Research in Health & Medical Sciences *Review Article*

2025 January; 4(1)

Bacterial biodegradation of microplastics: Mechanisms, applications, challenges, and future prospects

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Received: 2026/1; Revised: 2026/5; Accepted: 2026/5

Abstract

Microplastic pollution is recognized as a serious global threat to the environment and human health. The high persistence and slow natural degradation rate of these particles necessitate the development of sustainable management solutions. Among these, biodegradation using microorganisms, particularly bacteria, is considered a promising approach due to its advantages such as low energy consumption and compatibility with ecosystems. This review was conducted based on searches in the scientific databases PubMed, ScienceDirect, and Scopus from 2016 to 2025. Keywords including "biodegradation of microplastics by bacteria," "bacterial enzymes like PETase," and "challenges of biodegradable plastics" were combined. After screening, approximately 50 relevant articles were selected for final analysis. The review revealed that various bacteria, including Pseudomonas, Bacillus, and Ideonella sakaiensis, are capable of degrading different polymers such as PET, PE, and PP through the secretion of specialized enzymes (e.g., PETase, laccases, and hydrolases). The degradation mechanism generally involves bacterial attachment and biofilm formation, enzymatic depolymerization, and ultimate mineralization. Applying this process wastewater treatment systems showed positive results. However, major challenges include slow degradation rates under real environmental conditions and the resistance of certain polymers. Innovative strategies such as enzyme engineering and microbial consortia use hold potential to enhance efficiency. Bacterial biodegradation of microplastics shows high potential as a sustainable solution, yet large-scale application requires overcoming challenges like optimizing degradation rates and process scalability. Future research should focus on engineering more efficient strains and enzymes, gaining a deeper understanding of interactions in complex environments, and developing supportive policy frameworks.

Keywords: Biodegradation, plastic-degrading bacteria, microbial enzymes, biodegradable polymers, plastic pollution

Introduction

Recently, microplastics attracted extensive attention from the scientific community, policymakers, and international organizations as one of the most important and challenging emerging environmental contaminants (1). Microplastics are generally defined as plastic particles smaller than 5 mm. These particles are either produced primarily in industrial and consumer products (e.g., abrasives, cosmetic products, and industrial additives) or formed secondarily through the physical, chemical, and biological degradation of larger plastics in the environment (2). Their high chemical stability, wide diversity of polymers and additives, and extremely low natural degradation rate have led to their widespread detection in various environments, including aquatic ecosystems, soils, sediments, wastewater, and even the atmosphere (3).

The widespread presence of microplastics in the environment has brought about significant ecological and health consequences. Numerous studies showed that these particles can be ingested by a wide range of organisms, from plankton and invertebrates to fish and mammals, thereby entering food chains. The bioaccumulation and trophic transfer of microplastics not only affect species health and survival but also increase the risk of transfer to humans through the consumption of water and food (4). Furthermore, the high specific surface area and hydrophobic nature of microplastics make them effective adsorbents for heavy metals, persistent organic compounds, pesticides, and toxic additives such as phthalates and bisphenols. Thus, microplastics can act as multi-purpose carriers of pollutants and exacerbate environmental toxicity (5, 6).

From a human health perspective, growing evidence shows that microplastic exposure is associated with inflammatory responses, oxidative stress, immune dysregulation, and cellular alterations (7). Although uncertainties remain regarding long-term consequences, safe exposure thresholds, and dose-response relationships, the increasing detection of microplastics in human tissues and biological fluids has raised serious public health concerns. This situation underscores, more than ever, the need for effective action to control and mitigate microplastic pollution (8).

In response to this crisis, several approaches have been proposed for managing plastic pollution. These primarily include source-directed preventive measures (reducing plastic production and consumption) as well as removal and treatment methods applied in the environment or within engineered systems (9). Although reducing plastic use and substituting materials are considered essential strategies, the massive volume of plastics already accumulated in the environment means that these measures alone are insufficient. This insufficiency applies to addressing the existing pollution burden. Therefore, developing efficient methods to remove or reduce microplastics from contaminated environments has been established as a research priority (10).

Various methods for removing microplastics include physical processes (e.g., filtration and mechanical separation), chemical processes (advanced oxidation, chemical degradation), and biological processes. However, many physical and chemical methods face limitations such as high energy consumption, significant operational costs, limited efficiency in removing small particles, and the potential generation of secondary byproducts. These challenges have shifted researchers' attention toward biological approaches as more sustainable and environmentally friendly options (11, 12).

Biological methods, particularly the biodegradation of plastics, rely on harnessing the natural capacities of living organisms to break down polymer structures and convert them into simpler, less hazardous compounds (13). These methods offer significant environmental sustainability advantages due to lower energy consumption, minimal secondary pollutant generation, and alignment with natural ecosystem processes. Furthermore, biodegradation can be considered within the framework of a circular economy, as it enables the biological recycling of carbon and its return to natural cycles (14, 15).

Among various biological agents including fungi, algae, and bacteria, bacteria have prominent role in plastic biodegradation due to their high metabolic diversity, ability to adapt to diverse environmental conditions, rapid growth, and genetic manipulability. Many bacterial species are capable of breaking the chemical bonds of plastic polymers by secreting specific enzymes and using the resulting products as a carbon and energy source. Additionally, bacteria are able to form biofilms on plastic surfaces, enhancing enzymatic contact with the polymer surface and thereby increase degradation efficiency (16).

Among the important advantages of bacterial biodegradation are the feasibility of application under real environmental conditions, potential for scalability in treatment systems, compatibility with engineering and biotechnological processes, and alignment with modern sustainable management approaches (17). Furthermore, recent advances in biotechnology, metabolic engineering, and the discovery of genes and enzymes involved in plastic degradation have opened new horizons. These advances help optimize these processes and improve their efficiency (18).

This review aims to provide a comprehensive overview of current knowledge on plastic biodegradation, with a special focus on the role of bacteria. It examines the biological and enzymatic mechanisms involved, analyzes the advantages and limitations of this approach, and outlines future research pathways for developing efficient and sustainable strategies to reduce microplastic pollution.

Methods

This review article was prepared based on a review search of reputable scientific databases including PubMed, ScienceDirect, and Scopus. The search was conducted on articles published between 2016 and 2025 to cover recent advances in the field of microplastic biodegradation by bacteria, enzymatic mechanisms, challenges of biodegradable polymers, and future perspectives. The main keywords included combinations such as "biodegradation of microplastics by bacteria," "biodegradation of microplastics by bacterial enzymes such as PETase," "challenges of biodegradable plastics such as PLA and PHA in degradation rate," and "future perspective of microbial degradation of bioplastics." These were often combined using Boolean operators (AND/OR) and time filters to obtain relevant and up-to-date results.

Selected articles were chosen based on criteria such as journal credibility (high Impact Factor), direct relevance to the topic (role of bacteria, enzymes such as PETase and MHETase, and challenges of degradation rates in natural environments), and focus on experimental, review, and modeling studies. Over 100 initial articles were identified, and after removing duplicates and screening abstracts, approximately 50 primary sources remained for in-depth analysis. This review approach allowed comprehensive coverage of mechanisms, applications, limitations, and future research pathways, with an emphasis on recent advances in enzyme engineering and microbial consortia.

Results and Discussion

Principles of microplastic biodegradation and its advantages

The principles of microplastic biodegradation are based on harnessing the metabolic capacities of microorganisms, particularly bacteria, fungi, and algae, to break down complex polymer structures and convert them into simpler compounds such as carbon dioxide, water, and biomass. This process typically occurs through the secretion of specific enzymes such as hydrolases, oxidases, and depolymerases, which target the chemical bonds of polymers including polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) (19). Studies indicate that these mechanisms involve initial steps of adsorption, biofilm formation, and subsequent enzymatic degradation, with efficiency depending on environmental factors such as pH, temperature, and nutrient availability. Furthermore, recent advances in identifying efficient microbial strains, such as Pseudomonas and Bacillus species, had a key role in accelerating these processes and enabling application in real-world environments (20).

The advantages of biodegradation over physical and chemical methods are notable, as this approach is associated with low energy consumption, minimal secondary pollutant generation, and high compatibility with natural ecosystems. However, most of the reported advantages are derived from laboratory-based studies under optimized conditions, and there is a lack of direct comparative field studies that robustly demonstrate these benefits over physical and chemical methods under real-world variability. Unlike chemical methods, which often produce toxic byproducts, biodegradation enables biological carbon recycling and, within the framework of a circular economy, helps return materials to natural cycles. This method is scalable and cost-effective, especially in wastewater treatment and contaminated soils (21).

Despite existing challenges such as the slow degradation rate of certain polymers, the environmental benefits of biodegradation, including reduced ecotoxicological effects and support for biodiversity, made it a research priority. Reviews show that combining this method with novel technologies such as genetic engineering can enhance efficiency and provide long-term solutions for managing microplastic pollution. Ultimately, this approach not only helps reduce the pollution burden but also promotes green solutions, thereby bringing global sustainable development goals closer (22, 23).

Mechanisms of microplastic biodegradation by bacteria

Biodegradation of microplastics by bacteria is a multi-step process involving complex interactions between the chemical properties of the polymer, environmental conditions, and the metabolic capacity of microorganisms. These mechanisms are mainly divided into four main stages: biodeterioration, depolymerization, assimilation, and mineralization (19). In the biodeterioration stage, bacteria colonize the microplastic surface by forming a biofilm and facilitate physical changes such as increased surface roughness and crack formation, which enhance enzymatic contact. These stages are influenced by factors such as pH, temperature, and nutrient availability, and their efficiency is lower for polymers with resistant structures such as polyethylene (PE) and polypropylene (PP) (24). While PET degradation via enzymatic hydrolysis is well-documented, inconsistencies exist across studies regarding PE and PP degradation. Some reports claim significant weight loss, whereas others find minimal changes over similar timeframes, likely due to differences in experimental conditions, bacterial strains, or initial polymer properties. Figure 1 shows a schematic of the four main stages of the metabolic mechanism of biodegradation.

In the depolymerization stage, extracellular enzymes secreted by bacteria, such as hydrolases and oxidases, break the chemical bonds of polymer chains and convert them into smaller oligomers or monomers. This process is particularly more effective for polymers with hydrolyzable functional groups such as polyethylene terephthalate (PET), whereas hydrocarbon polymers require prior oxidation (25). Biofilm formation plays a key role in enhancing enzymatic efficiency at this stage, as it provides direct contact with the polymer surface and accelerates molecular changes such as reduced molecular weight (26). In the assimilation stage, depolymerization products are transported into bacterial cells and enter metabolic pathways as a carbon and energy source, ultimately leading to mineralization, where organic compounds are converted into carbon dioxide, water, and biomass (27). Completion of these stages indicates effective degradation, but challenges such as slow rates in real-world environments exist, which can be improved through genetic engineering of bacterial strains such as Pseudomonas and Bacillus. These mechanisms not only enhance

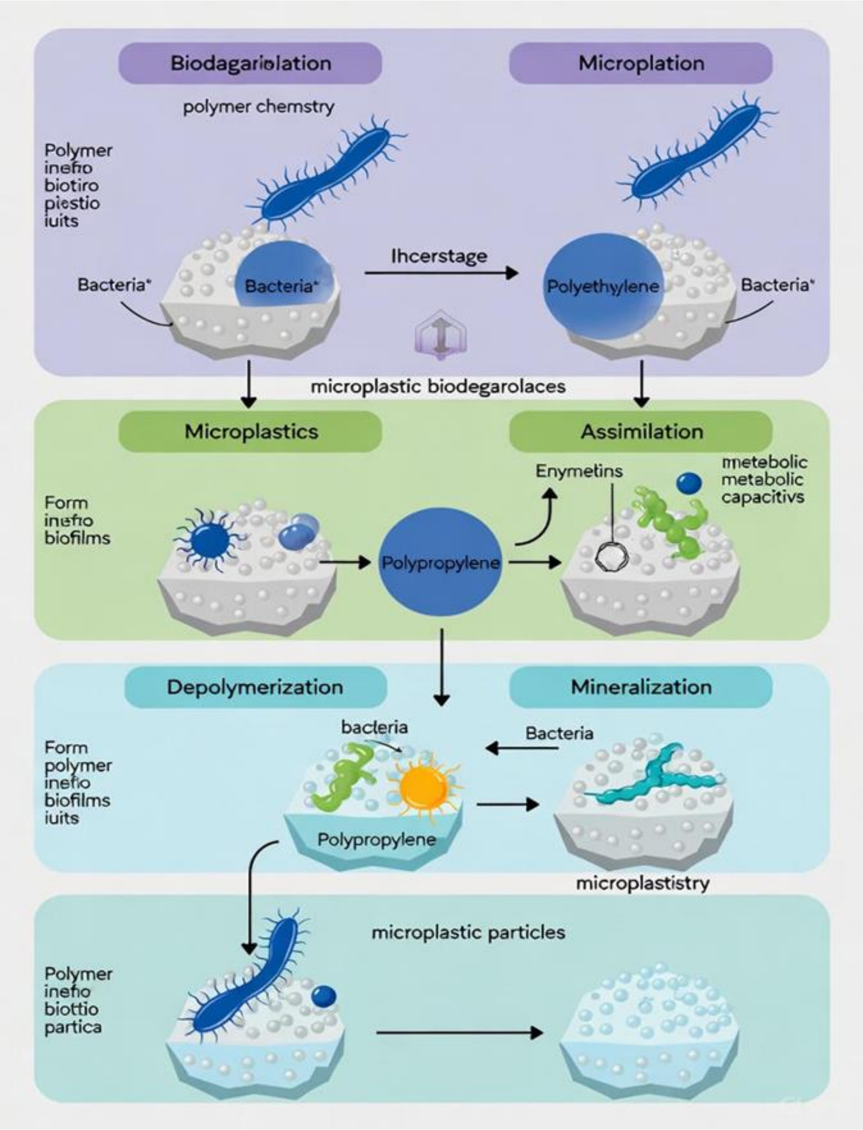

Figure 1. Schematic of the stages of microplastic biodegradation by microorganisms (biodeterioration, depolymerization, assimilation, and mineralization).

environmental sustainability but also offer potential for application in treatment systems (28).

Bacteria effective in microplastic biodegradation

Numerous studies show a wide diversity of bacteria effective in microplastic biodegradation, which have been primarily isolated from contaminated environments such as landfills, wastewater, and marine sediments. These bacteria degrade polymer structures by using specific metabolic pathways and enzymes, and often use degradation products as a carbon source (29). Reviews emphasize genera such as Bacillus, Pseudomonas, and Rhodococcus, which is important in degrading polymers such as polyethylene (PE) and polypropylene (PP) due to their high metabolic diversity and environmental adaptability. Furthermore, these bacteria often enhance enzymatic contact and improve process efficiency through biofilm formation (28).

The genus Pseudomonas is considered one of the most prominent agents in microplastic biodegradation due to its ability to produce oxidative enzymes and adapt to various conditions. Species such as Pseudomonas putida are capable of primary oxidation of polymer chains and reducing plastic weight. The genus Bacillus also induces significant structural changes in polyethylene polymers through the secretion of stable extracellular enzymes, and species such as Bacillus cereus have been reported as effective in case studies (30). Rhodococcus, particularly Rhodococcus ruber, is active in hydrocarbon-rich environments and uses oxidative pathways to break down hydrophobic structures (31).

Among specialized bacteria, Ideonella sakaiensis is recognized as a prominent species in the degradation of polyethylene terephthalate (PET), as it produces PETase and MHETase enzymes to convert the polymer into absorbable monomers. This bacterium represents an example of the high potential of microorganisms in practical applications, and when combined with other strains such as Acinetobacter and Streptomyces, it can enhance the efficiency of biological processes. Nevertheless, challenges such as slow degradation rates under real-world conditions require further research to optimize these strains (32, 33). Although PETase and MHETase show remarkable activity in vitro, the strength of evidence for their efficiency under environmental conditions (e.g., low temperature, variable pH, presence of inhibitors) is still moderate. Most studies lack long-term field validation, and few have directly compared enzyme-driven degradation across multiple polymer types simultaneously.

Role of enzymes in the biodegradation process

Enzymes act as key biological catalysts in the microplastic biodegradation process, enabling the breakdown of resistant bonds in polymer structures by lowering the activation energy of chemical reactions. These protein molecules, often secreted by microorganisms such as bacteria and fungi, depend on the chemical nature of the polymer and can facilitate hydrolytic or oxidative processes (34). Studies show that enzymes involved in these processes, including hydrolases and oxidases, are essential in converting complex polymers into simpler, absorbable compounds, thereby enhancing environmental sustainability. Furthermore, recent advances in the identification and engineering of these enzymes have opened new horizons for practical applications in plastic waste management (35).

For polymers with ester bonds such as polyethylene terephthalate (PET), enzymes such as PETase and MHETase play a central role. PETase hydrolyzes the ester bonds, converting PET into intermediate compounds such as mono (2-hydroxyethyl) terephthalate (MHET), which is then broken down by MHETase into simpler monomers such as terephthalic acid and ethylene glycol. These monomers can enter the metabolic pathways of microbial cells and be used as a carbon source (36). This mechanism, particularly in strains such as Ideonella sakaiensis, showed high efficiency and potential for application in industrial processes (37).

For hydrocarbon polymers such as polyethylene (PE) and polypropylene (PP), which lack hydrolyzable functional groups, oxidative enzymes such as laccases, monooxygenases, and peroxidases are more important. These enzymes introduce polar groups (e.g., carbonyl or hydroxyl) onto the polymer chains, increasing hydrophilicity and paving the way for further degradation. Although the degradation rate is slower for these polymers, the role of these enzymes in initiating the biological process is undeniable. Also, studies are focused on improving their efficiency through protein engineering (30, 38).

Practical applications of bacterial microplastic degradation in wastewater treatment systems, as a novel and sustainable pollution management approach, have shown significant progress. Case studies on wastewater treatment plants (WWTPs) indicate that bacteria such as Pseudomonas and

Bacillus can be integrated into conventional activated sludge (CAS) processes and membrane bioreactors (MBRs), where biofilm formation on microplastic surfaces facilitates degradation (39, 40). For example, in a study on municipal treatment systems, the use of enriched microorganisms resulted in a 20-30% reduction under laboratory-controlled conditions, but real-world variability and methodological limitations were not addressed. It should be noted that such percentages are not directly comparable across studies due to differences in initial microplastic concentrations, polymer types, hydraulic retention times, and detection methods. A systematic comparison of these factors is currently missing in the literature. These applications not only enhance removal efficiency but also may reduce operational costs in theory, but scalability remains unvalidated outside laboratory settings (41).

In real-world environments such as contaminated soils, marine sediments, and aquatic ecosystems, case studies have reported practical successes of bacterial degradation. For example, in landfills and coastal sediments, strains of Rhodococcus and Ideonella sakaiensis have been able to degrade polymers such as PE and PET, with degradation rates reaching up to 15% under quasi-natural conditions, though the study lacked proper controls for abiotic degradation and environmental variability (27). A field study in polluted areas showed that inoculating local bacteria into the soil reduced the negative ecological effects of microplastics and improved biodiversity. These applications highlight challenges such as slow degradation rates at low temperatures or in the presence of other pollutants, but they confirm the real potential for environmental remediation (42).

Combining bacterial degradation with engineering technologies has opened new horizons for increasing process efficiency. In engineered bioreactors, the integration of genetically engineered bacteria with advanced processes such as MBRs has led to more effective degradation (43). Laboratory and pilot-scale case studies show that this combination can increase PET degradation rates by up to 50%, using recombinant enzymes and precise control of environmental conditions. These approaches not only enhance environmental sustainability but also enable biological recycling within the framework of a circular economy, and require further research for industrial scalability (25).

Challenges, limitations, and optimization strategies

One of the main challenges of biodegradable polymers is their slow biological degradation rate in natural environments. For example, polylactic acid (PLA), one of the most widely used bioplastics, degrades well under industrial composting conditions, but in soil, freshwater, or marine environments, its degradation rate is very slow and may take years. This limitation is mainly due to the high crystallinity, high molecular weight, and hydrophobicity of the polymer, limiting the access of microbial enzymes (44, 45). Furthermore, polyhydroxyalkanoates (PHAs) also face challenges such as high production costs and slow degradation rates under suboptimal conditions, leading to the formation of biodegradable microplastics and posing a threat to aquatic ecosystems (46).

To overcome these limitations, recent advances in genetic engineering and biotechnology have played a key role. Protein engineering of plastic-degrading enzymes such as PETase and cutinase has increased their catalytic efficiency and thermal stability, improving degradation rates (47). Additionally, the use of engineered microbial consortia and the addition of plant fibers to the PLA matrix accelerate hydrolysis and biological degradation rates (48). For PHAs, metabolic engineering of bacteria to produce copolymers with lower crystallinity enhances degradability in natural environments (49). These approaches not only optimize degradation rates but also enable biological recycling and the conversion of plastics into valuable products. Despite promising lab-scale results, there is no consensus on whether engineered strains can outcompete native microbial communities in open environments. Furthermore, the long-term ecological risks of releasing genetically modified bacteria for plastic degradation have not been adequately assessed.

Future perspectives and research pathways

Biodegradable polymers, as sustainable alternatives to fossil-based plastics, have a promising future in the circular economy. Recent advances in enzyme engineering such as PETase and MHETase, along with smart polymer design and nanocomposites, have enabled biological recycling and the conversion of plastics into valuable products. The global production capacity of bioplastics is projected to increase from approximately 2.4 million tons in 2024 to over 7 million tons by 2030, driven primarily by growing demand in packaging, agriculture, and automotive industries. Figure 1 shows the projected production of biodegradable plastics for 2030 based on production data from 2018. This expansion not only reduces dependence on fossil resources but also improves the mechanical and thermal performance of these polymers through a focus on smart materials and AI-driven design (50).

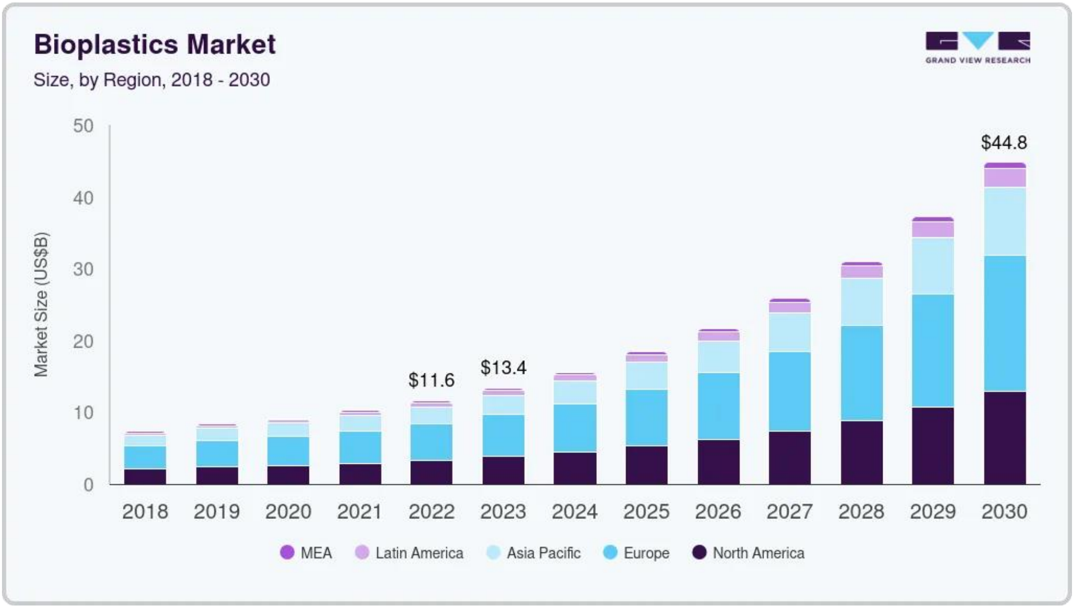

Figure 2. Projected global production of bioplastics

However, challenges such as high production costs, slow degradation rates in natural environments, and agricultural impacts on biodiversity underscore the need for further research. Proposed research directions include protein engineering to enhance the efficiency of degrading enzymes, the development of next-generation polymers with reduced crystallinity for faster degradation in marine and soil settings, and comprehensive life cycle assessments (LCA) to identify environmental hotspots (51). In addition, the use of second-generation feedstocks (e.g., agricultural waste) and integration with nanotechnology can improve sustainability and enable competition with conventional plastics (52).

Supportive policies will also be important in realizing this vision. These include standardized criteria for biodegradability, financial incentives for scalable production, and global frameworks such as the UN Plastic Treaty. Future research should prioritize scalability, socio-economic impact assessments, and the development of waste management infrastructure to position bioplastics as a viable solution for reducing plastic pollution (53, 54). Such approaches can contribute to achieving sustainable development goals and strengthening the circular plastic economy.

Conclusion

Microplastic pollution is a major environmental challenge of the current century, with extensive impacts on ecosystems, food chains, and human health. However, most evidence is laboratory-based, and claims of effectiveness require validation under real-world conditions. The findings indicate that enzymatic mechanisms, including hydrolysis and oxidation mediated by strains such as Pseudomonas, Bacillus, Rhodococcus, and Ideonella sakaiensis, hold significant potential for converting resistant polymers into simpler and less hazardous compounds. Practical applications of this approach in wastewater treatment systems, soil remediation, and sediment remediation, along with its advantages such as low energy consumption and compatibility with the circular economy, position it as a more sustainable alternative to physicochemical methods.

However, challenges such as slow degradation rates in natural environments—particularly for hydrocarbon polymers and bioplastics like PLA and PHA—remain obstacles to the widespread adoption of this technology. Recent advances in genetic engineering, protein engineering of enzymes (e.g., PETase and cutinase), and the use of microbial consortia have provided promising strategies to overcome these limitations.

Effective management of plastic pollution ultimately requires integrating fundamental research with supportive policies. Such an approach could transform bacterial biodegradation into a practical, globally applicable solution for reducing the environmental burden of plastics. This approach supports biodiversity, public health, and the circular economy.

A limitation of this review itself is that the majority of included studies were conducted under controlled laboratory conditions, which may not fully represent the complexity of natural ecosystems. Therefore, the conclusions should be interpreted with caution regarding real-world applicability.

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