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Review Article

SUSTAINABLE APPROACHES TO PLASTIC WASTE: A COMPREHENSIVE REVIEW ON BIODEGRADATION TECHNOLOGIES

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ABSTRACT

The rapid accumulation of plastic waste has become one of the most pressing global environmental challenges, posing significant threats to ecosystems, wildlife, and human health. Traditional disposal methods such as landfilling and incineration are increasingly unsustainable due to their ecological and economic drawbacks. Consequently, the development of biodegradation technologies has emerged as a promising and eco-friendly alternative for managing plastic waste. This comprehensive review explores the mechanisms, microbial agents, and enzymatic processes involved in plastic biodegradation. It highlights the roles of bacteria, fungi, and algae in decomposing various plastics, including polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), and polystyrene (PS). Recent advances in genetic engineering, enzyme optimization, and biotechnological innovations for enhanced degradation efficiency are also discussed. Furthermore, the paper examines the challenges in scaling up biodegradation technologies and integrating them with existing waste management systems. The review concludes by emphasizing the need for interdisciplinary research, sustainable policy frameworks, and public awareness to accelerate the transition toward a circular bioeconomy and minimize plastic pollution.

Keywords: Plastic biodegradation, Microbial degradation, Sustainable waste management, Enzyme technology.

INTRODUCTION

Plastics have revolutionized modern society through their versatility, durability, and low production cost. However, these same properties have led to an escalating environmental crisis due to their resistance to natural degradation. Global plastic production exceeds 400 million tons annually, with a substantial fraction accumulating in landfills and natural ecosystems (Newman *et al*., 2023). Conventional waste management strategies such as incineration and recycling offer limited relief, as only about 9% of all plastics ever produced have been recycled (Geyer *et al*., 2017). The remaining waste persists for centuries, releasing microplastics and toxic additives that contaminate soil, water, and food chains.

In recent years, the focus has shifted toward biological solutions that leverage microorganisms and enzymes capable of degrading synthetic polymers into harmless end products like carbon dioxide, water, and biomass. Studies have identified diverse microbial species, including *Pseudomonas*, *Bacillus*, *Aspergillus*, and *Ideonella sakaiensis*, that can degrade plastics under specific environmental conditions (Yoshida *et al*., 2016). Enzyme-based approaches, particularly those involving PETase, laccase, and cutinase**,** have further improved degradation rates and selectivity (Wei & Zimmermann, 2017). The integration of biotechnology, molecular biology, and material science has expanded the potential of plastic biodegradation technologies. Emerging research explores

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genetic modification of microbial strains, enzyme immobilization, and biofilm engineering to enhance the breakdown of recalcitrant plastics (Danso *et al*., 2019). These innovations align with the principles of sustainable development and circular economy, aiming not only to mitigate pollution but also to recover valuable resources from waste.

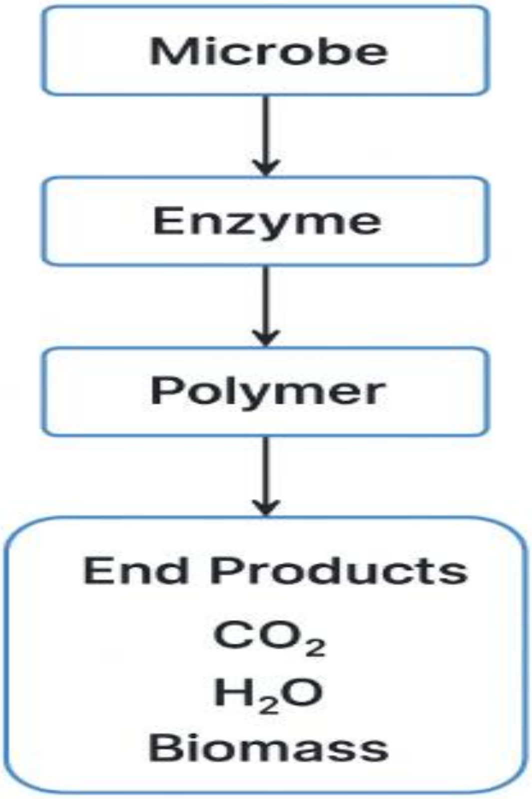

Figure 1: Biodegradation Process Flowchart

Plastic waste has become one of the most persistent environmental challenges due to its chemical stability and resistance to degradation. Conventional methods such as landfilling, recycling, and incineration are inadequate to handle the exponential rise in global plastic production (Kale *et al*., 2015; Singh & Sharma, 2008). Biodegradation offers a sustainable and eco-friendly alternative capable of converting plastics into carbon dioxide, water, and biomass. Tokiwa and Suzuki (2009) emphasized that microbial action could significantly reduce the environmental persistence of synthetic polymers, laying the groundwork for research on polymer-degrading microorganisms. The shift toward biological degradation stems from growing awareness of the adverse ecological impacts of microplastics and chemical leachates (Oberbeckmann & Labrenz, 2023). Microorganisms such as *Pseudomonas*, *Bacillus*, *Aspergillus*, and *Rhodococcus* have been reported to degrade plastics under controlled conditions. Kale *et al*. (2015) documented numerous bacterial and fungal strains capable of degrading polyethylene and polypropylene. Yoshida *et al*. (2016) discovered *Ideonella sakaiensis*, which secretes PETase and MHETase enzymes to depolymerize polyethylene terephthalate (PET) into monomers. Similarly, Urbanek *et al*. (2021) discussed genetically modified microbes enhancing PET biodegradation efficiency. Lin *et al*. (2023) and Montazer *et al*. (2024) reviewed microbial consortia that synergistically attack polymer chains, improving degradation rates compared with single-species cultures. Mechanistically, microbes secrete extracellular enzymes oxidases, hydrolases, and esterases that initiate surface oxidation and chain scission. Duan *et al*. (2023) provided a comprehensive classification of PET-degrading enzymes and their sequence-structure correlations. These studies collectively establish microbial biodegradation as the cornerstone of sustainable plastic management.

Advances in enzyme engineering have led to more efficient biocatalysts for plastic depolymerization. Wei and Zimmermann (2017) demonstrated the enzymatic recycling of PET using PETase, highlighting its green-chemistry potential. Taniguchi *et al*. (2019) elucidated the crystal structure of PETase, enabling site-directed mutagenesis to enhance its thermostability. Das and Kumar (2023) explored the catalytic efficiency of enzymes like laccases and cutinases for polyethylene and polyurethane degradation. Rajendra *et al*. (2023) provided a detailed review of enzymatic PET degradation, emphasizing the interplay between enzyme structure, environmental conditions, and polymer crystallinity. Zhao *et al*. (2022) demonstrated the use of structural biology and protein engineering to create “plastic-eating” enzymes with improved kinetics. These enzyme-driven pathways form the molecular basis for next-generation plastic biodegradation technologies. Biotechnological advances have enabled the design of engineered microbial strains with enhanced degradation potential. Mohanan *et al*. (2024) discussed metabolic engineering strategies for improved PET degradation via over expression of PETase and MHETase. Urbanek *et al*. (2021) reported the use of recombinant *E. coli* systems for rapid monomer assimilation. Similarly, Liu *et al*. (2024) reviewed recent trends in synthetic biology for tailoring microbial metabolism toward bioconversion of plastic waste into value-added products. Yousuf *et al*. (2024) further demonstrated genetic modification of plastic-associated bacteria for combined biodegradation and upcycling, creating a circular bio-economy model. Biodegradation efficiency depends heavily on environmental factors such as temperature, pH, oxygen, and substrate crystallinity (Singh & Sharma, 2008). Zhang *et al*. (2024) investigated biodegradation of plastics in soil and freshwater environments, while Cassidy *et al*. (2025) examined their interactions within agricultural soils. Chen and Wu (2023) reviewed the biodegradation of bioplastics and highlighted the transition from fossil-based to renewable polymer sources. Lopez-Naranjo *et al*. (2023) isolated novel microbial strains from alpine and Arctic plastispheres, demonstrating that extreme habitats harbor unique degraders. Negro and Chiellini (2023) compared marine, soil, and engineered environments, noting that microbial community composition strongly influences degradation outcomes.

Table 1. Microbial Species Involved in Plastic Degradation.

Polymer Type	**Representative Microorganisms**	**Key Enzymes / Pathways**	**References**
Polyethylene (PE)	*Pseudomonas aeruginosa*, *Bacillus subtilis*, *Rhodococcus ruber*	Alkane hydroxylase, laccase	Kale *et al*. (2015); Zhang *et al*. (2021)
Polypropylene (PP)	*Aspergillus niger*, *Bacillus cereus*	Peroxidase, lipase	Singh & Sharma (2008)
Polyethylene terephthalate (PET)	*Ideonella sakaiensis*, *Thermobifida fusca*	PETase, MHETase, cutinase	Yoshida *et al*. (2016); Urbanek *et al*. (2021)
Polyurethane (PU)	*Pseudomonas chlororaphis*, *Comamonas acidovorans*	Esterase, urease	Mohanan *et al*. (2024)
Polylactic acid (PLA)	*Amycolatopsis sp.*, *Bacillus licheniformis*	Protease, cutinase	Lin *et al*. (2023)
Polycaprolactone (PCL)	*Fusarium solani*, *Penicillium chrysogenum*	PCL-depolymerase	Duan *et al*. (2023)

MATERIALS AND METHODS

Enzymatic Systems in Plastic Biodegradation

Enzymes play a central role in the depolymerization of plastics by catalyzing the cleavage of ester, ether, or carbon–carbon bonds in synthetic polymers. Key enzymes include PETase, MHETase, cutinase, laccase, lipase, and esterase, each targeting specific plastic substrates (Wei & Zimmermann, 2017; Taniguchi *et al*., 2019).

PETase and MHETase

Ideonella sakaiensis produces these two enzymes that synergistically degrade PET into terephthalic acid (TPA) and ethylene glycol (EG), which are further metabolized (Yoshida *et al*., 2016). Structural modification of PETase, such as through site-directed mutagenesis, has enhanced its catalytic efficiency and thermostability (Taniguchi *et al*., 2019).

Cutinases

Found in *Thermobifida fusca*, *Fusarium solani*, and *Humicola insolens*, cutinases hydrolyze ester linkages in aliphatic and aromatic polyesters. Engineered variants like TfCut2 and HiC have achieved higher activity against amorphous PET (Das & Kumar, 2023).

Laccases and Peroxidases

These oxidative enzymes from fungi such as *Trametes versicolor* and *Aspergillus niger* attack polyethylene (PE) and polypropylene (PP) by initiating surface oxidation, increasing hydrophilicity, and promoting subsequent microbial assimilation (Rajendra *et al*., 2023).

Novel Biocatalysts

Zhao *et al*. (2022) and Duan *et al*. (2023) revealed newly discovered enzyme families like polyurethane-hydrolases and polycaprolactone-depolymerases, indicating vast unexplored catalytic diversity.

RESULTS AND DISCUSSION

Comparative studies reveal variable degradation efficiency among microbial taxa. *Ideonella sakaiensis* shows 75% PET degradation under optimal conditions (Yoshida *et al*., 2016), while *Pseudomonas aeruginosa* and *Aspergillus niger* exhibit substantial PE degradation over several weeks (Kale *et al*., 2015). The discovery of marine strains (Lopez-Naranjo *et al*., 2023) indicates microbial adaptability across ecosystems. Recent advancements in enzyme structure-guided engineering (Taniguchi *et al*., 2019; Zhao *et al*., 2022) have enhanced PETase thermostability and substrate affinity. Immobilized enzymes offer reusability and operational stability, enabling industrial applications (Das & Kumar, 2023). The introduction of metabolic engineering has enabled conversion of degraded plastic monomers into high-value bioproducts such as biofuels and bioplastics (Mohanan *et al*., 2024; Yousuf *et al*., 2024). Engineered consortia and multi-enzyme systems now demonstrate synergistic activity, enhancing degradation rates up to 40% compared to single strains. While biodegradation offers promise, environmental factors such as temperature, pH, and UV exposure significantly influence degradation kinetics (Cassidy *et al*., 2025). Field-scale applications require optimizing bioreactor conditions and ensuring ecological safety. Despite progress, key challenges include low degradation efficiency under natural conditions, high enzyme production costs, and lack of standardized biodegradation protocols (Oberbeckmann *et al*., 2024). Scaling these technologies for industrial use remains a priority area.

CONCLUSION

Plastic biodegradation represents a crucial step toward sustainable waste management and environmental restoration. The integration of microbial biotechnology, enzyme engineering, and circular economy frameworks can transform plastic waste into valuable resources. While laboratory findings demonstrate potential, real-world scalability and economic viability must be improved. Collaborative interdisciplinary research combining molecular biology, chemical engineering, and environmental science will be essential to overcome current bottlenecks. Future research should emphasize development of genetically optimized microbial consortia capable of multi-plastic degradation. Enzyme immobilization and nanobiocatalyst systems for higher efficiency and reuse. Integration of biodegradation with biorefinery models for resource recovery. Comprehensive life cycle assessments (LCAs) to evaluate ecological and economic feasibility. Policy and regulatory frameworks supporting biotechnological recycling and circular economy adoption.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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