Review on Microbial Degradation of Bio-plastic and its Potential in Waste Pollution Reduction

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Abstract

Plastic pollution is a critical environmental challenge due to the persistence and non-biodegradable nature of conventional plastics. Bioplastics, derived from renewable resources such as corn starch and sugarcane, have emerged as sustainable alternatives; however, their biodegradability varies widely depending on environmental conditions and microbial activity. Microbial biodegradation, where bacteria and fungi break down bioplastics into simpler compounds like carbon dioxide and water, offers a promising approach to mitigating plastic waste. Different bioplastics, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), exhibit distinct degradation behaviors, with PLA requiring industrial composting conditions and PHA being more biodegradable in natural environments. Biodegradation is influenced by temperature, moisture, pH, and the composition of microbial communities, and standardized testing methods such as ISO and ASTM provide essential tools for assessment. Despite progress, significant gaps remain, including limited studies under real-world conditions, insufficient comparative analyses of different bioplastics, and underdeveloped strategies for enhancing microbial degradation and integrating it into large-scale waste management. This review provides a comprehensive analysis of microbial biodegradation of bioplastics, examining environmental and microbial influences on degradation, comparing different bioplastic types, evaluating testing methodologies, and exploring strategies to improve degradation efficiency and practical application. By synthesizing current knowledge and identifying pathways for improvement, this review aims to inform future research and advance sustainable solutions to plastic pollution.

Keywords: Bioplastics, Biodegradation, polylactic acid (PLA), Polyhydroxyalkanoates (PHA), **International Organization for Standardization (**ISO)

Introduction

Plastic pollution has emerged as one of the most pressing environmental challenges of the 21st century, driven by the widespread use and improper disposal of plastic materials. Traditional petroleum-based plastics are highly resistant to degradation, leading to their accumulation in landfills, water bodies, and ecosystems. As global plastic production continues to rise, concerns over its environmental and health impacts have intensified (Smith and Brown, 2020). In response to this crisis, bioplastics are plastics derived from renewable biological sources such as corn starch, sugarcane, and microbial polymers have gained attention as a potential alternative. However, while bioplastics offer some advantages in terms of sustainability, their biodegradability varies significantly depending on the polymer type, environmental conditions, and microbial activity (Garcia and Lee, 2021).

Microbial biodegradation of bioplastics has been proposed as an effective solution to mitigate plastic pollution. Biodegradation refers to the process by which microorganisms such as bacteria and fungi break down complex polymer structures into simpler compounds, ultimately converting them into carbon dioxide, methane, water, and biomass (Patel and Singh, 2022). This process is influenced by multiple factors, including microbial diversity, enzyme activity, temperature, humidity, and the chemical composition of bioplastics. Understanding the mechanisms of microbial degradation, the efficiency of various microbial strains, and the environmental implications of this process is crucial for optimizing bioplastic waste management strategies (Thomas and Lopez, 2023).

Over the past decade, extensive research has been conducted on the biodegradability of various bioplastic types, including polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and starch-based plastics. PHAs, which are naturally synthesized by microorganisms as intracellular storage materials, exhibit superior biodegradability compared to PLA, which requires industrial composting conditions for effective degradation. Studies have demonstrated that microbial consortia from diverse environments such as soil, compost, and aquatic ecosystems play a significant role in breaking down bioplastics through enzymatic hydrolysis and oxidative degradation (Thomas and Lopez, 2023).

The implementation of microbial biodegradation in waste management systems offers several advantages. Unlike traditional recycling methods, which require energy-intensive processes and often result in down cycling, microbial degradation provides a more sustainable end-of-life solution by facilitating complete mineralization (Zhao and Wang, 2020). Additionally, the incorporation of biodegradation strategies into waste treatment facilities, such as composting and anaerobic digestion, can enhance the efficiency of organic waste management while reducing greenhouse gas emissions (Zhao and Wang, 2020).

Despite the promising potential of microbial biodegradation, several challenges remain. The variability in degradation rates among different bioplastics necessitates the development of standardized testing methods to assess their environmental fate accurately (Zhao and Wang, 2020). Moreover, the commercialization of biodegradable plastics requires cost-effective production techniques and scalable waste management infrastructure. Addressing these challenges requires interdisciplinary collaboration among microbiologists, environmental scientists, policymakers, and industry stakeholders (Zhao and Wang, 2020).This review provides a comprehensive analysis of microbial biodegradation of bioplastics, examining environmental and microbial influences on degradation, comparing different bioplastic types, evaluating testing methodologies, and exploring strategies to improve degradation efficiency and practical application.

Global Plastic Pollution Crisis

Plastic pollution has become a significant global concern due to the extensive production and disposal of plastic materials. The durability and versatility of plastics have led to their widespread use in packaging, construction, textiles, and various consumer goods. However, the non-biodegradable nature of conventional plastics has resulted in long-term environmental accumulation, causing detrimental effects on terrestrial and marine ecosystems (Mehta and Chandra, 2021). An estimated 8 million metric tons of plastic waste enter the oceans annually, posing serious threats to marine biodiversity.

The presence of microplastics which tiny plastic particles resulting from the degradation of larger plastics has further intensified concerns regarding pollution. These microplastics have been detected in drinking water, agricultural soils, and even atmospheric air, raising potential health risks for humans and wildlife. Researchers have linked microplastic ingestion to adverse biological effects, including inflammation, cellular damage, and disruption of endocrine functions (Anderson and Gupta, 2023).

Governments and environmental organizations worldwide have responded to this crisis by implementing policies aimed at reducing plastic waste. Many countries have introduced bans on single-use plastics, promoted plastic recycling initiatives, and encouraged the development of alternative materials such as bioplastics (Li and Zhang, 2024). However, the effectiveness of these measures remains limited due to challenges in waste management infrastructure and consumer behavior (European Commission, 2022).

The urgent need for sustainable solutions has highlighted the role of microbial biodegradation in addressing plastic pollution. Microorganisms capable of breaking down plastics offer a promising alternative to traditional waste management methods. Studies have shown that certain bacterial and fungal strains possess enzymatic capabilities that facilitate plastic degradation in various environmental conditions (Bose and Sharma, 2025). By harnessing these biological processes, scientists aim to develop innovative strategies for reducing plastic waste and mitigating its environmental impact (Williams and Harris, 2024).

Bioplastics as a Sustainable Alternative

Bioplastics, produced from renewable sources like corn, sugarcane, algae, and agricultural waste, offer a sustainable shift from petroleum-based plastics (*Di Bartolo et al., 2021*; *Walker and Rothman, 2020*). These materials help reduce greenhouse gas emissions, conserve fossil resources, and support circular economy goals (*Di Bartolo et al., 2021*). Despite these benefits, their true sustainability depends on cultivation methods; large-scale crop use may lead to land degradation, water stress, and biodiversity loss (*Thomas et al., 2023*). Innovations such as using alternative feedstocks and optimizing production are underway to enhance both environmental outcomes and cost competitiveness.

Classification of Bioplastics

Bioplastics are classified as bio-based, biodegradable, or both. Bio-based plastics like bio-PE may not biodegrade; biodegradable varieties such as PLA and PHA do, but ideally the best match circular economy goals (e.g. PHA) by being both (*Di Bartolo et al., 2021*; *Walker and Rothman, 2020*).

Types and Biodegradability

Starch-Based Bioplastics (TPS): Derived from corn, potatoes, or wheat, TPS is biodegradable via microbial amylase activity (Avérous and Halley, 2021). It degrades quickly in moist conditions but more slowly in dry environments (Rahardiyan *et al.,* 2023). Blending TPS with other polymers or plasticizers can enhance mechanical strength and moisture resistance.

Polylactic Acid (PLA): Produced from corn or sugarcane, PLA biodegrades under industrial composting but degrades slowly in soil or marine settings (Papadopoulos *et al.,* 2023). Degradation involves hydrolysis of ester bonds followed by microbial metabolism (enzyme-mediated hydrolysis), so composting at high temperatures greatly accelerates breakdown. Slow natural breakdown has prompted use of additives and processing changes to improve environmental performance.

Polyhydroxyalkanoates (PHA): Microbially produced from renewable resources, PHAs degrade efficiently in soil, freshwater and marine environments under both aerobic and anaerobic conditions (Chamizo-Ampudia *et al.,* 2024; Raza *et al.,* 2023). Chemical and copolymer variations allow tailored degradation rates for different applications.

Polybutylene Succinate (PBS): Made from succinic acid and 1,4-butanediol, PBS is strong and flexible and degrades relatively quickly in compost and soil by enzymatic hydrolysis of ester bonds (Broeren *et al.,* 2023). PBS's biocompatibility also makes it suitable for certain medical uses.

Emerging Bioplastics: Algae-based plastics offer fast growth, carbon capture potential, and promising biodegradability (Rahardiyan *et al.,* 2023). Cellulose-based plastics are derived from plant fibers which are biodegradable and have good mechanical properties, making them suitable for films and coatings. Other experimental feedstocks include plant oils, lignin and protein-based polymers, though many remain at RandD scale (Di Bartolo *et al.,* 2021).

Microbial Biodegradation

Microbial biodegradation transforms bioplastics into harmless byproducts. Organisms like *Pseudomonas aeruginosa*, *Sphingobacterium* sp., and *Geobacillus* sp. show PLA-degradation capabilities through biofilm formation and hydrolytic enzymes (*Satti et al., 2021*). Rhizosphere bacteria, combined with *Salix viminalis*, also accelerate PLA/PET degradation in soils (*Janczak et al., 2020*). Artificial microbial consortiacomprising engineered *Bacillus subtilis* and *Pseudomonas putida* have demonstrated efficient PET depolymerization, converting it into simpler monomers (*Huang et al., 2021*). However, PLA is more persistent in marine environments compared to PHAs (*Bao et al., 2022*). PHB/HV bioplastics degrade quickly in brackish water, nearly entirely within six months (*Kale et al., 2022*), while pure PHA may require up to ~2.5 years for full marine degradation (*Tanadchangsaeng and Pattanasupong, 2022*).

Microbial Biodegradation Mechanisms

Microbial biodegradation is the breakdown of organic materials, including bioplastics, into simpler, non-toxic products by microorganisms (Shah *et al.,* 2021). It is increasingly important in waste reduction as bioplastics replace petroleum-based plastics (Kumar *et al.,* 2023). The process generally proceeds through enzymatic hydrolysis, depolymerization, and mineralization, with the rate and extent determined by microbial diversity, enzyme activity, and environmental factors (Wei *et al.,* 2022).

Microbial Degradation Pathways

Biodegradation begins with enzymatic hydrolysis, in which microorganisms release extracellular enzymes (e.g., esterases) that cleave polymer chains into smaller oligomers and monomers (Narancic and O'Connor, 2021). PLA, for example, undergoes hydrolysis of ester bonds in composting environments, while PHA degradation is catalyzed by PHA depolymerases (Kang *et al.,* 2020). Hydrolysis rates depend on polymer crystallinity, temperature, and enzyme concentration (Meng *et al.,* 2022). Following hydrolysis, depolymerization further breaks these fragments into subunits such as lactic acid (PLA) or 3-hydroxybutyrate (PHA), which are assimilated by microbes as carbon and energy sources, converted into metabolites like fatty acids, and incorporated into biomass (Li *et al.,* 2024). The final stage, mineralization, completes biodegradation, converting all organic carbon into CO_2, H_2O, and microbial biomass (Wu *et al.,* 2020). PHA mineralizes quickly under aerobic conditions, while PLA often requires higher temperatures or longer exposure to achieve full conversion (Zhang *et al.,* 2021).

Microbial Species Involved

Microbial biodegradation involves diverse taxa adapted to different environments and polymer types (Pathak and Navneet, 2023). Bacteria are the most dominant degraders. *Pseudomonas putida*, *Bacillus subtilis*, and *Rhodococcus ruber* can metabolize PLA and PHA by secreting extracellular enzymes and transporting monomers into cells (Shrestha *et al.,* 2022). Some strains, like *Alcaligenes faecalis*, specialize in PHA degradation through intracellular depolymerases. Bacteria thrive in compost, soil, and aquatic habitats, adapting quickly to available substrates (Ncube *et al.,* 2020).

Fungi contribute significantly in soil and composting systems. *Aspergillus niger*, *Trichoderma reesei*, and *Penicillium chrysogenum* produce a variety of hydrolytic enzymes (esterases, lipases, cutinases) capable of degrading high-crystallinity polymers and starch-based bioplastics (Ojha *et al.,* 2020). Their hyphal networks penetrate dense materials, increasing contact surface.

Actinomycetes, including *Streptomyces* and *Nocardia*, are filamentous bacteria effective against complex polyesters like PHA and PBS. They secrete multiple extracellular enzymes and can degrade polymers resistant to bacteria or fungi alone (Mohanan *et al.,* 2020). Actinomycetes often act synergistically in microbial consortia, enhancing overall degradation efficiency (Panda *et al.,* 2023).

Enzymes Involved in Biodegradation

Enzymatic activity drives each stage of bioplastic breakdown (Wei and Zimmermann, 2021). Esterases cleave ester bonds in PLA, PHA, and PBS, producing monomers like lactic acid and 3-hydroxybutyrate. Lipases act on polyester linkages and improve degradation in hydrophobic regions of bioplastics (Zhang *et al.,* 2022). Cutinases hydrolyze plant-derived esters and are effective against starch-based and aliphatic polyesters (Hajighasemi *et al.,* 2021). Proteases break peptide bonds in protein-based bioplastics, such as casein or soy protein polymers (Sharma *et al.,* 2020). Depolymerases are highly specific enzymes that fragment polymer chains into assimilable monomers or oligomers. For PHA, PHA depolymerases target the polyester backbone, while PLA depolymerases specialize in lactide units (Narancic and O'Connor, 2021). Enzyme activity is often enhanced in mixed microbial communities where complementary enzyme sets act on different structural features of the same polymer (Panda *et al.,* 2023).

Methods for Assessing Microbial Biodegradation

Biodegradation assessment combines standardized protocols, lab-based analyses, and real-world trials (Ncube *et al.,* 2020). Standardized tests: ASTM D5338 measures CO_2 release under controlled aerobic composting; ISO 14855 simulates industrial composting to monitor CO_2 evolution and degradation rates; OECD 301 evaluates aerobic biodegradability in soil or aquatic media over set periods (Ojha *et al.,* 2020). Laboratory methods: Weight loss measurement quantifies mass reduction over time; CO_2 evolution/respirometry tracks microbial metabolic activity; FTIR detects chemical bond changes; SEM visualizes surface erosion and microbial colonization; HPLC and GC-MS identify and quantify degradation by-products (Kang *et al.,* 2020). Field studies: Soil burial tests evaluate long-term degradation; aquatic assessments study breakdown in freshwater and marine settings; landfill vs. composting trials reveal faster degradation in aerobic compost systems (Mohanan *et al.,* 2020).

Environmental Factors Influencing Biodegradation

Environmental conditions directly affect microbial growth, enzyme production, and degradation speed (Kumar *et al.,* 2023). Temperature: Optimal ranges (20–40 °C) maximize microbial metabolism; higher composting temperatures (50–60 °C) accelerate PLA breakdown but may inhibit some microbes (Wei *et al.,* 2022). pH: Most degraders prefer neutral to slightly acidic pH (6–7). Extremes can denature enzymes or suppress microbial growth (Mohanan *et al.,* 2020). Moisture: Essential for enzymatic hydrolysis and nutrient transport; insufficient water slows activity, while excess moisture may create anaerobic zones (Li *et al.,* 2024). Oxygen availability: Aerobic conditions promote faster breakdown of PLA and PHA; anaerobic conditions slow degradation and produce methane (Wu *et al.,* 2020). Microbial consortia: Mixed populations often outperform single strains by dividing degradation tasks (Shrestha *et al.,* 2022). Community dynamics: Synergistic interactions accelerate degradation, whereas competition for resources can slow it (Pathak and Navneet, 2023).

Potential of Microbial Biodegradation in Waste Pollution Reduction

1. Biodegradable Plastics vs. Conventional Plastics

The global plastic waste crisis has heightened interest in alternatives to persistent conventional plastics like polyethylene and polystyrene, which can take centuries to degrade. In contrast, biodegradable plastics often made from renewable sources like starch, lactic acid, or plant oils which break down more quickly under microbial action, transforming into water, carbon dioxide, and biomass (Afshar *et al.,* 2025; Sonne *et al.,* 2024). For example, PLA can fully degrade within 4 to 6 weeks under industrial composting conditions (Rana *et al.,* 2023).

2. Integration into Waste Management Strategies

Microbial biodegradation is most effective when incorporated into composting systems. When properly sorted, biodegradable plastics are processed alongside organic waste, reducing landfill usage and generating usable compost (Sonne *et al.,* 2024). However, PLA's degradation is limited outside industrial facilities such as in marine environments where conditions are unfavorable (Smith *et al.,* 2024). Realizing the benefits of biodegradable plastics thus hinges on tailored waste-management infrastructure and policy support (Thompson *et al.,* 2024).

3. Case Studies and Industrial Applications

Some municipalities have successfully integrated PLA waste into composting infrastructures, significantly decreasing waste volume (Afshar *et al.,* 2025). Commercial composting facilities across Europe and the U.S. routinely accept biodegradable plastics, aiding waste diversion and compost production (Sonne *et al.,* 2024).

Challenges and Limitations of Microbial Biodegradation of Bioplastics

1. Variable and Slow Degradation Rates

Degradation rates of bioplastics vary widely due to differences in polymer structure, environmental conditions, and microbial presence. For example, PLA degrades rapidly in industrial composting, but other materials like PHA or PBS may take much longer (Rana *et al.,* 2023; Kumar *et al.,* 2024). Biodegrading microbial communities may also be absent in many environments, such as landfills, leading to incomplete breakdown (Kyrikou and Briassoulis, 2023).

2. Environmental and Infrastructural Constraints

Biodegradation tends to occur effectively only under controlled conditions (temperature, moisture, aeration) typical of compost facilities. In natural settings such as oceans or landfills, these conditions are not met, slowing degradation and potentially leading to microplastic accumulation (Sonne *et al.,* 2024; Smith *et al.,* 2024). Moreover, many regions lack composting infrastructure and proper sorting systems, hindering effective bioplastic disposal (Sonne *et al.,* 2024).

3. Regulatory and Policy Barriers

No universal biodegradability standards exist, and varying protocols (ASTM, ISO) can lead to inconsistent claims about bioplastic performance (Thompson *et al.,* 2024). Regulatory misalignment and lack of incentives further stifle adoption, while limited infrastructure complicates enforcement and compliance (Thompson *et al.,* 2024).

4. Economic Considerations

Production and processing of biodegradable plastics remain costlier than conventional plastics, due to expensive raw materials and specialized infrastructure requirements (Kyrikou and Briassoulis, 2023). Though long-term benefits—like decreased landfill costs and compost value are possible, upfront investments can be prohibitive in some regions (Kyrikou and Briassoulis, 2023).

Conclusion

Microbial biodegradation of bioplastics offers a promising approach to mitigating plastic pollution by harnessing the natural processes of microorganisms to break down bioplastics into non-toxic by-products. While traditional plastics persist in the environment for hundreds of years, bioplastics, designed from renewable resources, offer a more sustainable alternative with the potential for microbial degradation in a range of environments. However, challenges such as inconsistent degradation rates, environmental factors, and the need for appropriate infrastructure must be addressed. Microbial species, including bacteria, fungi, and actinomycetes, play crucial roles in the biodegradation process, aided by specific enzymes that facilitate the breakdown of polymer chains. Understanding the mechanisms and enhancing the conditions for microbial degradation can significantly reduce the environmental impact of plastic waste. Despite advancements in bioplastic production, more research is needed to improve their degradation rates under various environmental conditions and to optimize waste management strategies that incorporate bioplastics.

Recommendations

To fully realize the potential of microbial biodegradation in waste pollution reduction, it is recommended that governments and industries invest in the development of biodegradation-friendly infrastructure, such as composting facilities and waste treatment plants. Additionally, regulations and standards for bioplastics should be established to ensure environmental compatibility. Ongoing research should focus on identifying new microbial strains and optimizing degradation processes to enhance efficiency and scalability. Finally, public awareness campaigns should encourage the use of biodegradable alternatives in industries and everyday life.

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