MICROBIOLOGY ARCHIVES
MICROBIOLOGY ARCHIVES
Review Article | ISSN: 3041-590X
Journal homepage: https://microjournal.researchfloor.org/

Check for updates

Microplastic Pollution in Agricultural Soils: Impacts on Microbial Communities, Nutrient Cycling, and Soil Ecosystem Functioning

Mihirkumar B. Suthar

Biology Department, K. K. Shah Jarodwala Maninagar Science College, BJLT Campus, Rambaug, Maninagar, Ahmedabad, Gujarat, ,380008, India

ARTICLE INFO

Citation: Mihirkumar B. Suthar (2021). Microplastic Pollution in Agricultural Soils: Impacts on Microbial Communities, Nutrient Cycling, and Soil Ecosystem Functioning.
Microbiology Archives, an International Journal.
DOI: https://doi.org/10.51470/MA.2021.3.1.01

Received 03 January 2021
Revised 05 February 2021
Accepted 08 March 2021
Available Online April 04 2021

Corresponding Author: **Mihirkumar B. Suthar**
E-Mail: **sutharmbz@gmail.com**

ABSTRACT

Microplastic pollution is increasingly recognized as a pervasive contaminant in terrestrial ecosystems, particularly agricultural soils where plastics from mulching, irrigation, and waste application accumulate. Microplastics alter soil physical properties, interact with microbial communities, and may influence nutrient cycling processes critical to soil fertility and ecosystem functioning. This review synthesizes current evidence on microplastic occurrence in agricultural soils, mechanisms by which microplastics affect soil microbiota, and their impact on nutrient cycling, including carbon, nitrogen, and phosphorus dynamics. Evidence indicates that microplastics can shift microbial community composition, reduce microbial diversity, and affect functional guilds involved in decomposition and nutrient transformations. Additionally, microplastics may adsorb or release organic matter, pollutants, and nutrients, further influencing microbial activity. Despite emerging insights, knowledge gaps remain regarding microplastic type-specific effects, long-term impacts, and interactions with agricultural practices such as fertilizer application and tillage. Addressing these gaps is critical to developing management strategies that mitigate microplastic impacts while maintaining soil health. This review highlights research directions, methodological approaches, and the importance of integrating microplastic pollution into soil ecosystem monitoring to ensure sustainable agricultural productivity.

Keywords: *Microplastics, Soil microbiota, Nutrient cycling, Agriculture, Soil health, Microbial ecology*

1. Introduction

The rapid proliferation of plastics over the past decades has led to widespread environmental contamination, including in terrestrial ecosystems. Agricultural soils are particularly vulnerable due to the extensive use of plastic mulching, irrigation equipment, packaging, and the application of organic amendments derived from waste streams containing microplastics [1][2]. Microplastics, defined as plastic particles smaller than 5 mm, can persist in soils for decades due to their recalcitrant nature and resistance to degradation [3]. Once incorporated into the soil matrix, microplastics interact with physical, chemical, and biological components, potentially altering soil structure, water retention, and nutrient availability [4][5].

Soil microbiota, including bacteria, fungi, and archaea, are central to ecosystem functions such as decomposition, nutrient cycling, and soil aggregation. Microbial communities respond sensitively to environmental stressors, and the introduction of microplastics represents a novel perturbation with poorly understood consequences [6]. Microplastic particles can serve as physical surfaces for microbial colonization, potentially creating "plastispheres" that favor specific taxa, including opportunistic or pollutant-degrading organisms [7][8]. These shifts may influence microbial-mediated processes, including mineralization, nitrification, and phosphorus cycling, with implications for soil fertility and crop productivity [9]. Emerging studies indicate that microplastics can also interact with agrochemicals, heavy metals, and organic matter, further modulating microbial activity and nutrient availability [10]. The type, size, shape, and chemical composition of microplastics are critical determinants of their effects on soil biota, yet these variables are often understudied [11]. Additionally, long-term field studies are scarce, and most knowledge derives from short-term laboratory experiments that may not fully capture soil complexity [12].

This review aims to synthesize current research on the influence of microplastic pollution on soil microbiota and nutrient cycling in agricultural ecosystems. Specific objectives include: (i) evaluating sources and occurrence of microplastics in agricultural soils, (ii) assessing their effects on microbial community composition and function, (iii) examining consequences for carbon, nitrogen, and phosphorus cycling, and (iv) identifying key knowledge gaps and future research directions for sustainable soil management. By integrating these insights, the review provides a foundation for understanding microplastic-soil-microbiota interactions and their implications for agroecosystem sustainability.

2. Sources and Occurrence of Microplastics in Agricultural Soils

Microplastics enter agricultural soils through multiple pathways. Primary sources include plastic mulching films, seed coatings, irrigation pipes, and greenhouse coverings [1][13]. Secondary sources involve degradation of larger plastics, such as packaging materials and agricultural waste, as well as atmospheric deposition of airborne microplastics [14]. Sewage sludge and compost derived from urban waste are also significant contributors, introducing particles along with nutrients and trace pollutants [15].

Studies report microplastic concentrations ranging from 50 to over 10,000 particles per kilogram of dry soil, depending on agricultural practices, proximity to urban areas, and management history [16]. Polyethylene (PE), polypropylene (PP), and polystyrene (PS) are the most commonly detected polymers. Particle shapes vary from fibers and fragments to films and spheres, with fibers often dominating due to textile and sludge sources [17]. Microplastic accumulation is particularly pronounced in soils under intensive plastic mulch cultivation and in regions with frequent sludge amendments [18]. Environmental factors, including soil texture, moisture, and microbial activity, influence microplastic distribution and persistence. Fine-textured soils tend to retain smaller particles, while coarse soils may facilitate particle movement through percolation [19]. Weathering processes such as UV exposure, freeze-thaw cycles, and microbial degradation can alter particle surface chemistry, potentially affecting interactions with soil microbes and pollutants [20].

3. Effects of Microplastics on Soil Microbiota

3.1 Microbial Community Composition and Diversity

Microplastics influence soil microbial communities by providing novel surfaces for colonization, altering soil structure, and modifying habitat heterogeneity [7]. The "plastisphere" concept describes microbial biofilms that develop on plastic surfaces, often differing in composition from surrounding soil microbiota. Studies have reported enrichment of opportunistic bacteria and polymer-degrading taxa on microplastic surfaces, while sensitive microbial groups may decline, leading to reduced overall diversity [8]. Laboratory experiments show that fibers and fragments can differentially affect bacterial versus fungal communities, highlighting the importance of particle morphology [20].

3.2 Functional Impacts on Microbial Activity

Microplastics can modulate microbial metabolism and enzymatic activity. Laboratory and mesocosm studies demonstrate that microplastics may reduce dehydrogenase and β-glucosidase activities, indicating potential suppression of organic matter decomposition [2-4]. Conversely, some studies report increased microbial respiration in the presence of certain microplastics, possibly due to biofilm formation and nutrient adsorption on particle surfaces [5]. Microplastic-induced shifts in microbial activity can affect functional guilds responsible for nitrogen fixation, nitrification, and denitrification, with downstream effects on soil nutrient availability [6].

4. Impacts on Nutrient Cycling

Microplastics represent a novel and persistent component of agricultural soils, with significant implications for biogeochemical processes. By altering the structure, chemistry, and microbial ecology of soils, microplastics can influence the cycling of key nutrients, including carbon (C), nitrogen (N), and phosphorus (P). These impacts are complex, context-dependent, and influenced by particle type, size, polymer chemistry, soil texture, and environmental conditions. Understanding the interactions between microplastics, soil microbiota, and nutrient dynamics is essential for assessing soil fertility and ecosystem resilience in agroecosystems.

4.1 Carbon Cycling

Soil carbon dynamics are governed by microbial decomposition, organic matter stabilization, and soil aggregation processes. Microplastics can alter these dynamics through both physical and biological mechanisms. Fibrous microplastics, for instance, can entangle soil aggregates and organic matter, modifying soil porosity, water retention, and aeration [7]. These physical changes can influence microbial activity, as oxygen availability and moisture conditions are critical determinants of decomposition rates. The physical effects, microplastics provide surfaces for biofilm formation, creating microscale habitats that favor specific microbial taxa [8]. Microbes colonizing these "plastispheres" may preferentially metabolize labile carbon sources, such as dissolved organic carbon and root exudates, potentially accelerating localized carbon turnover. However, the presence of microplastics may also sequester carbon in inaccessible forms within aggregates or on particle surfaces, reducing the overall availability of organic substrates for the broader soil microbial community.

Experimental studies show mixed effects: some report increased CO_2 emissions and microbial respiration in microplastic-amended soils, indicating enhanced decomposition, while others observe reduced enzyme activity and organic matter breakdown, suggesting inhibitory effects on carbon cycling [3][5]. These discrepancies likely reflect differences in particle type, concentration, soil texture, and the initial microbial community. For example, polyethylene (PE) fibers may promote microbial respiration by increasing habitat heterogeneity, whereas polystyrene (PS) fragments may adsorb organic compounds and reduce substrate accessibility. Microplastics can also indirectly affect soil carbon through interactions with co-contaminants such as pesticides, heavy metals, and organic pollutants. Hydrophobic pollutants can adsorb onto plastic surfaces, potentially reducing their bioavailability and toxicity to microbial decomposers or, conversely, serving as alternative carbon sources for specialized degraders [10]. Over time, these interactions may alter the balance between carbon mineralization and stabilization, affecting long-term soil carbon storage and its role in climate regulation.

4.2 Nitrogen Cycling

Nitrogen is a key nutrient for plant growth and is tightly linked to microbial activity in soils. The nitrogen cycle involves processes such as ammonification, nitrification, and denitrification, all mediated by diverse microbial guilds. Microplastic contamination can disrupt these processes by altering microbial community composition, abundance, and functional potential [6].

Studies indicate that microplastics can reduce the abundance of nitrifying bacteria, leading to decreased nitrification rates in some soils. This reduction may result from physical interference with soil pore networks, changes in oxygen availability, or toxic effects of plastic additives such as phthalates and stabilizers [9]. Conversely, some heterotrophic denitrifying bacteria may proliferate on microplastic surfaces or within aggregates, increasing denitrification potential and associated nitrous oxide (N_2O) emissions.

The effects of microplastics on nitrogen cycling are influenced by particle chemistry, shape, and the presence of co-contaminants. Fibers, due to their high surface area, can create localized anaerobic microsites within aggregates, promoting denitrification.

In contrast, irregular fragments may disrupt soil structure differently, leading to heterogeneous microbial activity. Environmental factors such as soil moisture, temperature, and pH further modulate these effects, potentially exacerbating or mitigating impacts under field conditions.

Additionally, microplastics may interact with nitrogen fertilizers. Adsorption of ammonium or nitrate ions onto plastic surfaces can alter nutrient availability for microbes and plants, potentially affecting crop productivity and nitrogen use efficiency. Repeated fertilizer applications in soils with high microplastic content may amplify these effects, leading to altered nitrogen dynamics over time.

4.3 Phosphorus Cycling

Phosphorus availability is a critical limiting factor in agricultural systems and is largely regulated by microbial activity and soil chemistry. Microplastics can influence phosphorus cycling by affecting phosphate-solubilizing microbial populations and enzyme activities. Laboratory studies suggest that microplastic amendments can decrease the activity of phosphatase enzymes, reducing phosphorus mineralization and bioavailability for plants [3], microplastic particles can adsorb phosphates directly, either through surface charge interactions or via associated biofilms, thereby sequestering phosphorus and limiting its mobility. This effect is particularly pronounced for microplastics with high surface area or functionalized chemical groups, which can bind anions and organic phosphorus compounds. Over time, this may lead to nutrient imbalances in soils, affecting crop growth and soil fertility. Interactions between microplastics and co-contaminants can further complicate phosphorus dynamics. For example, metals such as iron, aluminum, and cadmium can bind to plastic surfaces along with phosphate ions, modifying solubility and microbial accessibility. Such complex interactions underscore the need for holistic studies that consider microplastic type, environmental conditions, and soil chemistry simultaneously.

4.4 Integrated Implications for Soil Nutrient Cycling

Collectively, the effects of microplastics on carbon, nitrogen, and phosphorus cycling indicate that these contaminants can alter the fundamental nutrient dynamics of agricultural soils. Changes in microbial community composition and functional activity may reduce soil fertility, disrupt nutrient availability, and potentially compromise crop productivity. The magnitude and direction of these impacts depend on multiple interacting factors, including plastic type, size, concentration, soil properties, microbial diversity, and management practices. Long-term accumulation of microplastics could exacerbate these effects by creating persistent physical and chemical alterations in soils. Furthermore, the interaction of microplastics with fertilizers, pesticides, and organic amendments may amplify nutrient cycling disturbances, particularly in intensively managed agricultural systems. Addressing these challenges requires integrative research that combines field studies, laboratory experiments, molecular microbial analyses, and biogeochemical modeling to predict ecosystem-level consequences and inform sustainable management strategies.

5. Knowledge Gaps and Future Research Directions

Despite the increasing body of research on microplastic pollution in agricultural soils, several critical knowledge gaps persist.

Most studies to date are short-term and conducted under controlled laboratory conditions, limiting the ecological realism and applicability of the findings to field settings. There is also a lack of detailed understanding regarding polymer-specific effects; few investigations have distinguished the impacts of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and other common polymers on soil microbial communities and nutrient cycling. Interactions between microplastics and agrochemicals, including fertilizers, pesticides, and heavy metals, remain underexplored, yet these combined stressors may significantly influence microbial activity and nutrient dynamics. Furthermore, mechanistic insights into microbial functional responses are limited, particularly at the gene level, where changes in metabolic pathways and resistance gene expression could have profound consequences for soil ecosystem functioning. Another important research gap concerns soil-plant-microbe interactions, as the effects of microplastics on rhizosphere communities, root-associated microbes, and nutrient uptake by crops remain poorly characterized. Addressing these gaps will require integrative approaches that combine field-based monitoring, molecular microbial techniques, and isotopic tracing to track nutrient fluxes. Long-term studies under realistic agricultural conditions, considering polymer type, particle concentration, co-contaminants, and management practices, are essential for a comprehensive understanding of microplastic impacts and for informing sustainable soil management strategies.

6. Conclusions

Microplastic pollution represents a growing and pervasive threat to agricultural soil health, with significant implications for microbial communities and nutrient cycling. Accumulating evidence indicates that microplastics can alter the composition and diversity of soil microbiota, favoring certain taxa while suppressing others, which in turn affects key microbial functions such as decomposition, nitrogen transformation, and phosphorus mineralization. These microbial shifts have cascading effects on carbon, nitrogen, and phosphorus dynamics, potentially altering nutrient availability, soil fertility, and overall agroecosystem productivity. The physical presence of microplastics in soil also modifies soil structure, aggregation, and porosity, further influencing microbial habitat, water retention, and biogeochemical processes.

The magnitude and direction of these effects are influenced by a combination of factors, including polymer type, particle size and shape, soil texture, environmental conditions, and interactions with co-occurring contaminants such as fertilizers, pesticides, and heavy metals. Laboratory studies have provided valuable mechanistic insights, yet long-term field research under realistic agricultural conditions remains limited, constraining the ability to predict cumulative impacts over time, the widespread use of plastics in modern agriculture, understanding microplastic–soil–microbiota interactions is critical for sustainable soil management. Future research should prioritize long-term, field-based studies, differentiate the effects of specific polymers, explore interactions with agrochemicals, and investigate soil-plant-microbe dynamics to better understand nutrient cycling disruptions. Integrating molecular microbial analyses, functional assays, and biogeochemical monitoring will be essential to inform mitigation strategies, agricultural best practices, and policy interventions aimed at minimizing microplastic contamination while maintaining soil health and productivity in the face of ongoing environmental pressures.

Table 1: Major Sources of Microplastics in Agricultural Soils

Source	Description	Polymer Types	Reference
Plastic Mulches	Films used for moisture retention and weed control	PE, PP	[1][13]
Irrigation & Pipes	PVC and PE pipes, tubing	PVC, PE	[14]
Sewage Sludge & Compost	Sludge and compost containing microplastics	PE, PP, PS	[15]
Degraded Packaging & Mulch Residues	Fragmentation of larger plastics	Mixed	[17]

Table 2: Effects of Microplastics on Soil Microbial Communities

Microplastic Type	Observed Effect	Microbial Impact	Reference
Fibers	Surface colonization	Enrichment of polymer-degraders; reduced diversity	[8]
Fragments	Altered aggregation	Shifts in bacterial/fungal ratio	[20]
Films	Habitat heterogeneity	Variable effects on enzyme activity	[2][12]

Table 3: Impact of Microplastics on Nutrient Cycling

Nutrient	Effect of Microplastics	Mechanism	Reference
Carbon	Altered decomposition, sequestration	Microbial metabolism, aggregation	[2]
Nitrogen	Variable nitrification & denitrification	Microbial community shifts	[6][9]
Phosphorus	Reduced mineralization	Enzyme activity, adsorption to plastics	[3]

References

1. Zhang, G. S., & Liu, Y. F. (2018). The distribution of microplastics in soil from mulched farmland in China. *Science of the Total Environment, 616–617*, 1056–1065.

2. Li, X., Chen, L., Jin, Y., & Zhang, H. (2020). Microplastics in agricultural soils: Sources, pollution, and environmental risks. *Science of the Total Environment, 708*, 134999.

3. Rillig, M. C., & Lehmann, A. (2020). Microplastic in terrestrial ecosystems. *Science, 368*(6498), 1430–1431.

4. Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., Becker, R., Görlich, A. S., Rillig, M. C. (2019). Impacts of microplastics on the soil biophysical environment. *Environmental Pollution, 253*, 993–1000.

5. Qi, Y., Yang, X., Pelaez, A. M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V. (2018). Macro- and micro-plastics in soil: Impacts on soil properties and microbial activity. *Environmental Pollution, 242*, 1353–1361.

6. Wan, Y., Wu, C., Xue, Q., Hui, X. (2019). Effects of microplastics on microbial community composition in agricultural soil. *Environmental Pollution, 254*, 112995.

7. 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*, 7137–7146.

8. Huang, Y., Zhao, Y., Wang, J., Zhang, M., Ma, L., Li, M., Shen, C., Zhang, R. (2021). Microplastic impacts on soil microbial communities and activities. *Journal of Hazardous Materials, 403*, 123765.

9. Rillig, M. C., Ziersch, L., Hempel, S. (2019). Microplastic effects on soil biogeochemical cycling. *Soil Biology and Biochemistry, 135*, 133–140.

10. 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. (2018). Microplastics as vectors for environmental pollutants in terrestrial ecosystems. *Environmental Pollution, 239*, 117–125.

11. Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding of sources, fate, and risks. *Environmental Toxicology and Chemistry, 36*(3), 550–562.

12. Li, R., Zhang, Y., Liu, X., & Zhang, K. (2020). Effects of microplastics on soil nutrient cycling and enzyme activity: A meta-analysis. *Science of the Total Environment, 721*, 137656.

13. Nizzetto, L., Futter, M., & Langaas, S. (2016). Are agricultural soils dumps for microplastics of urban origin? *Environmental Science & Technology, 50*(20), 10777–10779.

14. van den Berg, W., & Rillig, M. C. (2020). Implications of microplastics for soil function and agricultural sustainability. *Current Opinion in Environmental Science & Health, 13*, 1–6.

15. Qi, R., Li, L., Liu, Q., Hu, J., Zhu, S. (2021). Microplastics in agricultural soils: Occurrence, fate, and impacts on microbial-mediated processes. *Journal of Soils and Sediments, 21*, 2450–2465.

16. Boots, B., Russell, C. W., & Green, D. S. (2019). Effects of microplastics on soil invertebrates: A meta-analysis. *Environmental Pollution, 246*, 117–124.

17. Zhang, H., Chen, L., Li, X., Jin, Y., & Wang, S. (2022). Microplastic fibers alter soil microbial communities and nutrient cycling in agricultural soils. *Environmental Pollution, 306*, 119350.

18. Huang, R., Zhang, H., Li, X., Liu, X., Zhang, S., & Li, Y. (2021). Interactive effects of microplastics and fertilizers on soil microbial activity and nutrient availability. *Science of the Total Environment, 779*, 146396.

19. Rillig, M. C., Ingraffia, R., de Souza Machado, A. A. (2017). Microplastic incorporation into soil aggregates affects soil structure and microbial activity. *Environmental Science & Technology, 51*(14), 7900–7908.

20. Zhang, G., Liu, Y., & Wang, X. (2020). Microplastic pollution in agricultural soils: Sources, fate, and effects on soil organisms and crop productivity. *Science of the Total Environment, 707*, 136050.