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Microbial Biodegradation of Plastics and Microplastics: Enzymatic Mechanisms, Biotechnological Applications, and Ecotoxicological Perspectives

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ABSTRACT

The global rise in plastic production has resulted in extensive environmental accumulation and fragmentation into microplastics and nanoplastics. These persistent particles are now found in aquatic, terrestrial, and atmospheric ecosystems, posing ecotoxicological risks by transporting toxic chemicals, disrupting microbial communities, and entering the food chain, with potential human health impacts. Biodegradation by microorganisms has therefore gained attention as a sustainable remediation strategy.

This review examines the role of microorganisms in degrading plastic and microplastics, focusing on enzymatic mechanisms, biotechnological applications, and associated risks. Bacteria such as *Ideonella sakaiensis*, *Pseudomonas, Bacillus*, and *Rhodococcus* exhibit strong degradative abilities via PETase, MHETase, cutinases, and oxidases, often enhanced by biofilm formation. Fungi, including *Aspergillus* and *Penicillium*, as well as microalgae, contribute through the production of extracellular enzymes and synergistic interactions. Environmental conditions—such as temperature, pH, salinity, and oxygen levels—directly influence microbial activity and enzyme performance. Biotechnological approaches have improved degradation efficiency through microbial consortia, genetic engineering, and omics-based discovery of novel enzymes. Laboratory-scale applications, including bioreactors and nanoparticle-assisted systems, have achieved higher degradation rates compared to single strains. However, major limitations persist, including microbial stability in natural environments, scalability, and the toxicity of degradation intermediates such as terephthalate and ethylene glycol.

Overall, microbial biodegradation offers a promising alternative to conventional treatments but requires careful evaluation of ecological safety and economic feasibility. This review emphasizes the importance of interdisciplinary strategies combining microbiology, biotechnology, and environmental toxicology to advance plastic biodegradation and support sustainable waste management.

Plastiklerin ve Mikroplastiklerin Mikrobiyal Biyodegredasyonu: Enzimatik Mekanizmalar, Biyoteknolojik Uygulamalar ve Ekotoksikolojik Perspektifler

ÖZET

Plastik üretimindeki küresel artış, mikroplastik ve nanoplastiklerin çevresel olarak yoğun bir şekilde birikmesine ve parçalanmasına yol açmıştır. Bu kalıcı parçacıklar artık sucul, karasal ve atmosferik ekosistemlerde bulunmakta ve toksik kimyasalları taşıyarak, mikrobiyal toplulukları bozarak ve besin zincirine girerek ekotoksikolojik riskler oluşturmakta ve potansiyel insan sağlığı etkilerine neden olmaktadır. Bu nedenle, mikroorganizmalar tarafından biyolojik olarak parçalanma, sürdürülebilir bir iyileştirme stratejisi olarak dikkat çekmektedir.

Bu derleme, mikroorganizmaların plastik ve mikroplastiklerin parçalanmasındaki rolünü inceleyerek enzimatik mekanizmalara, biyoteknolojik uygulamalara ve ilişkili risklere odaklanmaktadır. *Ideonella sakaiensis, Pseudomonas, Bacillus* ve *Rhodococcus* gibi bakteriler, genellikle biyofilm oluşumuyla güçlendirilen PETaz, MHETaz, kütinazlar ve oksidazlar aracılığıyla güçlü parçalanma yetenekleri sergilemektedir. *Aspergillus* ve *Penicillium* dahil olmak üzere mantarlar ve mikroalgler, hücre dışı enzimlerin üretimi ve sinerjik etkileşimler yoluyla katkıda bulunmaktadır. Sıcaklık, pH, tuzluluk ve oksijen seviyeleri gibi çevresel koşullar, mikrobiyal aktiviteyi ve enzim performansını doğrudan etkilemektedir. Biyoteknolojik yaklaşımlar, mikrobiyal konsorsiyumlar, genetik mühendisliği ve omik tabanlı yeni enzim keşfi yoluyla bozunma verimliliğini artırmaktadır. Biyoreaktörler ve nanopartikül destekli sistemler de dahil olmak üzere laboratuvar ölçekli uygulamalar, tek suşlara kıyasla daha yüksek bozunma oranlarına ulaşmaktadır. Ancak, doğal ortamlarda mikrobiyal stabilite, ölçeklenebilirlik ve tereftalat ve etilen glikol gibi bozunma ara maddelerinin toksisitesi gibi önemli sınırlamalar devam etmektedir.

Genel olarak, mikrobiyal biyolojik bozunma, geleneksel işlemlere umut verici bir alternatif sunmakla birlikte, ekolojik güvenlik ve ekonomik fizibilite açısından dikkatli bir değerlendirme gerektirmektedir. Bu derleme, plastik biyolojik bozunmasını ilerletmek ve sürdürülebilir atık yönetimini desteklemek için mikrobiyoloji, biyoteknoloji ve çevresel toksikolojiyi birleştiren disiplinlerarası stratejilerin önemini vurgulamaktadır.

1. INTRODUCTION

The rapid increase in plastic production over the last century has led to the accumulation of these materials in nature, creating significant global environmental problems. The poorly biodegradable nature of plastics leads to their breakdown into microplastics (<5 mm) and nanoplastics through physical and chemical processes. These small particles are widely detected in aquatic, terrestrial, and even atmospheric ecosystems. The environmental circulation of microplastics not only disrupts ecosystem integrity but also poses a potential risk to human health through the food chain [1,2]. Studies show that microplastics create multifaceted ecotoxicological impacts due to the adsorption and transport of toxic chemicals on their surfaces, the disruption of the physiological processes of aquatic organisms, alteration of the soil microbiota, and the risk of inhalation exposure [3].

The metabolic diversity and adaptability of microorganisms are central to the search for biotechnology-based solutions to this global problem. Bacteria and fungi, which can form biofilms on plastic surfaces, degrade polymer chains and utilize them as carbon sources, are considered important biological tools for reducing plastic pollution. The ability of common plastics, such as polyethylene terephthalate (PET), to be degraded by microbial enzymes (PETase) demonstrates that biodegradation is a feasible and applicable solution for plastics and microplastics [4,5]. The purpose of this review is to examine the role of microorganisms in the removal of plastic and microplastic pollution from the perspective of environmental microbiology and biotechnology, discuss enzymatic degradation mechanisms, summarize current biotechnological applications, and shed light on the ecotoxicological consequences of these approaches.

1.1. Sources and Ecotoxicological Effects of Plastic and Microplastic Pollution

Plastics are composed of common polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), and their environmental accumulation has increased with the acceleration of industrial production. These materials have been widely observed in aquatic and terrestrial ecosystems as a result of packaging waste, textiles, and industrial activities [6]. Microplastics, on the other hand, are defined as plastic particles smaller than 5 mm and are generally classified into two main groups, primary (directly produced) and secondary (formed by the breakdown of larger plastics) [7].

From an ecotoxicological perspective, microplastics have been reported to bioaccumulate in aquatic ecosystems and accumulate throughout the trophic chain. Studies in the Sea of Marmara confirmed the presence of microplastics in mussel and fish tissues, demonstrating that this poses a risk of transmission to human health through the food chain [8]. In soil ecosystems, microplastics have been shown to alter microbial community structure and negatively impact soil health [9]. Furthermore, increased use of plastic mulch in agricultural areas in Turkey has been associated with increased microplastic accumulation in soil [10]. From a human health perspective, microplastics have been reported to enter the body through food, drinking water, and respiration, and can cause effects such as oxidative stress, inflammation, and cellular toxicity [11].

1.2. The Role of Microorganisms in Plastic Degradation

The long-term persistence of plastics in nature has necessitated biodegradation, and microorganisms isolated from various ecosystems have played a critical role in this process. Thanks to their diverse enzyme systems and biofilm-forming abilities, microorganisms degrade polymers into simpler molecules and have demonstrated the potential to reduce environmental accumulation [12].

Among prokaryotic microorganisms, bacteria have been the most intensively studied group in plastic degradation. *Ideonella sakaiensis*, through its PETase and MHETase enzymes, converted PET polymers into their monomers and facilitated biodegradation [13]. *Pseudomonas putida* and *Pseudomonas stutzeri* accelerated oxidative degradation by forming biofilms on polymers such as PE and PS [14]. *Bacillus subtilis, Bacillus cereus*, and *Bacillus amyloliquefaciens* secreted enzymes on LDPE and HDPE surfaces, resulting in the cleavage of polymer chains [15]. *Rhodococcus ruber* contributed to the surface modification of plastics by long-term adhesion and biofilm formation on PE [15]. *Alcanivorax borkumensis*, isolated from marine ecosystems, supported the degradation process on PE and PP by adhesion and biofilm formation [16]. Furthermore, *Stenotrophomonas* sp. and *Micrococcus* sp. have been identified as playing an active role in the degradation of LDPE and PVC [17].

Among eukaryotic microorganisms, fungi have made significant contributions to plastic degradation. *Aspergillus niger, Aspergillus tubingensis*, and *Penicillium chrysogenum* produced esterase and lipase enzymes on LDPE and PET films, causing surface erosion [18]. Species such as *Fusarium solani* and *Cladosporium cladosporioides* have also been reported to be effective in polymer degradation. Among marine algae, *Chlorella vulgaris, Scenedesmus obliquus*, and *Navicula* have been observed to colonize plastic surfaces, support the growth of microbial consortia, and facilitate biodegradation [19].

Environmental conditions significantly influenced microbial activity in plastic degradation. Temperature directly affected enzyme activity and biofilm formation; PETase from *I. sakaiensis* showed maximum activity between 30–37°C [20]. pH changes affected enzyme stability and activity. Degradation rates were found to be higher at neutral pH. Salinity, particularly in marine bacteria, increased adhesion and biofilm formation on the plastic surface, while anaerobic bacteria degraded more slowly in oxygen-limited environments. In the soil environment, moisture and organic matter content were decisive for microbial growth and enzyme secretion.

Generally, bacteria emerged as the primary actors in plastic degradation, while fungi and algae played supporting roles. These findings, when evaluated from the perspective of environmental microbiology and biotechnology, demonstrate the great potential of biodegradation processes for both reducing ecotoxicological risks and developing sustainable waste management strategies.

1.3. Enzymes and Biotechnological Approaches in Plastic Degradation

Microorganisms have been central to enzymatic and biotechnological mechanisms in the biological remediation of plastic and microplastic pollution. Bacteria degrade PET polymers into monomers with PETase and MHETase, and oxidative and hydrolytic degradation of PE surfaces is achieved through cutinase and cutinase-like enzymes (*Thermobifida fusca, Bacillus,* and *Streptomyces species*) [13,21]. Studies have been conducted on the ability of these enzymes to bind to the polymer chain and break ester and carbon-carbon bonds. However, limitations such as thermostability, pH tolerance, and substrate access have limited their effectiveness in natural systems [22]. Oxidative enzymes such as laccase and peroxidase play a critical role in the oxidative degradation of aromatic polymers. Some *Rhodococcus, Pseudomonas*, and *Alcanivorax* species formed biofilms, increasing enzyme attachment to the substrate and biocatalytic activity [23]. Eukaryotic microorganisms, fungi, and algae, with their extracellular lipase, esterase, and laccase activities, caused surface degradation of PE, LDPE, and PVC polymers, supporting degradation through synergistic effects [18,19]. *Aspergillus niger, Penicillium chrysogenum, Fusarium solani*, and microalgae increased the effectiveness of microorganism consortia through surface colonization.

Biotechnological approaches have been developed to optimize these natural capabilities. Consortiums formed between microorganisms increased degradation rates through synergistic enzyme production and metabolic interactions. Genetic engineering and synthetic biology studies have transferred PETase, MHETase, and cutinase genes to heterologous systems, enhancing the enzymes' thermostability and substrate binding capacity [24]. Using omic technologies (metagenomics, transcriptomics, and proteomics), the genetic potential of polymer-degrading microorganism communities in natural ecosystems has been analyzed, and new PETase, MHETase, and cutinase-like enzyme candidates have been identified [20]. Metagenomic data have shown that hydrolase and oxidase gene clusters, particularly in *Pseudomonas, Bacillus*, and *Rhodococcus* species, have high expression potential. Transcriptomic analyses have revealed that enzyme expression can be induced by polymer contact and that synergistic genes are co-regulated. Proteomic studies confirmed the intensity and kinetics of extracellular enzyme secretion, and laccase and peroxidase activities were observed to accelerate polymer oxidation.

In bioreactor-scale applications, microorganism consortia generated from these isolates were tested in co-cultures against LDPE and PET substrates, and the consortia achieved 30–50% higher polymer degradation compared to single-species use. In nanoparticle-assisted systems, functionalized metal oxide nanoparticles on the polymer surface enhanced microorganism adhesion and optimized enzyme-substrate interactions [25]. This approach enabled both increased enzyme activity and the formation of biofilm layers, significantly increasing the kinetic rate of microplastic biodegradation at the laboratory scale.

1.4. Ecotoxicological Risks and Limitations

Biological degradation has offered a sustainable approach to reducing plastic and microplastic pollution. The enzymatic systems of microorganisms break down polymer chains into monomers and oligomers, resulting in lower energy consumption and environmental side effects compared to traditional physical and chemical methods [20,22]. However, micro- and nanoplastics and monomer intermediates generated during plastic degradation have bioaccumulated in aquatic and soil ecosystems, causing oxidative stress, cellular damage, and endocrine-disrupting effects in various living organisms [26]. Terephthalate, ethylene glycol, and oligomers, particularly those released during PET and PE degradation, have toxic effects on benthic and pelagic organisms. The long-term accumulation of some metabolites has negatively impacted ecosystem functions. Microbial and enzyme-based biotechnological approaches have achieved high degradation efficiency at the laboratory scale, but several limitations have been observed in field applications. The environmental stability of microorganisms is affected by factors such as temperature, pH, substrate access, nutrient sources, and competitive microflora [27]. Scalability and cost have been significant constraints, particularly in enzyme purification, consortia production, and the production of nanoparticle-supported systems. While the metal oxide and polymeric supports used in nanoparticle-supported biofilm systems provide high surface area, they have increased environmental toxicity risks and necessitated environmental safety assessments.

Although microorganisms modified through genetic engineering and synthetic biology have increased enzyme stability and substrate specificity, direct transfer of such applications to natural ecosystems carries potential risks in terms of horizontal gene transfer and microbial ecosystem balance. Biological degradation has provided significant advantages in terms of reducing plastic load in natural ecosystems, but factors such as the toxicity of the resulting intermediate products, environmental limitations of microorganisms and enzymes, and field-scale scalability and economic sustainability have necessitated careful planning and optimization of applications.

1.5. Potential Impacts of Microplastics on Human Health

The potential effects of microplastics and nanoplastics on human health have received increasing attention in environmental sciences and medicine in recent years. These particles are not only limited to environmental exposure, but can also be absorbed into the human body through food, water, and air, triggering biological responses at the cellular level [28]. It has been reported that microplastics can create mechanical stress and inflammatory responses on the mucosal barrier in the gastrointestinal tract, and that when passed into the circulatory system, they can cause intracellular oxidative stress, gene expression changes, and potential endocrine disrupting effects [28,29]. Ragusa et al. [30] detected microplastic particles in the human placenta for the first time, showing that the fetoplacental barrier may be permeable to these particles and that there is a risk of exposure even in the prenatal period. Similarly, Xu et al. [31] reported the presence of microplastics in human cervical cancer patients using Raman spectroscopy, suggesting that the circulatory system may also be a potential exposure pathway.

In this context, microscopic and spectroscopic techniques such as FTIR and Raman spectroscopy are widely used for the detection of microplastics in both environmental and human biological samples and provide high sensitivity. These techniques allow for the identification of polymer types, particle sizes, and surface properties, playing a critical role in monitoring exposure pathways and risk assessment [32]. Studies conducted in Türkiye have also revealed the accumulation of microplastics in species such as fish, mussels, and shrimp, particularly those in the marine food chain, and reported that this could constitute a potential exposure pathway through human diet [33]. These findings demonstrate that microplastics are not only an environmental pollutant but also a rising risk factor threatening public health.

2. CONCLUSION

This review examines the role of microorganisms in combating plastic and microplastic pollution, their enzymatic mechanisms, and biotechnological approaches from a holistic perspective. The data presented demonstrate that biological degradation offers a more sustainable alternative to traditional physical and chemical methods, but significant challenges remain in terms of field-scale applications and potential environmental risks. In addition to these environmental concerns, recent evidence on the detection of microplastics in human tissues underscores that this issue is not confined to ecosystems but also represents an emerging public health risk [30,31].

The review's most significant contribution is its emphasis on the high efficiency of *I. sakaiensis* in degrading PET into its monomers with its PETase and MHETase enzymes, presenting this finding in line with the general literature. This supports the work of researchers such as Yoshida et al. [13] and represents a fundamental milestone for biotechnological solutions. However, whether these enzymes exhibit optimal activity under natural environmental conditions remains a matter of debate. The optimal temperature ranges cited by Danso et al. [20] raise questions about the effectiveness of these approaches in colder or warmer ecosystems. The biofilm-forming abilities and oxidative degradation mechanisms of microorganisms such as *P. putida* and *A. borkumensis* have been evaluated as prerequisites for the degradation of more resilient polymers, particularly PE and PP. These findings suggest that the synergistic effects of microorganism consortia, compared to the use of individual species, can provide higher degradation rates in the removal of complex waste streams. This approach parallels the successes of researchers such as Shah et al. [17] in the degradation of LDPE and PVC. Such advances in microbial degradation are particularly relevant when considering that microplastics have been documented to accumulate in food webs and even in human biological samples, as shown by Ragusa et al. [30] and Xu et al. [31], highlighting an urgent need to mitigate human exposure through improved remediation strategies.

The review also highlights the role of genetic engineering and omics technologies in optimizing biological degradation processes. In particular, the transfer of PETase genes to heterologous systems and the enhancement of the enzyme's thermostability are consistent with studies such as Tokiwa et al. [27]. While these advances are promising, practical challenges remain, such as the cost and complexity of translating laboratory-scale successes into large-scale field projects. Finally, a key element of this review is its comprehensive discussion of the potential benefits of biodegradation, as well as the resulting ecotoxicological risks. The potential toxicity of micro- and nanoplastics, as well as intermediates such as terephthalate and ethylene glycol, highlights the need for careful consideration of the environmental impacts of the end products of the degradation process. Researchers such as Vo and Pham [26] and Pathak [25] have noted that these intermediates can cause oxidative stress and cellular damage in aquatic and soil ecosystems. This suggests that future biodegradation strategies should aim not only to reduce polymer mass but also to minimize the formation of harmful intermediates. Equally, integrating detection methods such as FTIR and Raman spectroscopy into environmental and biological monitoring can help track both the efficiency of degradation processes and the potential human health risks posed by residual particles [32]. Such approaches will also strengthen risk assessment frameworks by linking remediation performance directly with exposure pathways in humans [33].

This review demonstrates the potential of biotechnological solutions while highlighting the importance of an interdisciplinary approach to ensuring their environmental safety and sustainability. It also provides a guiding framework for researchers and developers in the fields of microbiology, environmental toxicology, and biotechnology. Future studies can fill the gaps in this area by conducting more in-depth research on topics such as optimization for field applications, environmental release of toxic intermediates, and the effects of environmental factors on degradation mechanisms. Moreover, future research should explicitly address how microbial and enzymatic degradation strategies can reduce the burden of microplastics in food, water, and air, thereby contributing not only to ecosystem restoration but also to the protection of human health.

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This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical, and quotation rules of ETOXEC in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Environmental Toxicology and Ecology and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Environmental Toxicology and Ecology.

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