



Microplastics in Agroecosystems: A Barrier to Soil Health and Crop Productivity

*K. Navya¹, Dr. M. Shankaraiah², Dr. Rajeshwar Malavath³ and Sandhya M⁴

¹Ph.D. Scholar, Department of Soil Science and Agriculture Chemistry, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana, India

²Principal Scientist, Soil Science & Agricultural Chemistry, AICRP on E MSPE, Soil Health Unit, ARI, PJTAU, Rajendranagar, Hyderabad-30, Telangana, India

³Professor, Department of Soil Science and Agricultural Chemistry, College of Agriculture, PJTAU, Rajendranagar, Hyderabad-30, Telangana, India

⁴Ph. D Scholar, University of Agricultural Sciences, Raichur, India

*Corresponding Author's email: navya30kothakapu@gmail.com

Healthy soil is the foundation of sustainable agriculture, supporting crop productivity, nutrient cycling and food security. The increasing use of plastics in agriculture has raised concerns about the accumulation of microplastics (MPs) in agricultural soils. Microplastics enter agroecosystems through plastic mulch films, irrigation materials, wastewater, compost, sewage-derived amendments and atmospheric deposition. Once present in soil, they can interact with soil particles, organic matter, water and microorganisms, potentially altering soil structure, nutrient cycling and microbial activity. Emerging evidence also suggests that MPs may influence root growth, nutrient uptake and crop physiological processes, although their effects depend on particle characteristics, concentration and soil conditions. This article highlights the sources, fate and potential impacts of microplastics on soil health and crop production. It also discusses biodegradable mulch films and other alternative materials as potential approaches for reducing persistent plastic inputs. However, the long-term environmental performance and complete degradation of these alternatives require further field-based evaluation. Responsible plastic use, improved waste management and scientifically validated alternatives are therefore essential for developing plastic-smart and sustainable agricultural systems.

Keywords: Microplastics, agricultural soils, soil health, crop productivity, soil-plant interactions, microbial communities, nutrient cycling, biodegradable plastics, biochar, sustainable agriculture.

Introduction

Microplastics (MPs), generally defined as plastic particles smaller than 5 mm, have emerged as persistent contaminants of increasing concern in terrestrial ecosystems, including agricultural soils (Vasic *et al.*, 2025; Yang *et al.*, 2025). Although early research on plastic pollution focused largely on marine environments, increasing evidence indicates that agricultural soils can act as important reservoirs and sinks for microplastics (Zhou *et al.*, 2024; FAO, 2025). Their occurrence in agricultural soils has been associated with the degradation of plastic mulch films, wastewater irrigation, biosolids and sewage-derived amendments, compost application and atmospheric deposition (Zhou *et al.*, 2024; Yang *et al.*, 2025; Samani *et al.*, 2025). Recent reviews have also highlighted considerable variation in microplastic abundance, polymer types, particle sizes and shapes across agricultural soils, while emphasizing the need for standardized analytical and monitoring approaches (Yang *et*

al., 2025; FAO, 2025). The relationship between agriculture and plastic pollution is complex because plastics provide several important agronomic benefits while also creating environmental challenges when they are poorly managed (FAO, 2025). Agricultural plastics are widely used for mulching, irrigation, greenhouse production, crop protection and other applications because they can conserve soil moisture, suppress weeds, improve resource-use efficiency and support crop productivity (Zhou *et al.*, 2024; FAO, 2025). However, incomplete collection, recycling and disposal of agricultural plastics can promote their fragmentation and persistence in soil, ultimately contributing to microplastic accumulation (Zhou *et al.*, 2024; Yang *et al.*, 2025). Consequently, the sustainability challenge is not simply the use of agricultural plastics but their life-cycle management, environmental persistence and potential transformation into micro- and nanoplastics (FAO, 2025; Yang *et al.*, 2025). Once introduced into agricultural soils, microplastics can interact with soil minerals, organic matter, water and biological communities (Zhou *et al.*, 2024; Vasic *et al.*, 2025). Their presence may alter soil aggregation, porosity, bulk density, water retention and other physical properties, although the magnitude and direction of these effects depend on polymer type, particle characteristics, concentration and soil conditions (FAO, 2025; Vasic *et al.*, 2025). Microplastics can also influence soil microbial abundance, community composition and functional activities, potentially affecting important soil processes such as carbon and nutrient cycling (Vasic *et al.*, 2025; Kundu, 2026). In particular, recent research has highlighted potential interactions between microplastic contamination and nitrogen transformation processes, including nitrogen mineralization, nitrification, denitrification and ammonia volatilization (Sarfraz *et al.*, 2025). Such changes may have implications for nutrient availability, nitrogen-use efficiency, greenhouse-gas emissions and crop productivity (Sarfraz *et al.*, 2025). Microplastics may additionally influence the transport, persistence and bioavailability of other contaminants in agricultural soils (Yang *et al.*, 2025; Zhou *et al.*, 2024). Their surfaces can interact with organic and inorganic contaminants, including pesticides and heavy metals, potentially modifying contaminant mobility and biological exposure (Yang *et al.*, 2025). Recent research therefore emphasizes that the ecological effects of microplastics cannot always be considered independently from their interactions with co-existing contaminants and soil constituents (Yang *et al.*, 2025). Exposure to micro- and nanoplastics has also been associated with changes in plant growth, photosynthesis, nutrient homeostasis, oxidative stress and other physiological processes in experimental studies (FAO, 2025). However, the extent to which these findings represent realistic agricultural field conditions remains uncertain because experimental concentrations, particle characteristics and exposure durations can differ substantially from those occurring naturally in agricultural soils (FAO, 2025; Vasic *et al.*, 2025). These findings have raised questions about the potential implications of microplastics for food safety. The possible uptake and translocation of plastic particles or associated contaminants into edible plant tissues provide a potential pathway linking contaminated agricultural soils with the food chain (FAO, 2025 Samani *et al.*, 2025). Nevertheless, the magnitude of dietary exposure and the associated human-health risks remain uncertain, highlighting the need for standardized analytical methods, realistic exposure assessments and long-term field investigations (FAO, 2025). Recent evidence therefore supports considering microplastic contamination within the broader framework of soil health and sustainable agriculture, rather than treating it solely as a soil-pollution issue (Vasic *et al.*, 2025; FAO, 2025). Microplastics have been reported to influence soil structure, water dynamics, soil chemistry, microbial communities and crop-related processes, although their effects are strongly dependent on particle properties, concentration, soil characteristics and environmental conditions (Vasic *et al.*, 2025; FAO, 2025). Importantly, recent reviews emphasize that more field-based research is required to distinguish experimentally observed effects from impacts that are likely to occur under realistic agricultural conditions (FAO, 2025; Yang *et al.*, 2025). An important component of the sustainability discussion is the development and evaluation of alternatives to conventional agricultural plastics. Soil-biodegradable mulch films and other alternative materials may reduce the persistence

associated with conventional polyethylene-based materials, but their environmental benefits cannot be assumed solely from their biodegradability (FAO, 2025; Vasic *et al.*, 2025). Their degradation rate, degradation products, additives, effects on soil organisms, agronomic performance and behaviour under different soil and climatic conditions require systematic field evaluation (FAO, 2025). Thus, biodegradable alternatives should be assessed through a life-cycle and soil-health perspective, rather than simply being considered automatically sustainable. Therefore, addressing microplastic contamination in agriculture requires a balanced approach involving prevention of plastic leakage, improved collection and waste management, recycling and recovery, responsible use of agricultural plastics, development of validated alternatives and long-term monitoring of soil health (FAO, 2025; Vasic *et al.*, 2025).

Sources of Microplastics in Agricultural Soils

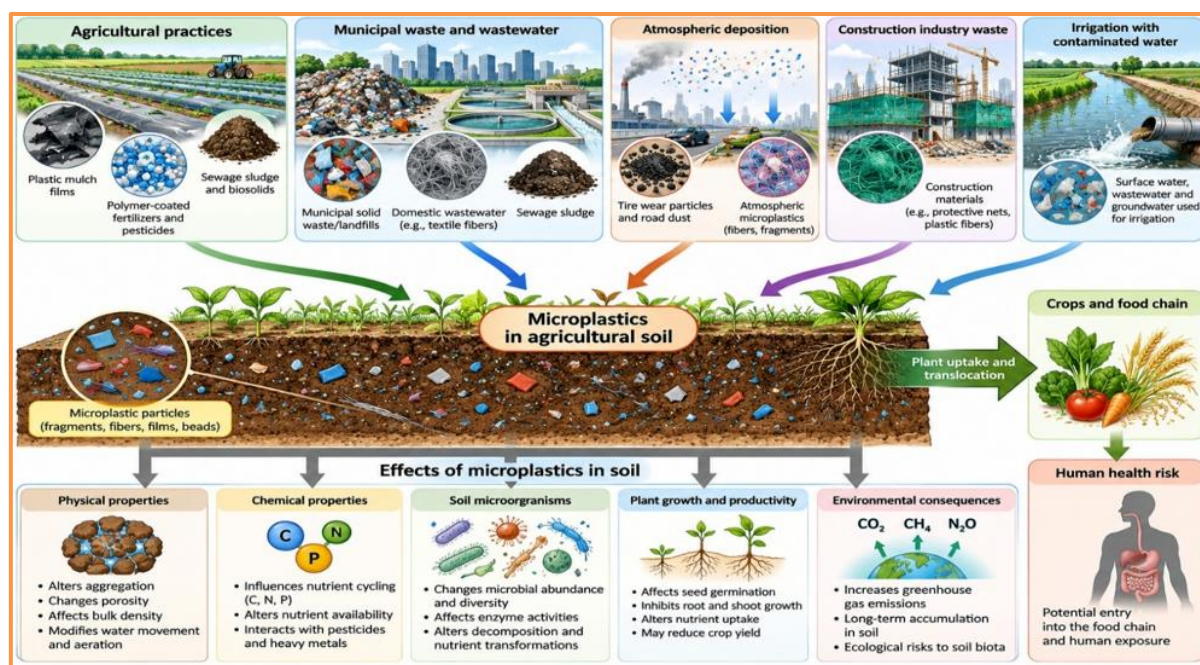


Figure 1. Sources, fate and potential impacts of microplastics in agricultural soils and agroecosystems

Microplastics (MPs) enter agricultural soils through multiple pathways, including agricultural plastic use, wastewater and biosolid application, contaminated compost and organic fertilizers, irrigation water, atmospheric deposition and surrounding human activities. Recent reviews identify plastic mulch films, sewage sludge/biosolids, wastewater and atmospheric deposition among the important sources of MPs in agricultural soils (Sahai *et al.*, 2025; Wu *et al.*, 2024).

Agricultural Practices

Plastic mulch films are an important source of MPs because repeated use, weathering, tillage and incomplete removal can cause plastic films to fragment into smaller particles and accumulate in soil. Long-term mulching has been associated with increased MP abundance in agricultural soils (Sattar *et al.*, 2025; Yu *et al.*, 2025). **Sewage sludge, biosolids, compost and other organic amendments** can introduce MPs into agricultural land because these materials may contain plastic particles originating from domestic, municipal and agricultural wastes. Application of contaminated organic fertilizers can therefore increase MP inputs to soil (Zhang *et al.*, 2024; Carpanez *et al.*, 2025). **Polymer-coated fertilizers and pesticides** represent another emerging pathway because polymeric materials used in controlled-release formulations may contribute to plastic residues in agricultural soils (Sahai *et al.*, 2025).

Wastewater and Organic Amendments

The agricultural reuse of **treated wastewater and biosolids** can transfer both microplastics and smaller plastic particles into soil. Their repeated application may contribute to the accumulation and vertical movement of plastic particles within the soil profile (Carpanez *et*

al., 2025). Similarly, **compost and organic fertilizers** may contain MPs derived from municipal waste, sewage, agricultural residues and other plastic-contaminated feedstocks. Processing such materials through composting or digestion may alter the size, shape and surface characteristics of MPs but does not necessarily eliminate them completely (Zhang *et al.*, 2024).

Atmospheric Deposition

MPs can also reach agricultural soils through **atmospheric deposition**. Fibres and other small plastic particles released from urban, industrial and agricultural activities can be transported by air and deposited directly onto soil surfaces. Atmospheric deposition is increasingly recognized as a pathway contributing to the background MP load of agricultural soils (Sahai *et al.*, 2025; Yu *et al.*, 2025).

Irrigation with Contaminated Water

Irrigation water, particularly wastewater and contaminated surface or groundwater, can transport MPs into agricultural soils. Irrigation and soil-water movement may also facilitate the downward migration of MPs into deeper soil layers. Recent field evidence indicates that irrigation practices can influence both the abundance and vertical distribution of MPs in agricultural soils (Yu *et al.*, 2025; Carpanez *et al.*, 2025).

Construction and Other Local Sources

Local sources such as **construction materials, plastic sheets, dust-proof nets, agricultural equipment and plastic waste** may also contribute to soil contamination, particularly in agricultural areas located near rapidly developing or urbanizing regions. Their contribution is generally site-specific and depends on surrounding land use and waste-management practices (Wu *et al.*, 2024).

Soil Pollution with Microplastics: Current Situation and Challenges

Microplastics (MPs) are increasingly recognized as persistent contaminants of terrestrial ecosystems, with agricultural soils acting as important sinks for these particles. Annual plastic inputs to land have been estimated to be 4–23 times greater than those entering the oceans, highlighting the need for greater attention to soil contamination (Horton *et al.*, 2017).

Agricultural soils receive MPs through plastic mulch residues, wastewater and biosolids, contaminated organic amendments, atmospheric deposition and other human activities. Continuous use of plastic mulch can progressively increase MP accumulation in soil (Huang *et al.*, 2020; Sattar *et al.*, 2025). Once introduced, MPs can persist and migrate within the soil profile because of their resistance to degradation (Wu *et al.*, 2024).

The presence of MPs may alter soil aggregation, porosity, water movement and aeration, while also affecting microbial communities and nutrient cycling. Recent reviews indicate that MPs can influence microbial diversity, enzyme activities and carbon and nitrogen transformations, although the magnitude and direction of effects depend on soil type, polymer characteristics and exposure conditions (Aralappanavar *et al.*, 2024; Ma and Yang, 2024). MPs may also interact with other contaminants such as heavy metals and pesticides, potentially modifying their mobility and bioavailability (Bian *et al.*, 2024).

A major challenge is the wide variation in MP size, shape, polymer type and concentration, together with the lack of fully standardized analytical methods. Consequently, reliable assessment of their long-term effects on soil health, crop productivity and food safety remains difficult and requires more field-based research (Sahai *et al.*, 2025; Wu *et al.*, 2024).

The Impact of Microplastics on Sustainable Agriculture

Microplastics (MPs) can influence agroecosystem functioning by altering soil physical properties, nutrient cycling, microbial communities and plant growth (Wu *et al.*, 2024; Kumar *et al.*, 2025). However, their effects vary with polymer type, particle size and concentration, soil texture, pH and environmental conditions (Sahai *et al.*, 2025; Vasic *et al.*, 2025).

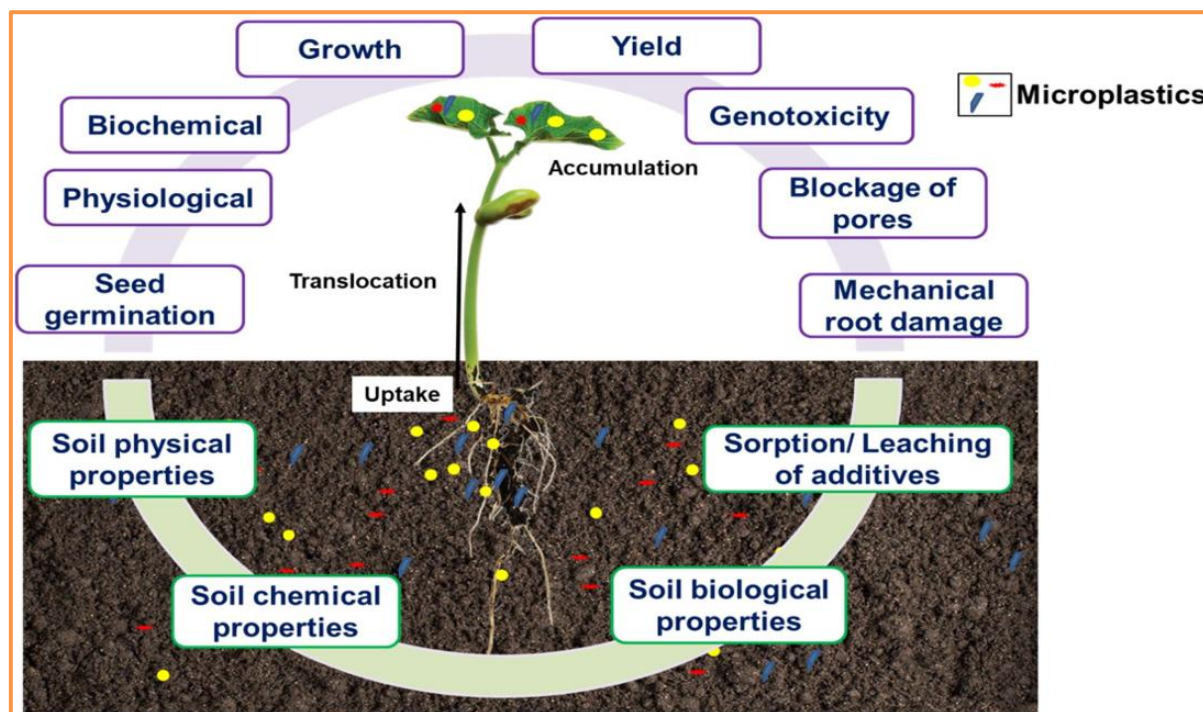


Figure 2. Effect of microplastics on agriculture crops

Impact on Soil Physical and Chemical Properties

MPs can modify soil aggregation, porosity, bulk density, water infiltration and water retention, thereby affecting soil aeration and root-zone conditions (Wu *et al.*, 2024; Vasic *et al.*, 2025). Their effects depend strongly on soil texture and the characteristics of the plastic particles. MPs can also modify soil pH, electrical conductivity and nutrient availability, influencing the availability of macro- and micronutrients (Vasic *et al.*, 2025; Sahai *et al.*, 2025). Changes in carbon and nitrogen cycling have also been reported, although the direction and magnitude of these effects vary among soils and MP types (Lan *et al.*, 2025; Kumar *et al.*, 2025). MPs may additionally alter the activities of enzymes such as urease, β -glucosidase and phosphatase, potentially affecting decomposition and nutrient transformation processes (Kumar *et al.*, 2025; Vasic *et al.*, 2025).

Effects on Soil Microorganisms

MPs can change the abundance, diversity and composition of soil microbial communities and modify microbial enzyme activities (Kumar *et al.*, 2025; Wu *et al.*, 2024). Plastic surfaces may provide new habitats for microorganisms, commonly referred to as the *plastisphere*, potentially changing microbial interactions and nutrient cycling (Kumar *et al.*, 2025). However, responses are not uniform, with some studies reporting limited or contrasting effects depending on MP characteristics and soil conditions (Vasic *et al.*, 2025).

Effects on Plant Growth and Productivity

Changes in soil structure, water availability and nutrient cycling can influence root development, nutrient uptake, photosynthesis, biomass accumulation and crop productivity (Wu *et al.*, 2024; Bethanis and Golia, 2024). Experimental studies have reported reductions in plant growth and physiological performance, although responses differ among crops and polymer types (Vasic *et al.*, 2025; Bethanis and Golia, 2024). Therefore, MP contamination should be considered a potential stress factor rather than a uniform cause of yield reduction, as responses are strongly dependent on environmental and experimental conditions.

Interactions with Pesticides and Heavy Metals

MPs can interact with pesticides and potentially toxic elements, altering their mobility, persistence and bioavailability (Wu *et al.*, 2024; Sattar *et al.*, 2025). For example, MPs may either increase or decrease pesticide degradation depending on the pesticide and environmental conditions (Vasic *et al.*, 2025). Similarly, interactions with metals such as Cd and As may modify their availability and toxicity to plants and soil organisms (Vasic *et al.*, 2025).

al.,2025). These combined effects make MP pollution particularly complex in agricultural soils.

Role of Beneficial Microorganisms and Sustainable Management

Arbuscular mycorrhizal fungi (AMF) may partly alleviate MP stress by improving plant water and nutrient acquisition, although MPs can also alter AMF communities (Vasic *et al.*, 2025). Thus, reducing unnecessary plastic inputs, improving plastic-waste management and evaluating biodegradable alternatives are important components of **plastic-smart and sustainable agriculture** (Sattar *et al.*, 2025; Gündoğdu *et al.*, 2025). Importantly, recent evidence indicates that MP effects can sometimes be neutral or context-dependent, emphasizing the need for **long-term, field-based studies** rather than generalized conclusions (Wu *et al.*, 2024; Vasic *et al.*,2025).

Table 1. Effects of microplastics on soil health and crop production

Soil/plant component	Potential effects of MPs	Mechanism/Process	Research evidence
Soil structure	Changes in aggregation, porosity and bulk density	Physical mixing and interactions with soil particles	Wu <i>et al.</i> , 2024; Vasić <i>et al.</i> , 2025
Water dynamics	Changes in infiltration, water retention and soil aeration	Modification of pore structure and hydrophobic/hydrophilic interactions	Wu <i>et al.</i> , 2024
Soil chemistry	Changes in pH, EC and nutrient availability	MP–soil and MP–organic matter interactions	Vasić <i>et al.</i> , 2025; Sahai <i>et al.</i> , 2025
C, N and P cycling	Changes in nutrient transformation and greenhouse-gas emissions	Altered microbial activity and C/N/P processes	Lan <i>et al.</i> , 2025
Microbial communities	Changes in abundance, diversity and community composition	Plastisphere formation and altered soil habitat	Kumar <i>et al.</i> , 2025
Soil enzymes	Changes in urease, β -glucosidase, phosphatase and other enzymes	Altered microbial activity and substrate availability	Kumar <i>et al.</i> , 2025
Plant roots	Changes in root growth and architecture	Altered soil conditions and direct root–MP interactions	Chen <i>et al.</i> , 2025
Nutrient uptake	Potential changes in nutrient acquisition and homeostasis	Changes in rhizosphere processes and root function	Chen <i>et al.</i> , 2025
Plant physiology	Changes in photosynthesis, oxidative stress and physiological responses	Direct and indirect MP stress	Chen <i>et al.</i> , 2025
Crop productivity	Variable responses in biomass and yield	Depends on polymer, size, concentration, crop and soil	Bethanis & Golia, 2024; Vasić <i>et al.</i> , 2025
Pesticides/heavy metals	Changes in mobility, persistence and bioavailability	Sorption/desorption and surface interactions	Yang <i>et al.</i> , 2025
Food chain	Possible movement into edible plant tissues	Root interaction and particle/contaminant transport	Samani <i>et al.</i> , 2025; Chen <i>et al.</i> , 2025

Risks for Sustainable Agriculture

Microplastics (MPs) pose a potential risk to sustainable agriculture because they can alter **soil structure, water movement, nutrient cycling and microbial activity**, with consequences for soil health and crop performance (Cusworth *et al.*, 2024; Wu *et al.*, 2024; Kumar *et al.*, 2025). MPs may disrupt **soil aggregation, porosity and water infiltration**, thereby affecting soil aeration and water availability to plants. They can also interact with nutrients, pesticides and heavy metals, potentially modifying their mobility and bioavailability (de Souza

Machado *et al.*, 2018; Sattar *et al.*, 2025). Microplastics can further influence **soil microbial communities, enzyme activities and biogeochemical processes**, including carbon and nitrogen cycling. These changes may affect nutrient availability and plant development, although their magnitude and direction depend on soil properties, MP characteristics and environmental conditions (Lan *et al.*, 2025; Kumar *et al.*, 2025). Overall, the long-term accumulation of MPs may create **combined physical, chemical and biological stresses** in agricultural soils, highlighting the need for improved plastic management, standardized monitoring and long-term field research to protect soil health and agricultural sustainability (Vasic *et al.*, 2025; Wu *et al.*, 2024).

Strategies for Mitigating the Negative Impacts of Microplastics

Mitigating microplastic (MP) pollution in agricultural soils requires a combination of **source reduction, improved plastic management, alternative materials and soil-based remediation**. Priority should be given to reducing unnecessary conventional plastic inputs, improving collection and recycling of agricultural plastics, and adopting mulching materials with demonstrated environmental performance. However, biodegradable plastics should not be considered automatically risk-free, as their degradation depends on soil temperature, moisture, pH and microbial activity, and incomplete degradation may leave residues in soil (Vasic *et al.*, 2025; Gündoğdu *et al.*, 2025). **Biochar and other soil amendments** are promising approaches for reducing MP-related stress. Biochar can improve soil aggregation, water retention, nutrient availability and microbial activity, while its porous surface may immobilize or reduce the mobility of plastic particles and associated contaminants. Recent studies indicate that biochar can alleviate MP-induced effects on soil microbial communities and crop growth, although results depend on biochar characteristics, MP type and application rate (Ji *et al.*, 2025; Liu *et al.*, 2025). Biological approaches, including **plastic-degrading microorganisms and beneficial rhizosphere microbes**, also offer potential for future MP remediation. In addition, organic amendments and non-plastic mulching materials such as **wool, flax and jute fibres** may reduce dependence on conventional plastic materials. Nevertheless, most mitigation technologies remain at the experimental or early field-validation stage. Therefore, **long-term field trials, standardized assessment of biodegradation, life-cycle evaluation and clear guidelines for farmers** are essential before large-scale adoption (Sattar *et al.*, 2025; Vasic *et al.*, 2025).

Table 2. Strategies for mitigating microplastic impacts

Mitigation strategy	Mechanism/approach	Potential benefit	Major limitation	Recent evidence
Source reduction	Reduce unnecessary agricultural plastic inputs	Prevents MP formation	Requires farmer awareness and suitable alternatives	Vasić <i>et al.</i> , 2025; Yang <i>et al.</i> , 2025
Collection and recycling	Recover mulch films and agricultural plastics after use	Reduces plastic leakage and soil accumulation	Contaminated/fragmented films are difficult to recycle	Yang <i>et al.</i> , 2025
Biodegradable mulch films	Replace persistent conventional mulch films	Potentially lowers persistent plastic residues	Incomplete degradation and residual MPs are possible	Gündoğdu <i>et al.</i> , 2026
Natural-fibre mulches	Wool, flax, jute and other plant/animal fibres	Reduces dependence on petroleum-based plastic	Durability, cost and scalability	Gündoğdu <i>et al.</i> , 2026
Living/organic mulches	Cover crops and organic mulch systems	Weed suppression and improved soil biological properties	Crop competition and management requirements	Bozzolo <i>et al.</i> , 2025

Mitigation strategy	Mechanism/approach	Potential benefit	Major limitation	Recent evidence
Biochar	Improve soil structure and microbial habitat; modify MP interactions	Potential improvement of soil quality and microbial function	Response depends on biochar and soil characteristics	Ji <i>et al.</i> , 2025
Organic amendments	Improve soil structure and nutrient availability	Supports soil resilience	Amendments may themselves contain MPs	Sattar <i>et al.</i> , 2025
Beneficial microorganisms	PGPR, AMF and potential plastic-degrading microorganisms	Potential biological mitigation	Mostly experimental; field validation required	Kumar <i>et al.</i> , 2025; Kundu, 2026
Monitoring and regulation	Standardized sampling, identification and long-term monitoring	Enables reliable risk assessment	No universally accepted monitoring framework	Sahai <i>et al.</i> , 2025; Chen <i>et al.</i> , 2025
Life-cycle assessment	Compare conventional and alternative materials from production to end-of-life	Prevents shifting environmental burdens	Requires comprehensive field and environmental data	Gündoğdu <i>et al.</i> , 2026

Conclusion

Microplastics are emerging as persistent contaminants that can disrupt soil structure, nutrient cycling, microbial functions and crop–soil interactions. Their effects are strongly context-dependent, varying with polymer type, particle size, concentration, soil properties and environmental conditions. Reducing plastic inputs, improving collection and recycling, and adopting validated biodegradable or natural-fibre alternatives are important components of sustainable management. Biochar, beneficial microorganisms and other soil-based approaches show promise, but require stronger long-term field validation before widespread adoption. Future research should prioritize standardized monitoring, realistic field exposure studies and life-cycle assessment to protect soil health, crop productivity and food security.

References

1. Aralappanavar, V. K., Mukhopadhyay, R., Yu, Y., Liu, J., Bhatnagar, A., Praveena, S. M., Li, Y., Paller, M., Adyel, T. M., Rinklebe, J., Bolan, N. S. and Sarkar, B. 2024. Effects of microplastics on soil microorganisms and microbial functions in nutrients and carbon cycling – A review. *Science of the Total Environment*. 924: 171435. <https://doi.org/10.1016/j.scitotenv.2024.171435>
2. Bethanis, J. and Golia, E. E. 2024. Micro- and nano-plastics in agricultural soils: A critical meta-analysis of their impact on plant growth, nutrition, metal accumulation in plant tissues and crop yield. *Applied Soil Ecology*. 194: 105202. <https://doi.org/10.1016/j.apsoil.2023.105202>
3. Bian, J., Peng, N., Zhou, Z., Yang, J. and Wang, X. 2024. A critical review of co-pollution of microplastics and heavy metals in agricultural soil environments. *Ecotoxicology and Environmental Safety*. 286: 117248. <https://doi.org/10.1016/j.ecoenv.2024.117248>
4. Bozzolo, A., Pecenka, J., Hamido, S. and Acharya, B. 2025. Living mulches, crimped cover crops, and plastic mulch influence on soil health, weed suppression, and yield in organic globe artichoke systems. *European Journal of Agronomy*. 170: 127759. <https://doi.org/10.1016/j.eja.2025.127759>
5. Carpanez, T. G., Castro, L. M. C., Amaral, M. C. S. and Moreira, V. R. 2025. Occurrence and environmental consequences of microplastics and nanoplastics from agricultural reuse of wastewater and biosolids in the soil ecosystem: A review. *Science of the Total Environment*. 980: 179538. <https://doi.org/10.1016/j.scitotenv.2025.179538>

6. Chen, H., Ingraffia, R., Schlöter, M., Brüggemann, N. and Rillig, M. C. 2025. Effects of multiple microplastic types on growth of winter wheat and soil properties vary in different agricultural soils. *Plants, People, Planet*. 7(1): 194–203. <https://doi.org/10.1002/ppp3.10573>
7. Chen, Z., Carter, L. J., Banwart, S. A. and Kay, P. 2025. Microplastics in soil–plant systems: Current knowledge, research gaps, and future directions for agricultural sustainability. *Agronomy*. 15(7): 1519. <https://doi.org/10.3390/agronomy15071519>
8. Cusworth, S. J., Davies, W. J., McAinsh, M. R. and Stevens, C. J. 2024. A nationwide assessment of microplastic abundance in agricultural soils: The influence of plastic crop covers within the United Kingdom. *Plants, People, Planet*. 6(2): 304–314. <https://doi.org/10.1002/ppp3.10430>
9. de Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R. and 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.8b02212>
10. FAO (Nizzetto, L., Hurley, R., Collard, F., Thompson, R. H. and Carcasci, G.). 2025. *State of research on the impacts of plastic pollution on soil health and crops*. Food and Agriculture Organization of the United Nations, Rome. ISBN 978-92-5-139996-5. <https://doi.org/10.4060/cd6407en>
11. Gündoğdu, S., Akça, M. O., Özkan, İ., Sarıdaş, M. A., Küçükel, E., Rodríguez-Seijo, A., Er, E. and Turgay, O. C. 2026. A review of non-petroleum alternatives of plastic mulches in agriculture: Knowledge gaps and future recommendations. *European Journal of Agronomy*. 172: 127831. <https://doi.org/10.1016/j.eja.2025.127831>
12. Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E. and Svendsen, C. 2017. Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment*. 586: 127–141. <https://doi.org/10.1016/j.scitotenv.2017.01.190>
13. Huang, Y., Liu, Q., Jia, W., Yan, C. and Wang, J. 2020. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environmental Pollution*. 260: 114096. <https://doi.org/10.1016/j.envpol.2020.114096>
14. Ji, H., Zhou, C. and Li, P. 2025. Applications of biochar in the remediation of soil microplastic pollution: A review. *Soil Science Society of America Journal*. 89(3): e70078. <https://doi.org/10.1002/saj2.70078>
15. Kumar, M., Kumar, R., Sharma, S., Mukherjee, S., Bolan, S., Shrivastava, A., Hettiarachchi, M., Siddique, K. H. M. and Bolan, N. 2025. Microplastics pollution modulating soil biological health – A review. *Soil Use and Management*. 41(1): e70009. <https://doi.org/10.1111/sum.70009>
16. Kundu, M. C. 2026. Microplastics in agricultural soils, their sources, environmental impacts, ecological risks, and mitigation strategies. *Discover Environment*. 4: 347. <https://doi.org/10.1007/s44274-026-00871-5>
17. Lan, G., Huang, X., Li, T., Huang, Y., Liao, Y., Zheng, Q., Zhao, Q., Yu, Y. and Lin, J. 2025. Effect of microplastics on carbon, nitrogen and phosphorus cycle in farmland soil: A meta-analysis. *Environmental Pollution*. 370: 125871. <https://doi.org/10.1016/j.envpol.2025.125871>
18. Liu, W., Su, Z., Xu, L., Li, W., Lu, J., Liu, X., Manevski, K. and Liu, F. 2025. Biochar and microplastics interactively modulate morpho-physiology and growth of maize under soil drying-rewetting cycles. *Plant and Soil*. 515(2): 2113–2133. <https://doi.org/10.1007/s11104-025-07709-8>
19. Ma, Y., Yang, K., Yu, H., Tan, W., Gao, Y. and Lv, B. 2024. Effects and mechanism of microplastics on organic carbon and nitrogen cycling in agricultural soil: A review. *Soil Use and Management*. 40(1): e12971. <https://doi.org/10.1111/sum.12971>
20. Sahai, H., Aguilera del Real, A. M., Alcayde, A., Martínez Bueno, M. J., Wang, C., Hernando, M. D. and Fernández-Alba, A. R. 2025. Key insights into microplastic

- pollution in agricultural soils: A comprehensive review of worldwide trends, sources, distribution, characteristics and analytical approaches. *TrAC Trends in Analytical Chemistry*. 185: 118176. <https://doi.org/10.1016/j.trac.2025.118176>
21. Samani, M., Ahlawat, Y. K., Yadav, S., Feizi, M., Rashti, M. R., Mohseni, A., Prakash, C., Ghotekar, S. and Kataria, N. 2025. Micro and nano plastics (MNPs) in agricultural soils: Challenges for food security and environmental health. *Environmental Monitoring and Assessment*. 197: 1369. <https://doi.org/10.1007/s10661-025-14810-z>
 22. Sarfraz, U., Qian, Y., Yu, Q., Cao, Y., Jiang, X., Mahreen, N., Tao, R., Ma, Q., Zhu, M., Ding, J., Li, C., Guo, W. and Zhu, X. 2025. Microplastic effects on soil nitrogen storage, nitrogen emissions, and ammonia volatilization in relation to soil health and crop productivity: Mechanism and future consideration. *Frontiers in Plant Science*. 16: 1621542. <https://doi.org/10.3389/fpls.2025.1621542>
 23. Sattar, B., Liu, G., Yousaf, B., Arif, M., Gulzar, M. Z., Haider, M. I. S., Safeer, R., Ijaz, S., Haider, M. A. and Aziz, K. 2025. Microplastic contamination in agricultural soils from mulch films and organic amendments: Transformation mechanism, soil-biota toxicity, and future perspectives. *Waste Management*. 205: 115032. <https://doi.org/10.1016/j.wasman.2025.115032>
 24. Vasić, V., Srećkov, Z., Mrkonjić, Z., Bojović, M., Nikolić, O. and Radić, D. 2025. Microplastics in agroecosystems: A barrier to soil health and crop productivity. *Italian Journal of Agronomy*. 20(4): 100057. <https://doi.org/10.1016/j.ijagro.2025.100057>
 25. Wu, J.-Y., Gao, J.-M., Pei, Y.-Z., Luo, K.-Y., Yang, W.-H., Wu, J.-C., Yue, X.-H., Wen, J. and Luo, Y. 2024. Microplastics in agricultural soils: A comprehensive perspective on occurrence, environmental behaviors and effects. *Chemical Engineering Journal*. 489: 151328. <https://doi.org/10.1016/j.cej.2024.151328>
 26. Yang, L., Yang, W., Li, Q., Zhao, Z., Zhou, H. and Wu, P. 2025. Microplastics in agricultural soils: Sources, fate, and interactions with other contaminants. *Journal of Agricultural and Food Chemistry*. 73(21): 12548–12562. <https://doi.org/10.1021/acs.jafc.5c03682>
 27. Yu, H., Zhang, W., Li, J., Yang, J., Yang, X., Hai, C., Wang, Y. and Yang, Y. 2025. Vertical distribution and multi-source pathways of microplastics in agricultural soils: A study of typical irrigation areas in the upper Yellow River basin. *Environmental Pollution*. 381: 126479. <https://doi.org/10.1016/j.envpol.2025.126479>
 28. Zhang, S., Li, Y., Jiang, L., Chen, X., Zhao, Y., Shi, W. and Xing, Z. 2024. From organic fertilizer to the soils: What happens to the microplastics? A critical review. *Science of the Total Environment*. 919: 170217. <https://doi.org/10.1016/j.scitotenv.2024.170217>
 29. Zhou, Y., Dou, M., Zhang, Y., Ning, K. and Li, Y. 2024. Distribution characteristics of soil microplastics and their impact on soil physicochemical properties in agricultural areas of the North China Plain. *Environmental Science: Processes & Impacts*. 26: 1556–1570. <https://doi.org/10.1039/D4EM00242C>