ENVIRONMENTAL SCIENCE ARCHIVES
ISSN: 2583-5092
Volume III Issue 2 (TPC2), 2024

www.envsciarch.com

Received: 2024/07/26
Accepted: 2024/09/02
Published: 2024/09/10

REVIEW

OPEN ACCESS

Bioremediation of Microplastics: A Promising Solution for Environmental Pollution

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Abstract
Microplastics have become a pervasive environmental pollutant, posing significant risks to ecosystems and human health. Conventional methods for mitigating microplastic pollution, such as mechanical filtration and chemical treatments, often have limitations in terms of efficiency, cost-effectiveness, and environmental sustainability. Bioremediation, leveraging natural microbial and enzymatic processes, presents a promising alternative to address this complex environmental challenge. As a biological engineered process utilizing microorganisms and enzymes, bioremediation presents a promising approach to mitigate microplastic contamination. This review explores the current understanding of bioremediation techniques for microplastics, including microbial degradation, enzymatic breakdown, and biofilm-mediated processes. Besides potential applications, challenges, and future directions of bioremediation in addressing microplastic pollution, emphasize the need for sustainable and effective strategies.

Keywords: Microplastics; Bioremediation; Pollution; Bioaccumulation

Introduction

Microplastics, defined as plastic particles smaller than 5 mm in size, have proliferated across terrestrial, aquatic, and atmospheric environments due to extensive plastic production and improper waste management practices (Singh, 2022; Tayal et al., 2023). The vast majority of monomers used in manufacturing of plastics, such as ethylene and propylene, are derived from fossil hydrocarbons. None of the commonly used plastics are biodegradable. As a result, they accumulate, rather than decompose, in landfills or the natural environment (Gupta et al., 2022; Geyer et al., 2017). Plastic waste entering aquatic environments results from various human activities, such as the discharge of industrial waste, marine fisheries, and the deposition of plastic fibres in the atmosphere (Barnes et al., 2009). These persistent pollutants pose ecological threats through ingestion by marine and terrestrial organisms, bioaccumulation in food chains, and potential health impacts on humans (Cole et al., 2017). Conventional methods for micro plastic removal, such as filtration and physical extraction, have limitations in efficiency and sustainability. Bioremediation, harnessing the natural degradation capabilities of microorganisms and enzymes, offers a promising alternative to mitigate micro plastic pollution effectively (Kaur et al., 2023; Raghupathi and Ramakrishna 2019).

Types and Sources of Microplastics

Microplastics originating from various sources have been classified in to two categories. *Primary microplastics:* Intentionally manufactured small plastic particles, including microbeads used in cosmetics and industrial abrasives. *Secondary microplastics:* Result from the breakdown of larger plastic items, such as bottles, packaging materials, and synthetic textiles.

These plastics enter the environment through multiple pathways, including urban runoff, wastewater discharge, and atmospheric deposition, contributing to their widespread distribution in aquatic and terrestrial ecosystems. Microplastics are easily ingested by low trophic level organisms, leading to biomagnification in higher trophic level organisms. Human health issues may be influenced by the accumulation of microplastics in the food chain. Chemical additives used in plastic manufacturing (Liu et al., 2022) as well as pollutants and persistent organic metals adsorbed on the surface of microplastics, may also be ingested by marine organisms during feeding, increasing the potential for toxicity (Liu and You 2023). The ingestion of microplastics and the potential increase in the concentration of harmful chemicals in species intended for human consumption raise concerns about human health as well (Zettler et al., 2013).

Bioremediation Techniques

In the context of microplastics, bioremediation involves the use of organisms, such as bacteria, algae, worms, and other living beings, to degrade or collect microplastics from the environment. Microbes produce enzymes that catalyze the cleavage of polymer bonds, converting complex plastics into simpler compounds that can be assimilated by microbial communities. Studies have identified microbial strains capable of degrading a variety of plastics under laboratory conditions, highlighting their potential in bioremediation strategies. Recent research by Zhang et al. (2020) demonstrated the Biodegradation and mineralization of polystyrene by plastic-eating mealworms *Larvae of Tenebrio molitor*. Some bacteria, like *Ideonella sakaiensis*, have been found to have the ability to break down polyethylene terephthalate (PET), a commonly used material in plastic bottle manufacturing (Sevilla et al., 2023). Different bacterial species are also being researched to assess their capability to degrade numerous varieties of microplastics. Certain species of algae show capability in degrading microplastics through enzymatic mechanisms or with the aid of absorbing microplastic particles. Various types of fungi, such as *Aspergillus tubingensis* and *Penicillium spp.* (Liu and You 2023) have also been studied for their ability to degrade microplastics. They use specific enzymes to break the chemical bonds in microplastics. Some early studies suggest that earthworms may also play a role in recycling microplastics by altering their chemical structure through digestion and biochemical processes in their intestines (Khaldoon et al., 2022). Microrganisms have the capabilities to degrade microplastics through a number of mechanisms although this process is still in the experimental stages of ongoing research.

Biofiltration and Biofilm Formation

Various organisms, including filter feeders and biofilm-forming bacteria, can accumulate microplastics on their surfaces or within biofilms. Bioaccumulation involves the uptake and concentration of microplastics by organisms such as mussels and plankton, offering potential applications in targeted clean-up efforts and wastewater treatment processes. Biofilms, composed of microbial communities adhering to surfaces, can enhance the retention and degradation of microplastics in aquatic environments, demonstrating the versatility of biological systems in managing plastic pollution. Biological filtration involves using microorganisms in the filtration process to collect microplastics from water. This method can be effective in removing microplastics from wastewater. Animal Feeding on Microplastics: Some marine creatures, such as small crustaceans, have been found capable of consuming microplastics (Wang et al., 2021). In some cases, this can help reduce the amount of microplastics in aquatic environments. Artificial Photosynthesis (Chauhan *et al* 2023) technology combines bacteria capable of degrading plastic with an artificial photosynthesis system that produces oxygen and energy, contributing to the bioremediation process.

Biofilm degradation of microplastics is another ecologically friendly approach. It has been reported that the degradation of microplastics by biofilm is significantly influenced by environmental factors (Sun et al., 2023). Conditions such as temperature, pH, and ultraviolet light must be within an optimal range for the degradation process. Biofilm degrades microplastic clusters, initially altering hydrophobicity and molecular weight as well as size through physical and chemical means. Biofilm degradation of microplastics has particularly few applications due to its low performance; however, enrichment of microplastics in freshwater environments and wastewater treatment plants is currently the most effective approach for treating microplastics with biofilms (Sun et al 2023).

Case Studies and Experimental Evidence

Experimental studies and field trials have evaluated the efficacy of bioremediation techniques in reducing microplastic concentrations in different environmental contexts. For instance, research conducted by Liu et al. (2019) investigated the use of bacterial consortia in freshwater systems, demonstrating significant reductions in microplastic abundance over time. These studies underscore the potential scalability and applicability of bioremediation strategies in mitigating microplastic pollution in natural habitats. Enzymes produced by microbes act mainly on the high-molecular-weight polymers of polyethylene terephthalate (PET) and ester-based polyurethane

(PUR). Unfortunately, the best PUR- and PET-active enzymes and microorganisms known still have moderate turnover rates (Danso et al., 2019).

Bioremediation of microplastics involves the use of bacteria capable of degrading plastic. Bacteria such as *Ideonella sakaiensis* have been proven to possess the ability to break down PET plastic, commonly used in plastic bottles. Poly(ethylene terephthalate) (PET) is one of the most abundantly produced synthetic polymers and is accumulating in the environment at an alarming rate as discarded packaging and textiles. The properties that make PET so useful also endow it with an alarming resistance to biodegradation, likely lasting centuries in the environment (Austin et al., 2018). Bacteria *I. sakaiensis* produce enzymes that can break the plastic bonds, transforming it into safer compounds. *I. sakaiensis* has demonstrated a unique ability to degrade PET plastic, which is widely used in plastic bottles, packaging material. The degradation process of PET plastic by *I. sakaiensis* occurs through two main enzymes produced by these bacteria. The first enzyme is PETase, which breaks the ester bonds within PET plastic. Two intermediate products are produced following the breakage of bonds which can be further be degraded by the second enzyme, MHETase. The ultimate products of this process are simpler compounds which can further be metabolized by bacteria, such as terephthalic acid and ethylene glycol (Wang et al., 2021). The discovery of *Ideonella sakaiensis* has generated a hope that bioremediation technology can be greatly helpful in solving microplastic pollution, especially PET, and offer a more sustainable solution to reduce the environmental impact of the same. Some studies have also explored the use of organisms other than bacteria such as worms, which can consume microplastics in the soil. Biological filtration systems are also utilized to extract microplastics from water bodies.

Challenges and Limitations

Despite its potential benefits, bioremediation faces challenges that must be addressed to optimize its effectiveness and practical application. Variability in environmental conditions, such as temperature and nutrient availability, can influence microbial activity and degrade biodegradation rates. Moreover, the scalability of bioremediation processes from laboratory settings to real-world environments requires careful consideration of logistical and economic factors.

Future Directions and Recommendations

Future research should focus on enhancing the efficiency and reliability of bioremediation techniques for diverse types of microplastics and environmental conditions. Further research directions for bioremediation of microplastics include:

Microbial diversity and functionality

Exploring novel plastic-degrading microorganisms and enzymes with enhanced degradation capabilities.

Environmental fate and transport

Understanding the long-term effects of bioremediation on microplastic persistence, bioavailability, and ecological interactions.

Technological innovations

Developing bioreactor systems, bio-based materials, and sustainable biocatalysts for efficient microplastic removal.

Collaborative efforts among researchers, industry stakeholders, policymakers, and the public are essential to advance bioremediation technologies and integrate them into comprehensive strategies for microplastic pollution management. Furthermore, the development of standardized protocols for monitoring microplastic levels in ecosystems will facilitate the assessment of bioremediation efficacy and environmental impact over time.

Conclusion

Bioremediation represents a promising and sustainable approach to mitigate the environmental impact of microplastic pollution, leveraging biological processes to degrade or sequester plastics in natural ecosystems. By harnessing the enzymatic capabilities of microorganisms and the bioaccumulative properties of certain organisms, bioremediation offers innovative solutions to reduce microplastic concentrations and safeguard aquatic and terrestrial environments. Continued research and technological advancements are crucial to optimize bioremediation strategies and implement them effectively on a global scale, thereby promoting environmental sustainability and resilience against plastic pollution.

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Author Contributions

AS and JS conceived the concept, wrote and approved the manuscript.

Acknowledgements

Not applicable.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Competing interest
The authors declare no competing interests.

Ethics approval
Not applicable.

Citation: Singh A and Singh J (2024) Bioremediation of Microplastics: A Promising Solution for Environmental Pollution. Environmental Science Archives 3(2): 71-75.