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Biodegradable Plastics: Sustainable Solution or Environmental Myth? A Critical Evaluation of Science, Policy, and Global Waste Management

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Abstract

The global plastic crisis has become one of the most pressing environmental challenges of the twenty-first century, compelling scientists, policymakers, and industries to search for alternatives to conventional petroleum-based polymers. Among the proposed alternatives, biodegradable plastics have emerged as a promising technological innovation, often marketed as environmentally benign materials capable of decomposing naturally after disposal. However, growing scientific evidence suggests that the environmental benefits of biodegradable plastics may depend heavily on specific conditions, including material composition, disposal infrastructure, microbial activity, temperature, and regulatory compliance. This study critically examines whether biodegradable plastics represent a genuine solution to plastic pollution or whether their perceived sustainability is partly shaped by industrial narratives and consumer misconceptions. Through an interdisciplinary review of polymer science, environmental chemistry, life-cycle assessment, waste management systems, biodegradation standards, and policy frameworks, the paper evaluates the actual ecological performance of biodegradable plastics across terrestrial, marine, and industrial composting environments. The analysis reveals that although certain biodegradable polymers such as polylactic acid, polyhydroxyalkanoates, and starch-based composites demonstrate significant potential under controlled conditions, their performance in real-world environments remains inconsistent. Inadequate waste segregation, limited composting infrastructure, microplastic formation, additive leaching, and ambiguous labelling further complicate their sustainability claims. The study concludes that biodegradable plastics should not be considered a universal replacement for conventional plastics but rather a context-dependent tool within a broader circular economy framework that prioritises reduction, reuse, and responsible end-of-life management.

***Keywords**: Biodegradable plastics; bioplastics; circular economy; plastic pollution; life-cycle assessment; compostability.*

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1. Introduction

Plastic materials have transformed modern civilisation by enabling affordable, lightweight, durable, and versatile products across multiple sectors, including packaging, medicine, agriculture, transportation, and electronics. Since the commercialisation of synthetic polymers in the early twentieth century, global plastic production has increased exponentially, surpassing 400 million metric tonnes annually. Despite their economic and functional benefits, conventional plastics have become one of the most persistent anthropogenic pollutants due to their resistance to biological degradation and their widespread accumulation in landfills, rivers, oceans, and soils. Scientific studies estimate that less than ten percent of all plastics ever produced have been effectively recycled, while the majority remain in the environment for decades or even centuries, fragmenting into microplastics and nanoplastics that pose ecological and human health risks (Geyer et al., 2017; Jambeck et al., 2015).

Growing public awareness of plastic pollution has intensified the demand for sustainable alternatives. In response, biodegradable plastics have been promoted as a promising solution capable of reducing environmental persistence and supporting more sustainable consumption patterns. These materials are generally defined as polymers that can be decomposed by microorganisms into carbon dioxide, methane, water, biomass, and inorganic compounds under specific environmental conditions. Unlike conventional plastics, biodegradable plastics are designed to enter biological cycles through microbial assimilation, potentially reducing long-term accumulation in ecosystems (Filiciotto & Rothenberg, 2021). However, the increasing commercial use of biodegradable plastics has also generated substantial scientific debate regarding their actual environmental performance.

The term “biodegradable plastic” often creates confusion among consumers because biodegradability is frequently interpreted as an intrinsic guarantee of environmental safety. In reality, biodegradation depends on complex interactions among polymer chemistry, environmental conditions, microbial communities, moisture, oxygen availability, and temperature. A plastic labelled biodegradable may degrade efficiently in industrial composting facilities operating at temperatures above 58°C but remain largely intact in marine environments, landfills, or open terrestrial ecosystems for extended periods (Rujnić-Sokele & Pilipović, 2017). Consequently, the sustainability of biodegradable plastics cannot be evaluated solely on the basis of marketing claims or material origin.

Another source of misunderstanding arises from the distinction between bio-based plastics and biodegradable plastics. Bio-based plastics are derived partially or entirely from renewable biological resources such as corn starch, sugarcane, cellulose, or algae, whereas biodegradable plastics are defined by their end-of-life degradation behaviour rather than their feedstock source. Some petroleum-derived polymers such as polybutylene adipate terephthalate are biodegradable, whereas certain bio-based plastics such as bio-polyethylene are chemically identical to conventional plastics and are not biodegradable (Emadian et al., 2017; Filiciotto & Rothenberg, 2021). This distinction highlights the need for greater scientific literacy and regulatory clarity in the emerging bioplastics sector.

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Recent advances in polymer science have produced several commercially viable biodegradable materials, including polylactic acid, polyhydroxyalkanoates, polycaprolactone, polybutylene succinate, and starch-based composites. These materials have been increasingly adopted in food packaging, disposable utensils, agricultural mulch films, biomedical implants, and consumer products. Industrial interest is driven by both environmental concerns and policy pressures, particularly bans on single-use plastics introduced by governments in Europe, Asia, and North America. Yet the rapid expansion of biodegradable plastics has raised important questions regarding resource use, agricultural land competition, greenhouse gas emissions, composting infrastructure, and economic scalability (Molina-Besch et al., 2022).

Life-cycle assessment studies have shown that biodegradable plastics may offer lower fossil fuel dependence and reduced carbon footprints compared with conventional petrochemical polymers under certain production scenarios. However, these advantages are not universal. Feedstock cultivation may require intensive irrigation, fertiliser application, and land conversion, potentially offsetting environmental gains. Furthermore, transportation, processing, additive incorporation, and end-of-life management can significantly influence total environmental impacts. Recent reviews emphasise that biodegradability alone does not guarantee sustainability; rather, the entire product life cycle must be evaluated to determine environmental performance (Bishop et al., 2022; Shanmugam et al., 2026).

End-of-life management represents one of the most critical challenges associated with biodegradable plastics. Most commercially available biodegradable polymers are designed for industrial composting, where temperature, humidity, oxygen levels, and microbial activity are carefully controlled. Yet industrial composting facilities remain inaccessible in many regions, especially in developing countries. As a result, biodegradable plastics often enter conventional waste streams, landfills, incinerators, or natural environments, where degradation may be incomplete or substantially delayed. Studies have shown that materials such as polylactic acid can persist for years under ambient environmental conditions if industrial composting requirements are not met (Yu & Flury, 2024).

Moreover, emerging evidence suggests that biodegradable plastics may still generate microplastic particles during fragmentation before complete mineralisation occurs. These particles can interact with soil organisms, aquatic species, and microbial communities, raising concerns about ecotoxicity and long-term ecosystem effects. Chemical additives, stabilisers, colourants, and plasticisers present in biodegradable formulations may also leach into surrounding environments during degradation processes, complicating claims of environmental harmlessness (Shanmugam et al., 2026).

International standards have attempted to establish measurable criteria for biodegradability and compostability through protocols such as ASTM D6400, EN 13432, ISO 17088, and related certification frameworks. These standards evaluate degradation rates, disintegration, ecotoxicity, and residual mass under controlled conditions. However, critics argue that laboratory certification does not always reflect real-world disposal environments. A material certified as compostable under industrial conditions may fail to degrade effectively in

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marine or soil ecosystems, creating a gap between regulatory compliance and environmental reality (Filiciotto & Rothenberg, 2021).

Public perception also plays a significant role in shaping the biodegradable plastics market. Consumer surveys and community discussions increasingly reveal confusion regarding the meaning of "biodegradable," "compostable," and "bio-based," with many individuals assuming that biodegradable plastics can be safely discarded in natural environments without consequences. Such misconceptions may unintentionally promote littering behaviour and weaken waste reduction initiatives. Online environmental communities frequently question whether biodegradable labels represent genuine innovation or a form of greenwashing, reflecting growing public scepticism toward sustainability claims.

Given these scientific, technological, economic, and social complexities, the central question remains: are biodegradable plastics a genuine environmental solution, or do they represent an oversimplified response to a much deeper systemic waste crisis? This paper addresses this question through a critical examination of polymer chemistry, degradation mechanisms, environmental performance, life-cycle impacts, regulatory frameworks, and global waste management practices. By integrating evidence from materials science, environmental engineering, policy studies, and sustainability research, the study seeks to distinguish scientific reality from industrial optimism and determine whether biodegradable plastics represent transformative innovation or an environmental myth.

2. Classification, Chemical Composition, and Material Properties of Biodegradable Plastics

The scientific understanding of biodegradable plastics begins with an accurate classification of their chemical origin, molecular architecture, degradation pathways, and functional applications. Although the terms "bioplastic," "bio-based plastic," "compostable plastic," and "biodegradable plastic" are frequently used interchangeably in public discourse, polymer science distinguishes these categories based on feedstock source, molecular structure, and end-of-life behaviour. Such distinctions are critical because the environmental performance of these materials depends not merely on their biological origin but on their chemical composition, crystallinity, molecular weight, hydrophobicity, and interaction with environmental microorganisms.

Biodegradable plastics may broadly be classified into three principal categories: naturally derived biodegradable polymers, synthetic biodegradable polymers derived from renewable resources, and synthetic biodegradable polymers derived from fossil resources. Each category possesses unique structural characteristics that influence biodegradation kinetics, mechanical performance, processing requirements, and environmental compatibility.

The first category includes naturally occurring polymers such as starch, cellulose, chitosan, lignin, gelatin, and protein-based materials. These polymers are synthesised by living organisms and have long participated in natural biogeochemical cycles. Their molecular structures contain glycosidic linkages, hydroxyl groups, amide bonds, and other hydrolysable functional groups that are readily recognised by enzymes secreted by bacteria, fungi, and other

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decomposers. Starch-based plastics, for example, are among the earliest biodegradable materials developed for packaging applications because of their abundance, low cost, and rapid biodegradability. However, pure starch exhibits poor moisture resistance, limited tensile strength, and thermal instability, necessitating blending with synthetic polymers or plasticisers to improve processability (Lackner et al., 2023).

Cellulose-based polymers represent another important class of naturally derived biodegradable materials. Cellulose acetate, regenerated cellulose films, and nanocellulose composites have demonstrated considerable promise in packaging, biomedical devices, and filtration systems due to their high mechanical strength, renewability, and biocompatibility. Yet their degradation rate varies significantly depending on the degree of acetylation, crystallinity, and environmental conditions. Highly crystalline cellulose structures often resist microbial attack, prolonging environmental persistence.

The second category comprises synthetic biodegradable polymers derived from renewable feedstocks. Among these, polylactic acid (PLA) has emerged as one of the most commercially significant biodegradable plastics. PLA is synthesised through the polymerisation of lactic acid, typically produced via microbial fermentation of carbohydrate-rich crops such as corn, sugarcane, cassava, or sugar beet. PLA possesses excellent transparency, rigidity, printability, and food-contact safety, making it highly attractive for disposable packaging, medical implants, and additive manufacturing applications.

Despite these advantages, PLA presents several limitations. Its relatively high glass transition temperature, brittleness, and sensitivity to hydrolytic degradation create challenges in flexible packaging applications. More importantly, although PLA is technically biodegradable, complete biodegradation generally requires industrial composting conditions involving temperatures above 55–60°C, high humidity, and controlled microbial populations. Under ambient marine or soil conditions, degradation may proceed very slowly, raising concerns regarding environmental persistence (Filiciotto & Rothenberg, 2021; Yu & Flury, 2024).

Another major renewable biodegradable polymer is polyhydroxyalkanoate (PHA), a family of polyesters synthesised intracellularly by bacteria as energy storage compounds. PHAs are particularly attractive because they can biodegrade in marine, freshwater, soil, and compost environments under relatively mild conditions. Their molecular structure contains ester linkages susceptible to enzymatic hydrolysis. Unlike PLA, PHAs often exhibit broader biodegradation potential across natural ecosystems.

However, PHAs face economic challenges due to high production costs, limited industrial scalability, and variable mechanical properties. Community discussions among polymer chemists have increasingly highlighted the need for long-term molecular weight studies to verify true environmental mineralisation rather than simple fragmentation, indicating that real-world performance may still require further validation.

The third category includes fossil-derived biodegradable polymers such as polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL), and polybutylene succinate (PBS).

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Although synthesised from petrochemical feedstocks, these materials possess hydrolysable ester bonds that enable microbial degradation under appropriate conditions.

PBAT is widely used in compostable bags, agricultural films, and flexible packaging due to its high flexibility and toughness. Its molecular structure combines aromatic and aliphatic components, allowing improved mechanical properties compared with many bio-based alternatives. PBAT is often blended with PLA or starch to create commercially viable biodegradable composites.

PCL, in contrast, is characterised by low melting temperature, excellent flexibility, and biocompatibility, making it valuable in biomedical engineering, tissue scaffolds, and drug delivery systems. Recent experimental studies have demonstrated that microbial and enzymatic modifications can significantly accelerate PCL degradation, opening possibilities for controlled biomedical applications (Guindani et al., 2024).

Beyond feedstock origin, polymer morphology plays a decisive role in biodegradation. Amorphous polymers generally degrade faster than crystalline polymers because their molecular chains are more accessible to water molecules and microbial enzymes. Crystallinity reduces chain mobility and limits hydrolysis, thereby prolonging degradation time. Similarly, molecular weight influences biodegradability; high molecular weight polymers often require initial abiotic fragmentation before microorganisms can assimilate the resulting oligomers.

Surface properties such as hydrophilicity, porosity, and roughness also affect microbial colonisation. Hydrophilic polymers absorb water more readily, promoting hydrolysis and enzymatic attack. In contrast, hydrophobic surfaces may resist microbial adhesion, delaying degradation.

Blending technologies further complicate classification. Many commercial biodegradable products are not composed of a single polymer but of composite formulations containing fillers, plasticisers, stabilisers, pigments, antioxidants, and reinforcing fibres. While these additives may improve mechanical performance, shelf life, or processing efficiency, they can alter degradation behaviour and potentially introduce ecotoxicological risks.

Recent environmental chemistry studies have shown that additive leaching during degradation remains insufficiently studied and may influence soil microbial communities, aquatic organisms, and nutrient cycles. Such findings challenge the simplistic assumption that biodegradable plastics are inherently environmentally harmless (Shanmugam et al., 2026).

International certification systems attempt to standardise biodegradable materials using protocols such as ASTM D6400, EN 13432, and ISO 17088. These standards assess biodegradation under controlled industrial composting conditions by measuring carbon dioxide evolution, mass loss, disintegration, and ecotoxicity. However, critics argue that certification under laboratory conditions may not accurately represent real environmental behaviour.

Recent reviews emphasise that biodegradation claims must increasingly be evaluated under environmentally relevant concentrations, natural microbial communities, and realistic disposal pathways rather than idealised laboratory simulations (Yu & Flury, 2024).

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Thus, the classification of biodegradable plastics reveals not a single material category but a complex family of polymers with widely differing chemical properties, environmental behaviours, and sustainability implications. Understanding these distinctions is essential before evaluating whether biodegradable plastics represent a genuine ecological solution or merely a technologically appealing narrative.

3. Biodegradation Mechanisms and Environmental Behaviour

Biodegradation is frequently presented in public communication as a simple and automatic process whereby biodegradable plastics disappear naturally after disposal. Such a representation, although appealing to consumers and policymakers, significantly oversimplifies a highly complex series of physicochemical, biochemical, and ecological interactions. In scientific terms, biodegradation refers to the transformation of polymeric materials into simpler compounds such as carbon dioxide, methane, water, mineral salts, and microbial biomass through the metabolic activity of microorganisms under specific environmental conditions. However, the rate, completeness, and ecological consequences of biodegradation vary considerably depending on polymer chemistry, environmental parameters, microbial diversity, and disposal pathways. Therefore, understanding the actual mechanisms of biodegradation is essential for assessing whether biodegradable plastics truly offer an environmentally sustainable alternative to conventional polymers.

The biodegradation of polymeric materials generally occurs through a multi-stage process involving biodeterioration, depolymerisation, assimilation, and mineralisation. Biodeterioration represents the initial stage, during which physical, chemical, or biological factors alter the surface properties of the polymer. Environmental exposure to ultraviolet radiation, oxygen, moisture, temperature fluctuations, and mechanical abrasion may create microcracks, increase surface roughness, and weaken intermolecular bonds, thereby making the polymer more susceptible to microbial colonisation. Bacteria, fungi, algae, and actinomycetes subsequently attach to the polymer surface, forming biofilms that facilitate enzymatic interaction with the material (Emadian et al., 2017).

The second stage, depolymerisation, involves the cleavage of polymer chains into smaller oligomers, dimers, and monomers. This process may occur through hydrolysis, oxidation, photodegradation, or enzymatic catalysis. Polymers containing hydrolysable functional groups such as ester, amide, or glycosidic bonds are particularly susceptible to degradation because these bonds can be broken in the presence of water and microbial enzymes. For example, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polycaprolactone (PCL) contain ester linkages that can undergo hydrolytic cleavage under suitable temperature and humidity conditions. In contrast, polymers with highly hydrophobic carbon-carbon backbones, such as conventional polyethylene, resist enzymatic degradation due to the absence of hydrolysable bonds (Filiciotto & Rothenberg, 2021).

After depolymerisation, the resulting low-molecular-weight compounds become available for microbial assimilation. Microorganisms transport these monomers into their cells, where they are metabolised through intracellular biochemical pathways. Under aerobic

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conditions, the final products are typically carbon dioxide, water, and biomass. Under anaerobic conditions, such as those found in landfills or sediment layers, biodegradation may produce methane in addition to carbon dioxide. The generation of methane raises important environmental considerations because methane possesses a global warming potential significantly higher than carbon dioxide over short-term climatic timescales (Bishop et al., 2022).

The biodegradation of biodegradable plastics is strongly influenced by environmental temperature. Temperature affects polymer chain mobility, water diffusion, enzymatic activity, and microbial metabolism. Industrial composting facilities generally operate at temperatures between 55°C and 65°C, conditions under which polymers such as PLA may degrade within several weeks or months. However, under ambient terrestrial conditions, where temperatures are considerably lower, degradation rates may decline dramatically. Experimental studies have shown that PLA products can remain structurally intact for extended periods in soil and freshwater environments when industrial composting conditions are absent (Yu & Flury, 2024).

Moisture content also plays a fundamental role in biodegradation. Water molecules facilitate hydrolysis by penetrating polymer matrices and cleaving susceptible bonds. Hydrophilic polymers such as starch-based plastics readily absorb water, accelerating degradation. Hydrophobic materials, on the other hand, may resist moisture penetration, thereby delaying hydrolysis and microbial colonisation. Relative humidity, rainfall, and soil moisture therefore significantly influence environmental degradation behaviour.

Oxygen availability further determines degradation pathways and end products. In aerobic composting systems, oxygen supports efficient microbial respiration, promoting complete mineralisation into carbon dioxide and biomass. In anaerobic environments such as landfills, oxygen limitation alters microbial metabolism and may generate methane. This distinction is particularly important because a biodegradable plastic disposed of in landfill may not necessarily reduce greenhouse gas emissions unless methane capture systems are in place (Rujnić-Sokele & Pilipović, 2017).

Microbial diversity is another decisive factor. Different microorganisms possess distinct enzymatic capabilities for degrading specific polymers. Bacterial genera such as *Pseudomonas*, *Bacillus*, *Streptomyces*, and *Ralstonia*, as well as fungal genera such as *Aspergillus* and *Penicillium*, have demonstrated the ability to degrade various biodegradable polymers. The composition of microbial communities varies significantly across marine, freshwater, soil, compost, and landfill ecosystems, resulting in highly variable degradation outcomes. A polymer that degrades efficiently in compost may remain largely intact in marine environments due to differences in temperature, salinity, nutrient availability, and microbial enzymatic activity.

Marine environments present particular challenges for biodegradable plastics. Ocean temperatures are generally lower, nutrient concentrations may be limited, ultraviolet exposure varies, and microbial densities differ from terrestrial compost systems. Several field studies have demonstrated that some certified compostable plastics exhibit slow degradation in marine

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conditions, persisting for months or even years. Such findings challenge the common assumption that biodegradable plastics automatically solve marine plastic pollution (Haider et al., 2019).

Soil environments also exhibit considerable variability. Soil texture, pH, organic matter content, moisture, microbial diversity, and agricultural management practices all influence degradation kinetics. Agricultural mulch films composed of biodegradable polymers have attracted significant interest as alternatives to polyethylene films. However, incomplete degradation may lead to polymer residues in soil, potentially affecting soil structure, microbial communities, and nutrient cycling. Recent research suggests that even biodegradable polymers may generate microplastic-like fragments during intermediate degradation stages before complete mineralisation occurs (Shanmugam et al., 2026).

The formation of microplastics during biodegradation represents one of the most significant emerging concerns. Fragmentation does not necessarily indicate complete biodegradation. Instead, polymers may first break into microscopic particles that persist in ecosystems until further microbial assimilation occurs. If environmental conditions are suboptimal, these fragments may accumulate in soils, sediments, and aquatic food webs. Laboratory studies have detected biodegradable microplastic particles interacting with earthworms, aquatic invertebrates, and microbial biofilms, suggesting potential ecological consequences that remain insufficiently understood.

Another important factor influencing biodegradation is polymer morphology. Crystalline regions of polymers are generally more resistant to enzymatic attack than amorphous regions because tightly packed molecular chains limit water penetration and enzyme accessibility. Consequently, polymers with higher crystallinity often degrade more slowly. Molecular weight, surface area, thickness, and additive composition also influence degradation kinetics.

Standardised biodegradation tests such as ASTM D6400, EN 13432, and ISO 17088 attempt to quantify biodegradability under controlled conditions by measuring carbon dioxide evolution, mass loss, and disintegration. While these standards provide useful benchmarks, critics argue that laboratory simulations may not accurately reflect natural ecosystems. A material that passes compostability tests may behave very differently in rivers, beaches, agricultural soils, or unmanaged waste streams (Filiciotto & Rothenberg, 2021).

Consumer disposal behaviour further complicates environmental outcomes. Misinterpretation of “biodegradable” labelling may encourage littering or improper disposal. Materials designed for industrial composting may enter municipal recycling streams, contaminating recyclable plastics, or may be discarded in landfills where degradation conditions are unsuitable. Such behavioural and infrastructural mismatches can significantly reduce the environmental benefits of biodegradable plastics.

Taken together, these findings demonstrate that biodegradation is neither universal nor automatic. Rather, it is a highly conditional process influenced by polymer chemistry, environmental parameters, microbial ecology, infrastructure, and human behaviour. Therefore, the ecological effectiveness of biodegradable plastics depends not simply on material design but on the compatibility between material properties and real-world disposal systems.

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4. Life-Cycle Assessment and Carbon Footprint of Biodegradable Plastics

The environmental sustainability of biodegradable plastics cannot be evaluated solely on the basis of their ability to decompose after disposal. A material may exhibit effective biodegradation under controlled conditions yet generate substantial environmental impacts during raw material extraction, cultivation, manufacturing, transportation, or waste processing. For this reason, life-cycle assessment (LCA) has emerged as one of the most reliable scientific tools for determining whether biodegradable plastics truly offer environmental advantages over conventional petroleum-based polymers. LCA examines the environmental impacts associated with every stage of a product's existence, including raw material acquisition, production, distribution, use, and end-of-life management, thereby providing a comprehensive "cradle-to-grave" or "cradle-to-cradle" perspective (ISO, 2006).

Biodegradable plastics derived from renewable feedstocks such as corn, sugarcane, cassava, starch, cellulose, and agricultural residues are often promoted as low-carbon alternatives because plants absorb atmospheric carbon dioxide during photosynthesis. This biological carbon fixation can potentially reduce dependence on fossil resources and lower greenhouse gas emissions during polymer production. Studies on polylactic acid (PLA) and polyhydroxyalkanoates (PHA) suggest that these materials may exhibit lower fossil energy consumption and reduced carbon footprints compared with conventional plastics such as polyethylene and polypropylene under optimised production conditions (Molina-Besch et al., 2022; Bishop et al., 2022).

However, these environmental benefits are not universally guaranteed. Agricultural production of biomass feedstocks often requires intensive irrigation, fertilisers, pesticides, machinery, and transportation, all of which contribute to greenhouse gas emissions, water consumption, and ecosystem degradation. Nitrogen fertilisers, in particular, may release nitrous oxide, a greenhouse gas with significantly greater warming potential than carbon dioxide. Furthermore, large-scale cultivation of industrial crops for bioplastic production may compete with food production and accelerate land-use change, biodiversity loss, and soil degradation (Emadian et al., 2017).

Manufacturing processes also influence the environmental profile of biodegradable plastics. Fermentation, polymerisation, purification, drying, and compounding require substantial energy inputs. If electricity is derived from fossil fuels, the climate advantages of biodegradable plastics may be significantly reduced. End-of-life management further affects overall sustainability. When biodegradable plastics are processed in industrial composting facilities, environmental benefits may be maximised. However, if they are disposed of in landfills, anaerobic degradation may produce methane, potentially offsetting carbon savings unless methane capture systems are available (Filiciotto & Rothenberg, 2021).

Therefore, life-cycle studies indicate that biodegradable plastics can reduce environmental impacts under carefully managed production and disposal systems, but their sustainability depends on feedstock sourcing, energy use, waste infrastructure, and regional policy implementation rather than biodegradability alone.

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5. Greenwashing, Policy Challenges, and Industrial Realities

Despite their growing popularity, biodegradable plastics are increasingly criticised for being associated with green marketing narratives that may exaggerate their environmental benefits. Many products labelled "biodegradable," "compostable," or "eco-friendly" create the impression that they can safely disappear in nature after disposal. However, scientific evidence shows that most biodegradable plastics require highly controlled industrial composting conditions involving specific temperature, humidity, oxygen levels, and microbial activity. In natural environments such as oceans, rivers, agricultural soils, or landfills, degradation may be significantly slower or incomplete, raising concerns about misleading sustainability claims (Filiciotto & Rothenberg, 2021).

This disconnect between marketing and scientific reality has led to accusations of greenwashing. Consumers often fail to distinguish between "bio-based," "biodegradable," and "compostable" materials, resulting in improper disposal practices. Some individuals assume that biodegradable plastics can be discarded in open environments without ecological consequences, which may unintentionally increase littering behaviour and weaken recycling initiatives. Furthermore, biodegradable plastics frequently enter conventional recycling streams, contaminating recyclable materials and creating operational challenges for waste management systems (Bishop et al., 2022).

Policy implementation remains equally challenging. Although regulatory frameworks such as ASTM D6400, EN 13432, and ISO 17088 establish standards for compostability and biodegradation, these certifications are generally based on laboratory or industrial composting conditions rather than real environmental settings. Many developing nations lack adequate composting infrastructure, waste segregation systems, and public awareness programmes necessary for effective implementation. Consequently, certified biodegradable plastics often end up in landfills or unmanaged waste streams where their environmental benefits are limited (Rujnić-Sokele & Pilipović, 2017).

Therefore, without transparent labelling, stronger regulatory oversight, consumer education, and investment in waste infrastructure, biodegradable plastics risk becoming more of a marketing solution than a genuine environmental transformation.

6. Future Prospects and Circular Economy Integration

The future of biodegradable plastics depends not only on advances in material science but also on their successful integration within a broader circular economy framework. A circular economy emphasises resource efficiency, waste minimisation, product redesign, reuse, recycling, and responsible end-of-life management. Within this model, biodegradable plastics should not be viewed as a direct replacement for all conventional plastics but as specialised materials designed for applications where recycling is difficult, contamination is unavoidable, or organic recovery offers environmental advantages (Geissdoerfer et al., 2017).

Recent developments in polymer engineering have focused on improving the mechanical strength, thermal stability, moisture resistance, and degradation efficiency of biodegradable materials such as polylactic acid, polyhydroxyalkanoates, and starch-based

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composites. Researchers are increasingly exploring second-generation feedstocks, including agricultural residues, food-processing waste, algae biomass, and microbial fermentation systems, to reduce competition with food resources and minimise land-use pressures (Shanmugam et al., 2026).

Biotechnology also offers promising opportunities. Genetic engineering of microorganisms may enhance polymer synthesis efficiency, lower production costs, and improve biodegradation performance across diverse environmental conditions. Smart materials capable of controlled degradation under specific triggers such as temperature, pH, or enzymatic exposure are also emerging as innovative solutions for medical, packaging, and agricultural applications.

However, technological innovation alone is insufficient. Effective adoption requires standardised labelling, public awareness, waste segregation, industrial composting infrastructure, and supportive government policies. Collaboration among scientists, industries, policymakers, and consumers is essential to ensure that biodegradable plastics contribute meaningfully to sustainable development rather than merely shifting environmental burdens.

Therefore, the future success of biodegradable plastics lies in aligning material innovation with circular economy principles, scientific accountability, and responsible consumption practices, ensuring that biodegradability becomes part of a systemic sustainability strategy rather than an isolated technological promise.

7. Conclusion

The growing environmental crisis caused by conventional plastic pollution has intensified global interest in biodegradable plastics as a potentially sustainable alternative. This study critically examined the scientific, environmental, economic, and policy dimensions of biodegradable plastics to determine whether they represent a genuine solution or an environmental myth. The analysis demonstrates that biodegradable plastics possess significant potential to reduce dependence on fossil resources and support sustainable material innovation. Polymers such as polylactic acid, polyhydroxyalkanoates, and starch-based composites show promising biodegradation characteristics, particularly under controlled industrial composting conditions.

However, the findings also reveal that biodegradability alone does not guarantee environmental sustainability. The degradation behaviour of these materials depends heavily on polymer chemistry, microbial activity, temperature, moisture, oxygen availability, and waste management infrastructure. In natural environments such as marine ecosystems, soils, and landfills, many biodegradable plastics degrade slowly or incompletely, sometimes generating microplastic fragments during intermediate stages. Life-cycle assessment further shows that feedstock cultivation, manufacturing energy consumption, transportation, and disposal practices significantly influence their overall environmental performance.

The study also highlights critical challenges related to greenwashing, consumer misunderstanding, inadequate labelling, and limited composting infrastructure, particularly in

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developing economies. Without effective regulation, waste segregation, and public awareness, the environmental benefits of biodegradable plastics may remain largely theoretical.

Therefore, biodegradable plastics should not be regarded as a universal solution to the global plastic crisis. Instead, they should be viewed as one component of a broader circular economy strategy that prioritises reduction, reuse, recycling, responsible consumption, and scientifically informed policy implementation. Only through the integration of technological innovation, environmental accountability, and systemic waste management can biodegradable plastics contribute meaningfully to long-term ecological sustainability.

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