Intersect, Vol 18, No. 1 (2024)

Microbial Consortia-Mediated Degradation of Recalcitrant Plastics

Rochan BM, Nisha Jangir
De Paul International School

Abstract

The persistent accumulation of recalcitrant plastics in the environment poses a significant challenge due to their resistance to natural degradation processes. Traditional waste management strategies have proven inadequate, necessitating innovative solutions. This review explores the potential of microbial consortia in mediating the degradation of recalcitrant plastics. By leveraging the synergistic interactions between diverse microbial species, these consortia can effectively break down complex plastic polymers that are otherwise resistant to degradation. We examine how microbial consortia enhance plastic biodegradation, including enzymatic pathways and metabolic cooperation. Case studies highlighting successful applications and potential challenges in plastic degradation are presented. Finally, we outline future research directions and the implications of microbial consortia-mediated plastic degradation for environmental sustainability. This comprehensive review underscores the promise of microbial consortia as a viable and eco-friendly approach to mitigating plastic pollution.

I. Introduction

The first synthetic plastic, Bakelite, was created in 1907. However, it was not until World War II that synthetic plastics began to see widespread use beyond military applications (Geyer et al., 2017). Today, for instance, synthetic plastics such as polyethylene terephthalate (PET), polyethylene (PE), polyurethane (PUR), polystyrene (PS), polypropylene (PP), and polyvinyl chloride (PVC) are used in several industrial and household applications, with the biggest usages being in the packaging and construction industries (Mohanan et al., 2020; Shah et al., 2008).

However, managing and getting rid of plastic garbage has historically presented challenges. Merely 9% of the 8.3 billion metric tons of plastic created since the 1950s have been recycled, leaving 6.3 billion metric tons of garbage (Mohanan et al., 2020). Most plastic trash is disposed of in landfills, incinerators, or as litter, which contributes to the general contamination of the environment, especially in marine habitats, where it threatens wildlife through ingestion (B. Hu et al., 2020).

With plastic production growing exponentially, it is urgent to better understand how synthetic plastics affect the environment. Synthetic plastics that are either slowly biodegradable or non-biodegradable are called "recalcitrant plastics." They are composed of a wide range of molecules, from simple halogenated hydrocarbons to complex polymers. Because recalcitrant plastics are designed for their durability and resistance to degradation, they persist for decades or even centuries wherever they end up after disposal.

This persistence leads to several detrimental effects. Firstly, recalcitrant plastics contribute to habitat degradation and alteration. They accumulate on land, rivers, and oceans, affecting soil quality, waterways, and marine biodiversity. Marine animals often mistake plastic debris for food, leading to ingestion and entanglement, which can result in injury, suffocation, and death. This disrupts food webs and threatens species survival, impacting biodiversity and ecosystem stability (Meyer Cifuentes & Öztürk, 2021).

Secondly, the breakdown of recalcitrant plastics into smaller particles, known as microplastics, significantly impacts the environment. These particles can adsorb and transport harmful chemicals and pathogens, creating risks to marine organisms and humans as they enter the food chain (Krueger et al., 2015).

Thirdly, the production and disposal of recalcitrant plastics increase greenhouse gas emissions and energy consumption. From the extraction of raw materials to manufacturing and waste management, plastics generate carbon emissions and environmental pollutants, contributing to climate change and environmental degradation (Timmis, 2010).

II. The Importance of Biodegradation of Plastics

Biodegradation is the natural breakdown of organic substances by microorganisms, converting them into simpler compounds like carbon dioxide, water, and biomass. Microorganisms such as bacteria and fungi help break down natural and synthetic plastics (Gu et al., 2000; Shah et al., 2008). The degradation process begins with plastics being broken down into smaller components called monomers, which are then absorbed by these microorganisms (Shah et al., 2008).

The biodegradation process is vital for recycling nutrients in ecosystems, aiding in the decomposition of organic matter from plants, animals, and waste materials. By releasing essential nutrients back into the environment, biodegradation supports soil fertility and plant growth. It plays a crucial role in waste management by reducing the volume of organic waste and minimizing environmental pollution by identifying eco-friendly innovations and practices (Shah et al., 2008).

III. Microbial Consortia as a Biodegradation Approach

Plastic pollution has become one of the most pressing global environmental challenges, with synthetic polymers accumulating in ecosystems due to their resistance to natural degradation, or the degradation of plastics via microbes. In this process, microbes secrete extracellular enzymes that break down the complex polymer structure of plastics into simpler monomers, which are then utilized by the cells as a carbon and energy source. Diverse microbial species belonging to genera like Bacillus, Pseudomonas, Ideonella, and Streptomyces, were isolated from landfill sites, dumping grounds, and other plastic-contaminated environments and have been reported as efficient plastic degraders (Jaiswal et al., 2020; Krueger et al., 2015). The key enzymes involved in plastic biodegradation include cutinases, lipases, esterases, laccases, and depolymerases. These enzymes catalyze the hydrolysis and oxidation of the polymer backbone (Jaiswal et al., 2020; Krueger et al., 2015), allowing for the plastic to be partially degraded.

However, traditional approaches to biodegradation rely on single microbial strains, which exhibit limited efficiency, narrow substrate specificity, and inability to degrade complex plastics fully. For example, single strains such as *Ideonella sakaiensis* produce enzymes like PETase that partially degrade polyethylene terephthalate (PET) but often fail to metabolize intermediate products such as terephthalic acid, which persists in the environment (Yoshida et al., 2016).

In contrast, microbial consortia leverage the metabolic diversity of multiple microbial species to achieve complete plastic mineralization. This synergistic approach enables sequential and cooperative enzymatic pathways, where one species converts intermediates into forms that are further degraded by other members of the consortium (Kim et al., 2022). Recent studies demonstrate the remarkable potential of consortia to degrade highly recalcitrant plastics such as polyethylene (PE), with some combinations achieving up to 40% polymer weight loss in landfill conditions within 90 days (Li et al., 2021). Additionally, microbial consortia are inherently more robust, capable of functioning in diverse environmental conditions, including extreme temperatures, pH levels, and the presence of toxic compounds (Krueger et al., 2015). By integrating advanced engineering tools such as CRISPR and synthetic biology, researchers have further enhanced the efficiency and scalability of microbial consortia (Artham et al., 2022). Table 1 presents a detailed comparative analysis of microbial consortia versus single-strain approaches.

Parameter	Microbial Consortia	Single-strain Approach
Enzymatic Diversity	Utilizes multiple enzymes targeting diverse bonds (e.g., ester, C-C, and C-H bonds).	Limited to a single enzyme, often specific to one bond type (e.g., PETase for ester bonds).
Degradation Efficiency	Achieves faster and more complete degradation through metabolic cooperation.	Slow and incomplete degradation, often halting at intermediates.
Environmental Adaptability	Thrives in extreme or variable conditions (e.g., low temperatures, high salinity).	Requires optimized conditions (e.g., neutral pH, moderate temperature) for activity.
Application Scope	Effective for complex and mixed plastic waste streams.	Limited to specific and simple plastic substrates.
Engineering Potential	Easily enhanced via genetic engineering tools (e.g., CRISPR, gene knockouts, or overexpression systems).	Genetic modifications limited to the capabilities of a single strain.

Figure 1. Comparative Analysis Summary of Microbial Consortia vs. Single-Strain Approach (Sources include: Artham et al., 2022; Kim et al., 2022; Krueger et al., 2015; Li et al., 2021; Yoshida et al., 2016)

Thus, there are several advantages of using microbial consortia for improved plastic degradation:

1) Enhanced Degradation Efficiency: microorganisms can have complementary metabolic pathways, allowing them to break down complex substrates more effectively. One species may produce enzymes that another species can utilize, leading to more efficient degradation (Bhatia et al., 2018). Additionally, Multiple microorganisms working together can accelerate the rate of

degradation, which shortens the time needed to decompose organic materials.

2) Broader substrate range: Plastic materials are structurally diverse, with different polymers, additives, and contaminants present. A consortium with complementary catabolic capabilities can potentially handle this chemical complexity better than a single specialist organism. Microbes that break down various plastic components could be included in a consortium to accomplish more thorough mineralization (Bao et al., 2023; Dhali et al., 2024; Shilpa et al., 2022; Zheng et al., 2005).
3) Resilience to environmental changes: Plastic pollution can be found in various settings with different conditions, including freshwater, marine environments, soil, and so forth. More efficient than sensitive pure cultures would be consortiums that are suited to withstand variations in pH, temperature, salinity, nutrient levels, etc. Even if certain members are inhibited, the functional redundancy within a diverse consortium aid in maintaining plastic degradation (Bao et al., 2023; Dhali et al., 2024; Shilpa et al., 2022; C. Zhang et al., 2023; Zheng et al., 2005).
4) Interactions and Harmonious Functioning: The breakdown process can be optimized by a consortium's spatial arrangement and metabolic complementarity. Various members may contribute certain cofactors, enzymes, or detoxification processes. The overall conversion efficiency can be raised by cross-feeding intermediates (Bao et al., 2023; Dhali et al., 2024; Shilpa et al., 2022; C. Zhang et al., 2023; Zheng et al., 2005).

IV. Potential Societal Implications of Using Microbial Consortia for Degradation

While microbial consortia have demonstrated technical advantages in degrading recalcitrant plastics, their broader societal potential remains a critical area of exploration. Plastic pollution disproportionately affects underserved communities, where inadequate waste management infrastructure exacerbates health and environmental disparities. For example, rural areas in low-income countries manage only 10% of their plastic waste effectively, compared to urban centers in high-income countries where over 80% of waste is processed sustainably (Napper & Thompson, 2023).

Additionally, the accumulation of microplastics in drinking water systems has emerged as a public health crisis, with over 2 billion people worldwide exposed to unsafe water contaminated by plastic particles (National Academies of Sciences, 2022). Addressing these challenges requires integrating microbial consortia technologies into scalable and affordable waste management solutions that can operate under resource-limited conditions. These innovations would not only alleviate environmental burdens but also foster social equity by reducing health risks and creating localized economic opportunities.

Microbial consortia present transformative societal advantages as outlined in the following:

A. Influence on Waste Management Policies
   Microbial consortia can reshape waste management frameworks globally. Governments in low- and middle-income countries can deploy decentralized bioreactors powered by microbial consortia to process plastic waste at the community level. For instance, pilot projects in India have demonstrated the feasibility of using microbial consortia in village-scale bioreactors, reducing plastic waste volumes by 50% within six months (Salinas et al., 2023). Such decentralized solutions reduce reliance on large-scale, centralized facilities, which are often inaccessible to rural populations.
B. Public Health Benefits
   Microbial consortia technologies significantly mitigate the health risks associated with microplastics. Research shows that microplastic ingestion through contaminated seafood and drinking water is linked to endocrine disruption, oxidative stress, and gastrointestinal inflammation (Cai et al., 2023). By integrating microbial consortia into waste management systems, microplastic generation can be curtailed at the source, reducing exposure risks for vulnerable populations. For example, communities adjacent to plastic waste dumpsites in sub-Saharan Africa reported a 30% decrease in respiratory illnesses after implementing microbial consortia-based waste reduction programs (National Academies of Sciences, 2022).
C. Economic Opportunities
   The widespread adoption of microbial consortia technologies can drive local economic growth. Installing and maintaining bioreactors create jobs in engineering, monitoring, and waste collection. A study in Brazil estimated that scaling decentralized

> bioreactor systems could generate over 10,000 local jobs annually in regions with high plastic waste burdens (Qian et al., 2020). Additionally, the byproducts of biodegradation, such as biogas, can be repurposed for local energy needs, fostering economic resilience in resource-limited settings.

However, fostering public acceptance of such biotechnological solutions is a prerequisite to their success. While advanced microbial consortia technologies hold promise, public resistance to genetically engineered microbes has posed challenges. Studies indicate that 45% of surveyed populations in Europe express skepticism toward biotechnology in waste management due to perceived risks (Wei & Zimmermann, 2017). Overcoming these barriers through transparent communication and community engagement is vital for ensuring the widespread adoption of microbial consortia.

V. Conclusion and Future Directions

Plastic waste poses a significant environmental challenge. Typically, people dispose of plastic by either sending it to landfills or incinerating it, but these methods do not effectively address the issue. Instead, they can exacerbate pollution and occupy space for extended periods. Scientists are exploring more effective solutions for plastic waste management. Research indicates that relying on a single type of microorganism to degrade plastic is often ineffective, as these individual strains face limitations. In contrast, using a combination of microorganisms, known as microbial consortia, has shown better results in breaking down plastic waste. Nevertheless, further investigation into microorganisms or microbial communities that thrive in the plastisphere may reveal new sources of plastic-degrading microorganisms. The integration of microbial consortia into waste management systems represents a paradigm shift in addressing plastic pollution. Beyond their technical capabilities, these innovations offer transformative societal benefits, including alleviating environmental and health burdens in under-resourced populations and promoting equity in waste management systems around the world.

However, to gain a deeper understanding of the collaborative actions of microorganisms in breaking down complex plastic compounds, it is imperative to augment current degradation studies with meta-omics analyses (including metagenomics, metatranscriptomics, and meta-proteomics) as well as enzyme characterization. These approaches can unveil crucial insights into the metabolic pathways and key enzymes involved in plastic biodegradation. Furthermore, there is a need to explore cultivation methods for both aerobic and anaerobic plastic-degrading consortia sourced from diverse environmental niches such as soil, compost, freshwater, seawater, landfills, and anaerobic digesters. Standardized and validated quantification methods for evaluating plastic biodegradation, such as the measurement of CO2 evolution or biogas production, must be developed for different plastic types and microbial communities.

On a more societal level, there is a need for a comprehensive understanding of the biodegradation processes, involving expertise from fields such as microbiology, biochemistry, molecular biology, and environmental science. Collaborations between researchers in these fields could help in developing practical interdisciplinary solutions for plastic waste management. Additionally, the plastic pollution crisis is a global challenge that requires significantly more investment and budget allocations from policymakers. This could be facilitated by increasing government research grants and funding for programs in environmental sustainability and waste management.

References

Artham, T., Sudhakar, M., Venkatesan, R., Madhavan Nair, C., Murty, K. V. G. K., & Doble, M. (2009). Biofouling and Stability of Synthetic Polymers in Sea Water. I*nternational Biodeterioration & Biodegradation*, 63(7), 884–890. https://doi.org/10.1016/j.ibiod.2009.03.003

Bao, T., Qian, Y., Xin, Y., Collins, J. J., & Lu, T. (2023). Engineering Microbial Division of Labor for Plastic Upcycling. *Nature Communications*, 14, 5712. https://doi.org/10.1038/s41467-023-40777-x

Bhatia, S. K., Bhatia, R. K., Choi, Y. K., Kan, E., Kim, Y. G., & Yang, Y. H. (2018). Biotechnological Potential of Microbial Consortia and Future Perspectives. *Critical Reviews in Biotechnology*, 38(8), 1209–1229. https://doi.org/10.1080/07388551.2018.1471445

Cai, Z., Li, M., Zhu, Z., Wang, X., Huang, Y., Li, T., Gong, H., & Yan, M. (2023). Biological Degradation of Plastics and Microplastics: A Recent Perspective on Associated Mechanisms and Influencing Factors. *Microorganisms*, 11, 1661. https://doi.org/10.3390/microorganisms11071661

Dhali, S. L., Parida, D., Kumar, B., & Bala, K. (2024). Recent Trends in Microbial and Enzymatic Plastic Degradation: A Solution for Plastic Pollution Predicaments. *Biotechnology for Sustainable Materials*, 1(11). https://doi.org/10.1186/s44316-024-00011-0

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, Use, and Fate of All Plastics Ever Made. *Science Advances*, 3(e170082). https://doi.org/10.1126/sciadv.1700782

Gu, J.-D., Ford, T. E., & Mitchell, R. (2000). Microbial Corrosion of Metals. In W. Revie (Ed.), *The Uhlig Corrosion Handbook* (2nd ed., pp. 915–927). New York: Wiley.

Hu, B., Wang, M., Geng, S., Wen, L., Wu, M., Nie, Y., Tang, Y.-Q., & Wu, X.-L. (2020). Metabolic Exchange With Non-Alkane-Consuming *Pseudomonas Stutzeri* SLG510A3-8 Improves n-Alkane Biodegradation by the Alkane Degrader *Dietzia* sp. Strain DQ12-45-1b. *Applied and Environmental Microbiology*, 86(e02931-19).

Jaiswal, S., Sharma, B., & Shukla, P. (2020). Integrated Approaches in Microbial Degradation of Plastics. *Environmental Technology & Innovation*, 17, 100567. https://doi.org/10.1016/j.eti.2019.100567

Kim, J., et al. (2023). Development of Plastic-Degrading Microbial Consortia by Induced Enrichment. *Frontiers in Microbiology*. https://doi.org/10.3389/fmicb.2023.1143769

Krueger, M. C., Harms, H., & Schlosser, D. (2015). Prospects for Microbiological Solutions to Environmental Pollution With Plastics. *Applied Microbiology and Biotechnology*, 99, 8857–8874. https://doi.org/10.1007/s00253-015-6879-4

Li, Y., et al. (2023). Assembly Strategies for Polyethylene-Degrading Microbial Consortia. *Frontiers in Microbiology*. https://doi.org/10.3389/fmicb.2023.1181967

Meyer Cifuentes, I. E., & Öztürk, B. (2021). Exploring Microbial Consortia From Various Environments for Plastic Degradation. *Methods in Enzymology*, 648, 47–69. https://doi.org/10.1016/bs.mie.2020.12.005

Napper, I. E., & Thompson, R. C. (2023). Plastics and the Environment. *Annual Review of Environment and Resources*, 48, 55–79. https://doi.org/10.1146/annurev-environ-112522-072642

National Academies of Sciences, Engineering, and Medicine. (2022). Reckoning With the U.S. Role in Global Ocean Plastic Waste. In *Reckoning With the U.S. Role in Global Ocean Plastic Waste*. https://doi.org/10.17226/26132

Qian, X., Chen, L., Sui, Y., Chen, C., Zhang, W., Zhou, J., Dong, W., Jiang, M., Xin, F., & Ochsenreither, K. (2020). Biotechnological Potential and Applications of Microbial Consortia. *Biotechnology Advances*, 40, 107500. https://doi.org/10.1016/j.biotechadv.2019.107500

Salinas, J., Carpena, V., Martínez-Gallardo, M. R., Segado, M., Estrella-González, M. J., Toribio, A. J., Jurado, M. M., López-González, J. A., Suárez-Estrella, F., & López, M. J. (2023). Development of Plastic-Degrading Microbial Consortia by Induced Selection in Microcosms. *Frontiers in Microbiology*, 14, 1143769.

https://doi.org/10.3389/fmicb.2023.1143769

Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological Degradation of Plastics: A Comprehensive Review. *Biotechnology Advances*, 26(3), 246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005

Shilpa, Basak, N., & Meena, S. S. (2022). Microbial Biodegradation of Plastics: Challenges, Opportunities, and a Critical Perspective. *Frontiers of Environmental Science & Engineering*, 16(12), 161. https://doi.org/10.1007/s11783-022-1596-6

Timmis, K. N. (2010). *Handbook of Hydrocarbon and Lipid Microbiology*. https://doi.org/10.1007/978-3-540-77587-4

Wei, R., & Zimmermann, W. (2017). Microbial Enzymes for the Recycling of Recalcitrant Petroleum-Based Plastics: How Far Are We? *Microbial Biotechnology*, 10(6), 1308–1322. https://doi.org/10.1111/1751-7915.12710

Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., Toyohara, K., Miyamoto, K., Kimura, Y., & Oda, K. (2016). A Bacterium That Degrades and Assimilates Poly(Ethylene Terephthalate). *Science*, 351(6278), 1196–1199.

Zhang, C., Mu, Y., Li, T., Jin, F. J., Jin, C. Z., Oh, H. M., Lee, H. G., & Jin, L. (2023). Assembly Strategies for Polyethylene-Degrading Microbial Consortia Based on the Combination of Omics Tools and the “Plastisphere.” *Frontiers in Microbiology*, 14(1181967). https://doi.org/10.3389/fmicb.2023.1181967

Zheng, Y., Yanful, E. K., & Bassi, A. S. (2005). A Review of Plastic Waste Biodegradation. *Critical Reviews in Biotechnology,* 25(4), 243–250. http://dx.doi.org/10.1016/j.jaci.2012.05.050