

## Microbe-mediated degradation of microplastics in soil: A sustainable solution for agricultural ecosystems

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### **Abstract: -**

*Microplastic pollution has become a growing concern in agricultural ecosystems due to its widespread accumulation in soils through sources such as plastic mulches, sewage sludge, compost, wastewater irrigation and atmospheric deposition. These particles adversely affect soil structure, nutrient cycling, microbial communities and crop productivity, posing risks to environmental and human health. Microbial degradation has emerged as a promising and environmentally friendly approach for mitigating microplastic contamination. Various bacteria and fungi can colonize plastic surfaces, produce degradative enzymes and convert plastic polymers into simpler compounds. Enhancing microbial biodegradation offers a sustainable strategy for restoring soil health and supporting resilient agricultural systems.*

**Keywords:** *Microplastics, Agricultural soils, Microbial degradation, Soil health, Sustainable agriculture etc.*

### **Introduction**

Microplastics are extremely small plastic fragments, typically less than 5 mm in diameter, that result either from the fragmentation of larger plastic items or from products intentionally manufactured at microscopic sizes, such as synthetic textiles, cosmetic ingredients, and industrial resin pellets. Over the past few years, microplastic

contamination has become a major environmental issue because these particles are now widely distributed across both land and water ecosystems, with agricultural soils being particularly affected. Farmlands are exposed to microplastics through several sources, including plastic mulch residues, the application of sewage sludge and compost,

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irrigation with wastewater, atmospheric deposition and the breakdown of agrochemical containers and packaging materials. After entering the soil, microplastics can remain for extended periods due to their durable polymer composition. Their persistence can negatively influence soil quality by disrupting microbial communities, altering nutrient cycling processes, reducing soil fertility and affecting crop growth and productivity. In addition, these particles can absorb and transport harmful chemicals, increasing the likelihood of their movement through the food chain and creating potential risks to both environmental and human health. As plastic pollution in agricultural systems continues to increase, there is an urgent need for sustainable and environmentally responsible remediation strategies. One of the promising approaches is microbial degradation, which has attracted significant interest as a natural and eco-friendly solution. In this process, bacteria, fungi and other microorganisms use plastic polymers as a carbon source, gradually converting them into simpler and less harmful substances. Consequently, microbe-assisted degradation of microplastics represents a valuable strategy for reducing plastic contamination, improving soil health and supporting the long-term sustainability of agricultural ecosystems.

### **Sources of microplastics in agricultural soils**

Agricultural soils receive microplastics from a variety of direct and indirect sources linked to contemporary farming activities. One of the primary sources is the widespread use of plastic mulch films, which are commonly employed to retain soil moisture, regulate soil temperature and control weed growth. With prolonged exposure to sunlight, changing temperatures and mechanical cultivation, these plastic films gradually break down into tiny particles that persist in the soil for extended periods. Likewise, drip irrigation equipment and greenhouse coverings made from polyethylene and other plastic materials undergo weathering and repeated wear, leading to the release of microplastic fragments into agricultural fields. The use of sewage sludge and compost as organic soil amendments also represents a significant route of microplastic contamination. During wastewater treatment, synthetic fibres, cosmetic microbeads and various plastic particles are captured and become concentrated in sewage sludge. When this sludge is applied to farmland, large amounts of microplastics can enter the soil environment. Similarly, compost produced from municipal solid waste may contain plastic residues because of inadequate waste separation and the incomplete breakdown of plastic materials during composting. Additional contributions come from agricultural plastic products such

as fertilizer sacks, pesticide containers, silage films and seedling trays. When these materials are improperly disposed of or deteriorate under field conditions, they release plastic particles into the surrounding soil. Beyond farm-related sources, atmospheric deposition has become an increasingly important pathway for microplastic distribution. Fine plastic particles and synthetic fibres generated from urban activities, industrial operations, vehicle emissions and textile products can be carried by air currents over considerable distances before being deposited onto agricultural lands through rainfall or direct settling. The ongoing accumulation of microplastics from these multiple sources can modify soil physical properties, disrupt microbial populations and create challenges for sustainable agriculture and food security in the long term.

### **Impact of microplastics on soil health**

Microplastics have a substantial impact on soil health by affecting the physical, chemical and biological characteristics of agricultural soils. One of the most noticeable effects is the alteration of soil structure and porosity. The accumulation of plastic particles can modify soil aggregation and bulk density, leading to changes in pore space that vary according to the size, shape and concentration of the microplastics. These changes can influence soil aeration and restrict root growth and penetration. The presence of microplastics

also affects the movement and storage of water within the soil. Certain forms, particularly fibrous and film-like particles, may enhance water retention in some soil types, whereas in others they can reduce water infiltration and hydraulic conductivity. As a result, the natural regulation of soil moisture can be disrupted. Microplastics further influence nutrient dynamics by binding essential nutrients and harmful contaminants to their surfaces, thereby modifying nutrient cycling processes and reducing nutrient availability to plants and beneficial soil microorganisms. Additionally, they can transport pesticides, heavy metals and other pollutants, increasing the extent of soil contamination. The biological functioning of soil is particularly vulnerable to microplastic pollution. The accumulation of these particles can alter the diversity, abundance and activity of important soil organisms such as bacteria, fungi, earthworms and other microfauna. Changes in microbial communities may hinder key processes including organic matter decomposition, enzyme activity and nutrient mineralisation, all of which are vital for maintaining soil fertility. Moreover, soil-dwelling organisms that ingest microplastics may experience physiological stress, reduced growth and impaired biological functions. Together, these impacts can adversely affect crop performance by restricting root development, limiting nutrient absorption and

reducing overall plant growth. Consequently, long-term microplastic contamination poses a serious threat to soil quality, agricultural productivity, and food security, potentially undermining the sustainability of farming systems.

### **Role of soil microorganisms in plastic breakdown**

Soil microorganisms are essential for maintaining ecological balance because they decompose organic matter and recycle nutrients within the environment. In natural soil ecosystems, diverse groups of microorganisms, including bacteria, fungi and actinomycetes, break down complex organic materials into simpler compounds that can be reused by plants and other organisms. Owing to their broad metabolic capabilities, certain microorganisms can also utilize synthetic polymers as sources of carbon and energy, making them valuable agents for the biological remediation of plastic-contaminated soils. Several bacterial genera have demonstrated significant potential for degrading various plastic polymers, including polyethylene (PE), polyethylene terephthalate (PET), polyurethane (PU) and polystyrene (PS). Among the most widely studied plastic-degrading bacteria are species of *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Streptomyces* and *Ideonella*. A notable example is *Ideonella sakaiensis*, which

attracted considerable scientific interest because of its ability to produce the PETase enzyme, an enzyme capable of efficiently breaking down PET plastics. Likewise, *Pseudomonas* species produce oxidative and hydrolytic enzymes that aid in the degradation of polyethylene and polyurethane, whereas *Bacillus* species support plastic breakdown through effective biofilm formation and the secretion of depolymerising enzymes under soil conditions.

Fungi are widely recognized as effective organisms for the degradation of microplastics due to their extensive hyphal growth, strong ability to colonize surfaces and capacity to produce a variety of powerful extracellular enzymes, including laccases, peroxidases, esterases and cutinases. Several fungal genera, such as *Aspergillus*, *Penicillium*, *Fusarium* and *Trichoderma*, along with white-rot fungi like *Phanerochaete chrysosporium*, have shown considerable potential for breaking down synthetic polymers under both laboratory and environmental conditions. Among these, white-rot fungi are especially significant because their ligninolytic enzyme systems exhibit broad substrate specificity. This allows them to degrade complex plastic polymers, like the natural decomposition of lignin. Their ability to attack a wide range of recalcitrant compounds makes them promising candidates

for the biological remediation of plastic-contaminated environments. In agricultural soils affected by plastic pollution, microbial diversity plays a vital role in achieving efficient biodegradation. Different microorganisms contribute distinct metabolic activities during the degradation process and their combined actions facilitate the breakdown of complex plastic materials. A diverse microbial community improves degradation efficiency, strengthens ecosystem resilience and enhances tolerance to environmental stress through synergistic interactions among bacteria, fungi and other soil organisms. However, the excessive accumulation of microplastics can negatively affect soil microbial communities by altering their composition, reducing the abundance of beneficial microorganisms and disturbing ecological balance. Such changes may impair decomposition processes, decrease soil fertility and weaken the natural capacity of soils to recover from contamination. Therefore, maintaining and promoting microbial diversity in agricultural ecosystems is essential for supporting natural biodegradation mechanisms and ensuring the long-term remediation of microplastic pollution.

### **Mechanisms of microbial degradation of microplastics**

Microbial degradation of microplastics is a multifaceted biological process that starts

with the attachment of microorganisms to plastic surfaces in the soil. Because most synthetic polymers are highly hydrophobic and resistant to natural breakdown, microbial colonization is regarded as the initial and most important step in biodegradation. Various soil microorganisms, including bacteria, fungi and actinomycetes, adhere to plastic particles through physicochemical interactions and gradually form stable microbial communities collectively known as the *plastisphere*. The success of this colonization process is influenced by environmental conditions such as soil moisture, temperature, pH and nutrient availability. Following attachment, microorganisms secrete extracellular polymeric substances (EPS), which promote the development of biofilms on plastic surfaces. These biofilms provide a protective microenvironment that supports microbial growth and ensures close contact between microbial cells and the plastic substrate. Biofilm formation also helps retain degradative enzymes near the polymer surface, thereby enhancing the efficiency of degradation. Within the biofilm, different microbial species often interact cooperatively, enabling the sequential breakdown of complex plastic materials. In addition, biofilm activity contributes to physical and chemical changes in the plastic, such as surface erosion, cracking, oxidation and reduced crystallinity,

making the material more vulnerable to microbial attack.

Once colonization is established, microorganisms begin the enzymatic degradation of plastic polymers by releasing extracellular enzymes, including hydrolases, esterases, lipases, cutinases, laccases and peroxidases. These enzymes break long polymer chains into smaller units such as oligomers, dimers and monomers through processes including hydrolysis, oxidation, and depolymerization. Different microorganisms possess specialized enzymes that target specific plastic types. For example, the enzymes PETase and MHETase produced by *Ideonella sakaiensis* are capable of efficiently degrading polyethylene terephthalate (PET), whereas ligninolytic enzymes produced by

white-rot fungi can facilitate the breakdown of polyethylene and polyurethane. After the polymer chains have been fragmented into smaller molecules, these compounds are absorbed by microbial cells and incorporated into various metabolic pathways, where they serve as sources of carbon and energy. Through intracellular metabolism, the degradation products are further transformed into simpler compounds. Under aerobic conditions, the final products are primarily carbon dioxide, water and microbial biomass, whereas methane may also be generated under anaerobic conditions. This ultimate stage known as mineralisation, represents the complete biological conversion of plastic materials into naturally occurring substances and is essential for reducing the long-term

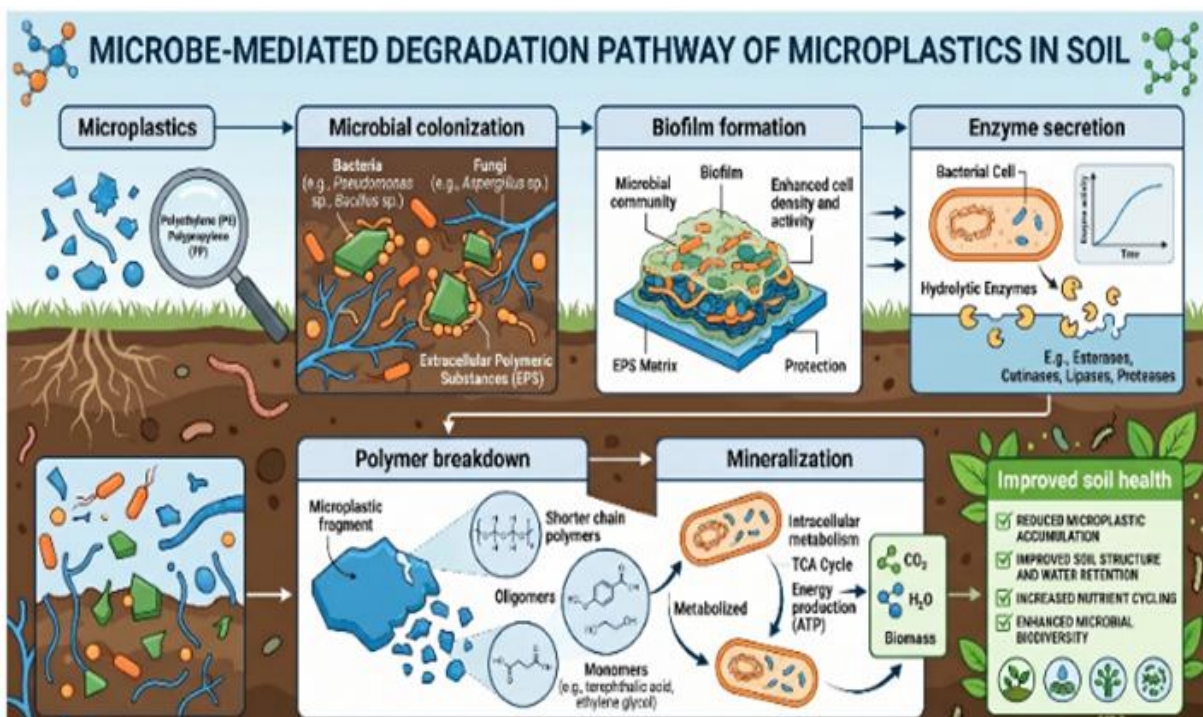


Figure 1. Microbe-mediated degradation pathway of microplastics in soil

persistence of microplastics in agricultural soils. The effectiveness of mineralisation depends on several factors, including the diversity and activity of microbial communities, environmental conditions, and the chemical characteristics of the plastic polymers. The overall mechanism of microbe-mediated microplastic degradation in soil is illustrated in **Figure 1**.

### Important microbes involved in plastic degradation

A wide variety of microbes play a key role in the biodegradation of microplastics in soil. Bacteria such as *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Streptomyces* and *Ideonella sakaiensis* degrade plastics including PE, PET, PU and PS through specialized enzymes, with *I. sakaiensis* producing the PET-degrading enzymes PETase and MHETase. Similarly, fungi such as *Aspergillus*, *Penicillium*, *Fusarium*, *Trichoderma* and *Phanerochaete chrysosporium* contribute by secreting

extracellular enzymes like laccases and peroxidases that break down complex polymers. Together, these microorganisms enhance the degradation and detoxification of microplastics in contaminated soils. The major bacterial and fungal species involved in microplastic degradation, together with their associated enzymes and degradation mechanisms, are presented in Tables 1 and 2, respectively.

### Benefits of microbial degradation in agriculture

Microbial degradation of microplastics provides significant benefits to agricultural ecosystems by reducing the accumulation of plastic pollutants in soil and converting them into less harmful substances. This process helps restore soil structure, porosity and water-holding capacity while enhancing nutrient cycling through improved organic matter decomposition and nutrient mineralisation. Active and diverse microbial communities also

**Table 1. Major fungal organisms involved in microplastic degradation**

Fungal organism	Plastic degradation mechanism	Major enzymes involved
<i>Aspergillus niger</i>	Colonization and oxidative degradation of polyethylene	Laccases, Esterases
<i>Aspergillus flavus</i>	Surface erosion and polymer depolymerization	Oxidases, Peroxidases
<i>Penicillium spp.</i>	Hydrolysis of plastic polymers	Esterases, Cutinases
<i>Fusarium spp.</i>	Extracellular enzymatic degradation of plastics	Lipases, Peroxidases
<i>Trichoderma spp.</i>	Biofilm formation and polymer fragmentation	Cellulase-like enzymes, Laccases
<i>Phanerochaete chrysosporium</i>	Ligninolytic degradation of complex polymers	Lignin peroxidase, Manganese peroxidase, Laccase

**Table 2. Major bacterial organisms involved in microplastic degradation**

Bacterial organism	Plastic degradation mechanism	Major enzymes involved
<i>Ideonella sakaiensis</i>	Hydrolysis and depolymerization of PET polymers	PETase, MHETase
<i>Pseudomonas spp.</i>	Oxidative degradation and biofilm-mediated polymer breakdown	Oxygenases, Esterases, Lipases
<i>Bacillus spp.</i>	Surface colonization and extracellular polymer degradation	Proteases, Lipases, Cutinases
<i>Rhodococcus spp.</i>	Utilization of hydrophobic polymers as carbon source	Monooxygenases, Hydrolases
<i>Streptomyces spp.</i>	Enzymatic fragmentation of polyethylene and polyurethane	Peroxidases, Esterases
<i>Arthrobacter spp.</i>	Biodegradation of plastic-derived hydrocarbons	Oxidoreductases, Hydrolases

support ecological balance, stimulate beneficial soil processes, and promote healthier plant growth, leading to improved root development, nutrient uptake and crop productivity. As an environmentally friendly and sustainable approach, microbial degradation offers an effective alternative to conventional plastic removal methods, contributing to soil fertility, sustainable agriculture and long-term food security.

### Challenges and limitations

Microbial degradation of microplastics faces several limitations, including the slow breakdown of highly resistant plastic polymers, environmental influences on microbial activity and the possible formation of harmful intermediate products. Many plastic-degrading microorganisms perform effectively in laboratory conditions but show limited efficiency in field environments.

Additionally, mixed plastic wastes and other contaminants can reduce biodegradation rates. Therefore, further research is needed to develop efficient microbial consortia and practical strategies for large-scale microplastic remediation in agricultural soils.

### Future Perspectives

Future research should focus on developing efficient microbial consortia and bioaugmentation strategies to enhance microplastic degradation in agricultural soils. Combining microbial remediation with sustainable farming practices, such as organic amendments and reduced plastic use, can further improve soil health and biodegradation efficiency. Advances in metagenomics, molecular biology and enzyme engineering will aid in discovering novel plastic-degrading microorganisms and optimising their performance, while interdisciplinary research

is essential for developing safe and sustainable solutions to microplastic pollution in agroecosystems.

## Conclusion

Microplastic pollution has emerged as a significant challenge to agricultural sustainability, affecting soil health, microbial diversity and crop productivity. Microorganisms such as bacteria and fungi offer a promising, eco-friendly solution by breaking down plastic particles into less harmful compounds through natural biodegradation processes. Although several challenges remain in improving degradation efficiency under field conditions, continued research and the adoption of sustainable agricultural practices can enhance the potential of microbial remediation. Harnessing the capabilities of soil microorganisms will be crucial for reducing microplastic contamination, restoring soil quality and ensuring the long-term sustainability of agricultural ecosystems and food production.

## References

1. Amobonye, A., Bhagwat, P., Singh, S., Pillai, S., & Gupta, V. K. (2021). Plastic biodegradation: Frontline microbes and their enzymes. *Science of the Total Environment*, 759, 143536. <https://doi.org/10.1016/j.scitotenv.2020.143536>
2. Boots, B., Russell, C. W., & Green, D. S. (2019). Effects of microplastics in soil ecosystems: Above and below ground. *Environmental Science & Technology*, 53(19), 11496–11506. <https://doi.org/10.1021/acs.est.9b03304>
3. Danso, D., Chow, J., & Streit, W. R. (2019). Plastics: Environmental and biotechnological perspectives on microbial degradation. *Applied and Environmental Microbiology*, 85(19), e01095-19. <https://doi.org/10.1128/AEM.01095-19>
4. de Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., Becker, R., Görlich, A. S., & Rillig, M. C. (2019). Microplastics can change soil properties and affect plant performance. *Environmental Science & Technology*, 53(10), 6044–6052. <https://doi.org/10.1021/acs.est.9b01339>
5. de Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2018). Impacts of microplastics on the soil biophysical environment. *Environmental Science & Technology*, 52(17), 9656–9665.

- <https://doi.org/10.1021/acs.est.8b0221>  
2
6. Ghosh, S. K., Pal, S., & Ray, S. (2013). Study of microbes having potentiality for biodegradation of plastics. *Environmental Science and Pollution Research*, 20(7), 4339–4355. <https://doi.org/10.1007/s11356-013-1706-x>
7. Guo, J. J., Huang, X. P., Xiang, L., Wang, Y. Z., Li, Y. W., Li, H., Cai, Q. Y., Mo, C. H., & Wong, M. H. (2020). Source, migration and toxicology of microplastics in soil. *Environment International*, 137, 105263. <https://doi.org/10.1016/j.envint.2019.105263>
8. He, D., Luo, Y., Lu, S., Liu, M., Song, Y., & Lei, L. (2018). Microplastics in soils: Analytical methods, pollution characteristics and ecological risks. *TrAC Trends in Analytical Chemistry*, 109, 163–172. <https://doi.org/10.1016/j.trac.2018.10.006>
9. Kumar, M., Xiong, X., He, M., Tsang, D. C. W., Gupta, J., Khan, E., Harrad, S., Hou, D., Ok, Y. S., & Bolan, N. S. (2020). Microplastics as pollutants in agricultural soils. *Environmental Pollution*, 265(Part A), 114980. <https://doi.org/10.1016/j.envpol.2020.114980>
10. Nizzetto, L., Futter, M., & Langaas, S. (2016). Are agricultural soils dumps for microplastics of urban origin? *Environmental Science & Technology*, 50(20), 10777–10779. <https://doi.org/10.1021/acs.est.6b04140>
11. Payanthoth, N. S., Nik Mut, N. N., Samanta, P., Li, G., & Jung, J. (2024). A review of biodegradation and formation of biodegradable microplastics in soil and freshwater environments. *Applied Biological Chemistry*, 67, 110. <https://doi.org/10.1186/s13765-024-00959-7>
12. Pérez-Reverón, R., Álvarez-Méndez, S. J., Kropp, R. M., Perdomo-González, A., Hernández-Borges, J., & Díaz-Peña, F. J. (2022). Microplastics in agricultural systems: Analytical methodologies and effects on soil quality and crop yield. *Agriculture*, 12(8), 1162. <https://doi.org/10.3390/agriculture12081162>
13. Rillig, M. C., Lehmann, A., de Souza Machado, A. A., & Yang, G. (2019). Microplastic effects on plants. *New*

- Phytologist*, 223(3), 1066–1070.  
<https://doi.org/10.1111/nph.15794>
14. Ru, J., Huo, Y., & Yang, Y. (2020). Microbial degradation and valorization of plastic wastes. *Frontiers in Microbiology*, 11, 442. <https://doi.org/10.3389/fmicb.2020.00442>
15. Sánchez, C. (2020). Fungal potential for the degradation of petroleum-based polymers: An overview of macro- and microplastics biodegradation. *Biotechnology Advances*, 40, 107501. <https://doi.org/10.1016/j.biotechadv.2019.107501>
16. Tariq, M., Iqbal, B., Khan, I., Khan, A. R., Jho, E. H., Salam, A., Zhou, H., Zhao, X., Li, G., & Du, D. (2024). Microplastic contamination in the agricultural soil—Mitigation strategies, heavy metals contamination, and impact on human health: A review. *Plant Cell Reports*, 43, 65. <https://doi.org/10.1007/s00299-024-03162-6>
17. Wang, K., Wang, F., Yu, Y., Yang, S., Han, Y., & Yao, H. (2025). Microplastics and soil microbiomes. *BMC Biology*, 23, 273. <https://doi.org/10.1186/s12915-025-02387-5>
18. 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. <https://doi.org/10.1126/science.aad6359>
19. Zettler, E. R., Mincer, T. J., & Amaral-Zettler, L. A. (2013). Life in the “plastisphere”: Microbial communities on plastic marine debris. *Environmental Science & Technology*, 47(13), 7137–7146. <https://doi.org/10.1021/es401288x>
20. Zhou, Y., Liu, X., Wang, J., & Chen, Y. (2021). Systematical review of interactions between microplastics and microorganisms in the soil environment. *Journal of Hazardous Materials*, 418, 126288. <https://doi.org/10.1016/j.jhazmat.2021.126288>