Environment, 2025). However, its brittleness and low heat resistance restrict certain applications (Moleculess, 2025).

2. **Polyhydroxyalkanoates (PHAs)**

PHAs are microbial polyesters naturally accumulated by bacteria. PHB (a PHA member) and copolymers like PHBV exhibit good biodegradability across environments, including soil, compost, and marine conditions, and are sometimes used in films and packaging applications (Agbogo et al., 2025; MDPI Environmental Nanomaterials, 2025). PHAs can biodegrade even in the marine environment within a year, making them promising for applications where plastics might end up in nature (European Polymer Journal, 2025).

3. **Thermoplastic Starch (TPS)**

TPS is derived from starch (corn, potato) using glycerol or sorbitol. TPS is biodegradable and derived entirely from renewable resources. TPS is fully biodegradable and cost-effective. Pure TPS is brittle and moisture-sensitive; therefore, it is often blended with other polymers (e.g., PBAT, PLA) to enhance mechanical properties. Starch blends can biodegrade rapidly in compost and soil due to microbial consumption of starch (Olonisakin et al., 2025; Journal of Polymers and the Environment, 2024).

4. **Cellulose and Derivatives**

Cellulose, the most abundant natural polymer, and its derivatives (e.g., cellophane, cellulose acetate with low substitution) are biodegradable, though mechanical performance may be inferior to synthetic plastics. Cellulose nanocomposites are emerging to enhance strength while maintaining biodegradability (Advanced composites…, 2025).

Synthetic Biodegradable Polymers

Aliphatic polyesters such as polybutylene succinate (PBS) and copolymers like PBAT are designed for biodegradability via microbial enzymatic hydrolysis. These materials are often used in compostable films or bags and are compatible with existing processing technologies. Polycaprolactone (PCL) is another fossil-derived, fully biodegradable polyester used in blends. Other polymers like polyvinyl alcohol (PVA) and polyglycolic acid (PGA) offer biodegradable options but have specific processing challenges (Polymer Engineering & Science, 2024; Environmental Science Reports, 2025).

Biodegradation Mechanism and Standards

Biodegradation occurs through microbial enzymatic action breaking polymer chains into low-molecular-weight compounds that microorganisms can assimilate (International Biodeterioration & Biodegradation, 2024). Factors influencing biodegradation include polymer chemical structure, crystallinity, molecular weight, environmental conditions (temperature, moisture, microbial communities), and availability of oxygen (RSC Publishing, 2025).

1. Standard for Biodegradability

Industrial composting standards (e.g., ASTM D6400, ISO 17088) require >90% conversion to CO_2 within a set timeframe and conditions. Home composting standards (e.g., AS 5810) set benchmarks for lower temperatures (20-30 °C) (International Standards…, 2024). Notably, a compostable polymer may not biodegrade effectively in a landfill or marine environment unless designed for those conditions. Figure 2. shows the stages of biodegradation: biodeterioration, depolymerization, assimilation, and mineralization.

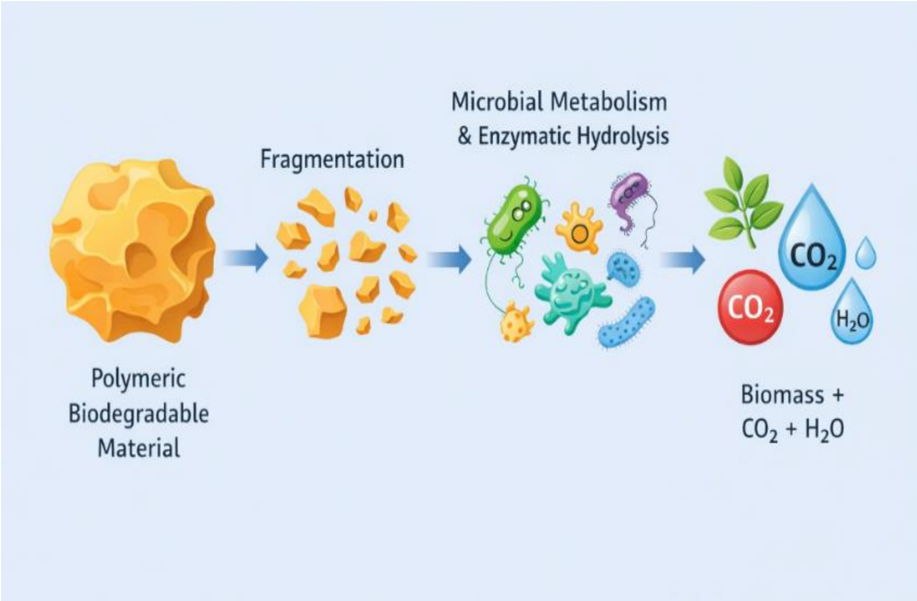

Figure 2. Mechanism of biodegradation of biodegradable polymers

Diagram showing polymer surface erosion, enzymatic chain scission, microbial uptake, and conversion to CO_2 and H_2O. Biodegradation occurs through enzymatic hydrolysis followed by microbial assimilation. Factors influencing degradation include crystallinity, molecular weight, temperature, humidity, and microbial population.

Comparative Studies: Conventional vs Biodegradable Plastics

While conventional plastics offer superior mechanical performance and economic advantages, their environmental impact is severe and log-lasting. Biodegradable plastic represents a promising sustainable solution, particularly for short-life applications. Strategic material design, policy support, and industrial scalability are essential for widespread adoption (ScienceDirect, 2024; Resources, Conservation & Recycling Reports, 2024). Table-1 represents the comparision of conventional plastics and biodegradable polymers while and Table-2 represents degradation behavior under different environment.

Table 1. Comparison of conventional plastics and biodegradable polymers

Property	PE/PP	PLA	PHAs	TPS	PBS/PBAT
Feedstock	Petroleum	Renewable	Renewable	Renewable	Fossil / Bio
Biodegradability	Non-biodegradable	Industrial compost	Soil, marine	Soil, compost	Compost
Tensile strength (MPa)	20–35	50–70	30–40	5–15	20–30
Heat resistance	High	Moderate	Moderate	Low	Moderate
Cost	Low	Medium	High	Low	Medium

Table 2. Degradation behavior under different environments

Polymer	Soil	Industrial Compost	Marine
PE	No degradation	No	No
PLA	Very slow	Fast	Negligible
PHAs	Moderate	Fast	Moderate
TPS	Fast	Fast	Moderate
PBS/PBAT	Moderate	Fast	Low

Applications of Biodegradable Polymers (Single-Use Products)

Biodegradable polymers are increasingly used in single-use packaging, disposable cutlery, bags, agricultural mulch films, and even medical disposables (sutures). PLA is widely used in food packaging and disposable cups; PHAs are explored for films and agricultural applications due to broad environmental biodegradability. TPS and PBS/PBAT blends produce compostable bags meeting industrial standards (Razzaq et al., 2024; Future Market Insights, 2025). Figure 3 represnts the major application areas of biodegradable polymers in single-use products.

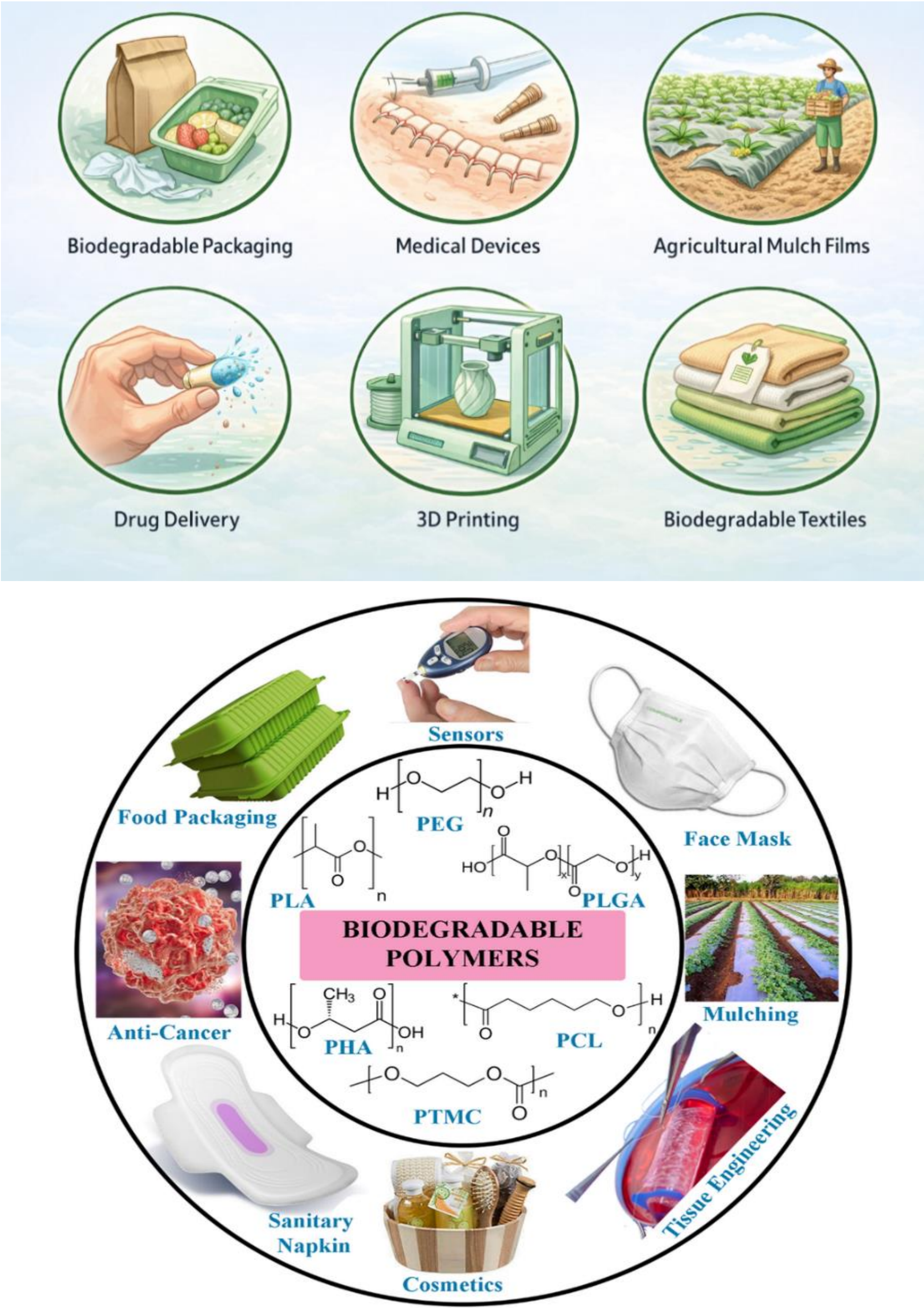

Figure 3. Applications of biodegradable polymers

Above diagram depicting food packaging, carry bags, curtlery, agricultural mulch films, and medical disposables. Biodegradable polymers are increasingly used in:

- Food packaging films and trays (PLA, PBAT blends)
- Compostable bags (PBS/PBAT-TPS blends)

- Disposable curtlery and cups (PLA, PHAs)
- Agricultural mulch films (PHAs, starch blends)

Enhancing Performance: Polymer Blends and Biocomposites

Biodegradable polymers often face mechanical and thermal limitations compared to polyethylene and polypropylene. Recent advances show that polymer blends and biocomposites can tailor properties (Olonisakin et al., 2025; European Polymer Journal, 2025). Compatibilizers (e.g., maleic anhydride) and natural fillers (rice straw, turmeric powder, coffee grounds) can improve miscibility, mechanical properties, and biodegradation rates (Journal of Composite Materials Science, 2025). Such strategies help overcome brittleness, low moisture resistance, and cost barriers. Figure 4 depicts the enhancement of biodegradable polymer properties using blending and biocomposites.

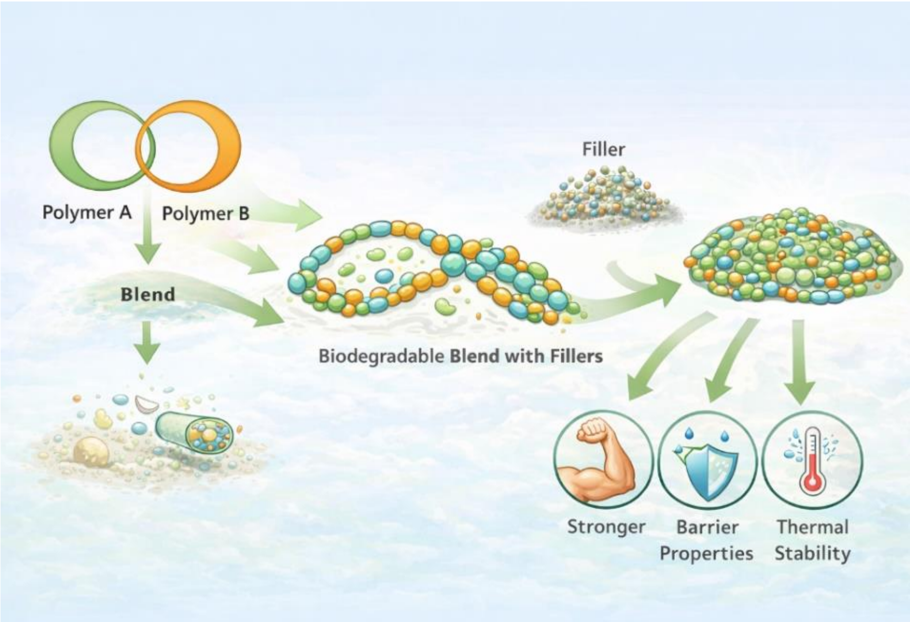

Figure 4: Strategy for Improving Properties Using Blends and Fillers

Diagram showing PLA blended with PBAT or reinforced with natural fibers/nanocellulose. Blending biodegradable polymers improves flexibility, toughness, and barrier properties. Addition of natural fibers (jute, cellulose nanofibers) enhances mechanical streingh while maintaining biodegradability (Olonisakin et al., 2025).

Environmental and Health Considerations

Although biodegradable polymers are marketed as environmentally friendly, there are emerging concerns:

- **Incomplete biodegradation and microplastic formation:** Some biodegradable plastics fragment into micro/ nano-plastics or intermediate oligomers that persist, affecting ecosystems.
- **Human and ecological toxicity:** Recent research suggests that certain starch-based bioplastics may exert similar adverse health effects to petroleum plastics in animal models, raising questions about assumed safety (Environmental Sciences Europe, 2025; Nature Sustainability Insights, 2024).
- **Public misconceptions:** Many consumers confuse “biodegradable” with “compostable in any environment,” leading to improper disposal and reduced efficacy (Journal of Environmental Management, 2024).

Life cycle assessment (LCA) studies reveal that some biodegradable plastics may have higher greenhouse gas emissions during production compared to PE unless renewable energy is used (Science of the Total Environment, 2025).

Overall, industrial composting infrastructure and policy support are critical to ensure biodegradable plastics achieve intended environmental benefits.

Challenges and Future Perspectives

Key challenges include (Journal of Circular Economy and Policies, 2025):

High cost of PHAs
Dependence on industrial composting
Lack of consumer awareness
Regulatory inconsistencies

Future research should focus on (Next-generation biodegradable polymers…, 2025)**:**

- **Enhancing ambient biodegradability;** so, polymers can degrade in natural conditions outside industrial facilities.
- **Cost-effective production:** Reducing costs of PHAs and other high-performance biopolymers to achieve broader adoption.

- **Circular economy-based waste management:** Combining biodegradables with recycling, composting, and sustainable feedstocks to minimize environmental impacts.
- **Innovation in bio-based materials (Advanced Biocomposites):** New materials such as protein-derived plastics and seawater-degradable plastics show promise for reducing microplastic pollution (ongoing research reports).

Conclusion

Biodegradable polymers present a viable and necessary alternative to conventional single-use plastics. Comparative studies show that while no single biodegradable polymer can fully replace petroleum-based plastics in all applications, strategic blending and material innovation can bridge performance gaps (Agbogo et al., 2025; Science of the Total Environment, 2025). Strong policy frameworks, infrastructure development, and public education are essential for successful large-scale adoption.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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