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MICROPLASTICS AND NANOPLASTICS IN AGRICULTURAL SOIL PROPERTIES, MICROBIAL COMMUNITIES, AND CROP PRODUCTIVITY: A REVIEW

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ABSTRACT
The appearance of microplastics (MPs) and nanoplastics (NPs) as environmental contaminants has generated great concern about the sustainability of agriculture, soil fertility and food security. The application of plastic mulch films, irrigation systems, greenhouse covers, sewage sludge, compost and other agricultural inputs containing plastic waste is responsible for increased contamination of agricultural soils with plastic particles. Microplastics are defined as plastic particles smaller than 5 mm, while nanoplastics are considerably smaller particles usually described as below 1 µm, although there might be some differences in definition depending on the research. They interact with soil minerals, organic matter, water and microorganisms, affecting the physical, chemical and biological properties of soil. MPs may affect the properties of soil aggregates, soil bulk density, porosity, soil water content, soil pH, nutrient content and activities of soil enzymes. Also, MPs may affect microbial diversity, community structure and functional activities related to C, N and P cycles. Exposure to microplastics and nanoplastics in plants may affect seed germination, root growth, nutrient content, photosynthesis, oxidative stress and biomass production. But the intensity and nature of their effects are variable depending on plastic type, particle size, concentration, shape, duration of exposure and plant species. This review summarizes the major sources, environmental behaviour and ecological effects of microplastics and nanoplastics in agricultural soils, with particular emphasis on soil properties, microbial communities and crop productivity. It also discusses research gaps and potential management strategies for reducing plastic contamination and maintaining sustainable agricultural production.

KEYWORDS: Agricultural soil, Microplastics, Nanoplastics, Soil health, and Soil microbiome

1. INTRODUCTION

Plastic materials play an essential role in contemporary agriculture due to their high durability, flexibility, low cost, and broad application possibilities. Plastics are used in agricultural practice in the form of mulching films, greenhouses covers, irrigation pipes, seedling trays, fertilizers coatings, packaging, and protective nets to enhance crop productivity and optimize resource consumption. However, despite numerous benefits of the materials, their improper disposal, weathering, and fragmentation have become sources of environmental pollution, (Boctor, et al., 2025).

Nowadays, MPs and NPs are regarded as contaminants of terrestrial ecosystems. Microplastics can be defined as plastic fragments that are less than 5 mm in size according to a commonly accepted definition, while nanoplastics are plastic fragments that are less than 1 µm in size. MPs can be generated due to fragmentation of plastics or produced directly during the manufacturing, application, and decomposition of plastic products, (Bethanis et al.,2024).

Soils in the agricultural area are prone to plastic contamination due to intensive plastic application and regular application of organic materials and irrigation water to the agricultural lands (Wu, et al., 2024). Soil contamination with plastics occurs via such routes as plastic mulch debris, sewage sludge, wastewater irrigation, polluted compost, and air deposition. Once introduced into the soil, these particles may persist, undergo physical and chemical transformation, interact with soil constituents and affect soil organisms, (de Souza Machado et al., 2018).

The effects of microplastics on terrestrial ecosystems were highlighted by de Souza Machado et al. (2018), who identified their potential to influence soil geochemistry, biological interactions and ecosystem functioning. Subsequent research has demonstrated that microplastics can modify soil physical characteristics and influence

plant performance (de Souza Machado et al., 2019). Soil is a dynamic biological system that supports plant growth through nutrient cycling, water regulation, organic matter decomposition and interactions among microorganisms, soil fauna and plant roots. Any disturbance in these processes may influence soil fertility and agricultural productivity. Therefore, understanding the interactions of microplastics and nanoplastics with soil properties, microbial communities and crop plants is essential for developing sustainable agricultural practices.

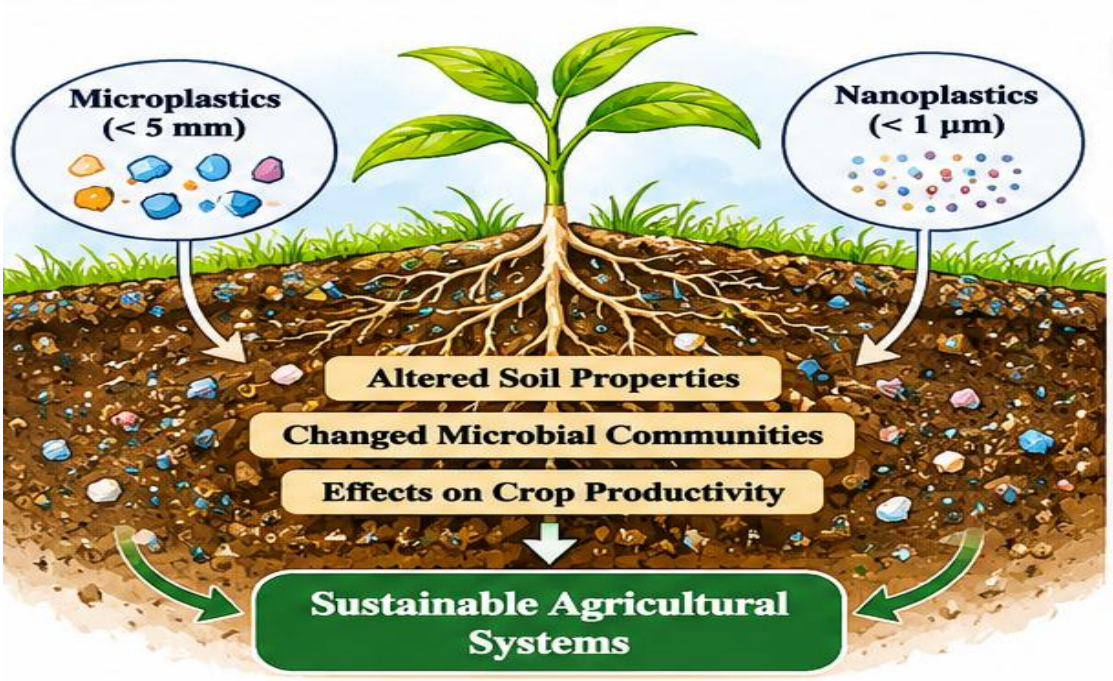


Fig.-1. Used of Microplastics and Nanoplastics in agriculture

2. Sources of Microplastics and Nanoplastics in Agricultural Soil

The sources of plastics pollution in the soil are many. The major sources of plastics are explained below.

2.1 Use of Plastic Mulching

Use of plastic mulching in agriculture is widely practiced for moisture conservation, weed suppression, controlling soil temperature and for better-quality production. PE is commonly used plastic film for agricultural mulching. Prolonged exposure of plastics to ultraviolet radiation, changing temperatures, mechanical operations and microbes leads to degradation of plastic material and fragmentation into small pieces. Uncontrolled disposal of agricultural mulch films after harvest is one of the sources of microplastics pollution, especially in vegetable farms, (Salama, and Geyer, 2023).

2.2 Sewage Sludge and Organic Soil Amendments

Sewage sludges and other wastewater-based organic materials could have significant amounts of microplastics within them. The use of such materials for enriching the organic matter content and nutrients of soils would add microplastics to the soil matrix, (Nath, et al., 2024).

Compost prepared from urban solid waste and inadequately separated organic wastes might contain plastics. The repeated application of such contaminated materials would lead to an increased concentration of microplastics within agricultural lands, (Bandini, et al., 2024).

2.3 Irrigation Water

Water used for irrigation purposes such as that from rivers, wastewater treatment facilities, drainage channels and contaminated surface water bodies might contain microplastics within them. Such microplastics might get accumulated within the upper soil layers or infiltrate into deeper soil horizons depending on their size, shape, density and other factors, (Wolff Leal, et al., 2025).

2.4 Fertilizers and Agricultural Inputs

Plastic coated fertilizers, polymer based slow release fertilizers and other agricultural contaminants could lead to the presence of microplastics within soil. There are instances of some agricultural chemicals and fertilizers being sold in plastic containers as well, (Azeem, et al., 2021).

2.5 Atmospheric Deposition

Plastic fibres and fragments originating from textiles, industries, road traffic, and other anthropogenic sources can become airborne, travel through the atmosphere, and deposit in agricultural soils. Atmospheric deposition constitutes yet another contamination pathway, even for those locations in which the usage of plastic is not high, (Boctor et al., 2025).

Table 1. Major sources of plastic contamination in agricultural soils

Sources	Examples	Entry pathways
Agricultural plastics	Mulch films, greenhouse covers	Fragmentation and weathering
Wastewater	Treated and untreated wastewater	Irrigation
Organic amendments	Sewage sludge and compost	Repeated soil application
Fertilizer products	Polymer-coated fertilizers	Application of agricultural inputs
Atmospheric deposition	Plastic fibres and dust	Wind and rainfall
Plastic waste	Packaging, irrigation pipes and containers	Improper disposal and fragmentation

3. Behavior and Transformations of Microplastics and Nanoplastics in Soils

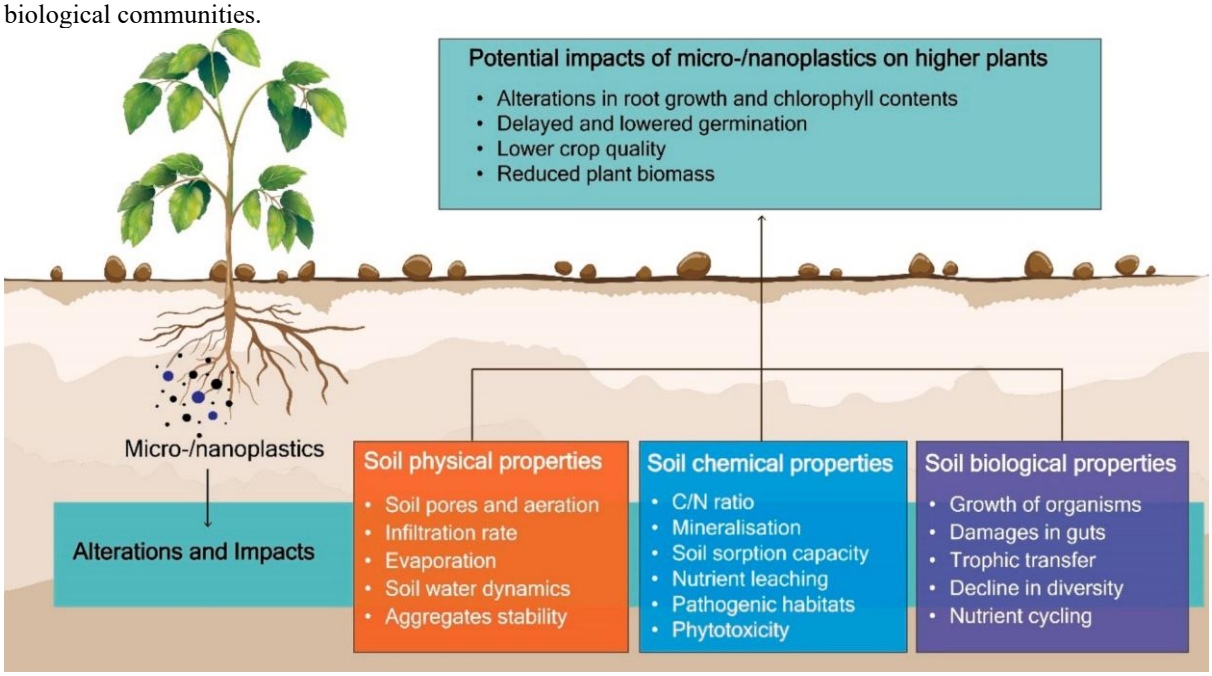
Several physical, chemical, and biological transformation processes take place after the entry of plastic particles into agricultural soils. The behavior of plastics in the environment is determined by their polymers, sizes, densities, surface properties and their interaction with soil components, (Shafea, et al., 2023).

Physical processes such as tillage, erosion, irrigation, and rainfall affect the re-distribution of plastic particles. Light weight plastic particles can get transported by the surface runoff, while smaller particles can travel through soil pores along with infiltrating water, (Liu, et al., 2021). Chemical weathering, ultraviolet radiation and oxidation can alter the surface properties of plastic particles. These processes may increase surface roughness and modify their ability to interact with soil minerals, organic matter and environmental contaminants.

Biological processes involving bacteria, fungi and soil fauna may contribute to surface modification and partial degradation of some polymers (Shi, et al., 2022). However, complete biodegradation and mineralization of conventional plastics generally occur slowly under natural soil conditions.

Nanoplastics are particularly important because their smaller particle size provides a relatively high surface-area-to-volume ratio and may facilitate interactions with biological membranes and soil constituents. Nevertheless, their movement, persistence and uptake by plants remain difficult to quantify because of analytical limitations.

Astner et al. (2023) emphasized that the formation, transport and environmental effects of microplastics and nanoplastics in agricultural soils are influenced by complex interactions among particles, soil constituents and biological communities.

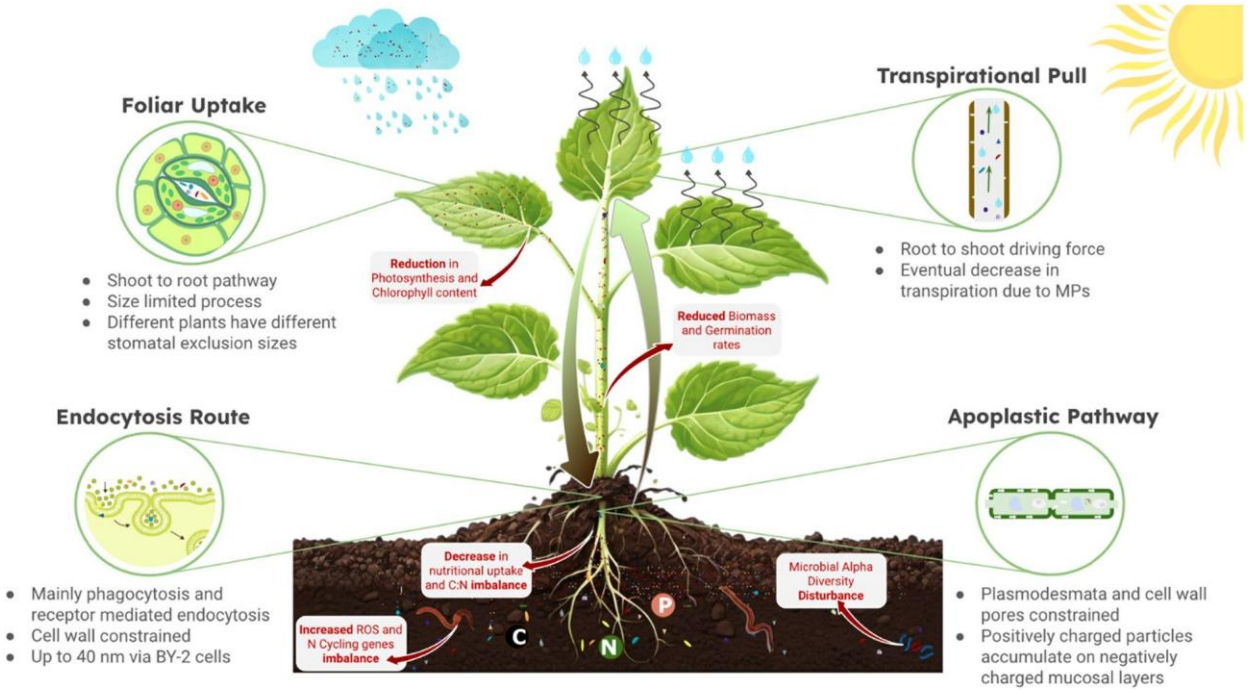


(Source., Seo et al., 2024)

Fig. 2. Potential alterations and impacts of micro-/nanoplastics on properties of the soil based on current studies.

4. Effect of Microplastics and Nanoplastics on Physical Properties of the Soil

Physical properties of soil affect the movement of water through the soil, aeration, root development, stability of soil aggregates and the ability of soil to support plant growth (Hanif, et al., 2024). Addition of plastics may alter these properties.



(Source, Boctor et al., 2025)

Fig. 3. Schematic representation of the uptake and translocation pathways of microplastics (MPs) and nanoplastics (NPs) in plants, illustrating root-to-shoot and shoot-to-root transport mechanisms and their potential effects on soil organisms, plant physiological functions, and overall crop growth and development.

Table 2. Summary of adverse effects of micro-/nano- plastic on plant germination.

Plant Specie	**Polymer Type**	**Effect**	
White clover (*Trifolium repens* L.) Chinese violet cress (*Orychophragmus violaceus)* Garden balsam (*Impatiens balsamina* L.)	Polystyrene (PS)	Germination rate reduction	(Guo, et al., 2022)
Onion (*Allium cepa* L.)	Polystyrene (PS)	No effect on seed germination	(Giorgetti, et al., 2020)
Rice (*Oryza sativa* L.)	Polystyrene (PS) Polytetrafluoroethylene (PTFE) Polyethylene and biodegradable mulch films	Germination rate reduction	Dong, et al., 2020 and Yang, C., & Gao, X. (2022).
Black Gram (*Vigna mungo* L.)	Polyethylene (PE)	Germination rate reduction	Sahasa, et al., 2023)
Tomato (*Solanum lycopersicum* L.)	Polyethylene (PE)	No effect on seed germination	Sahasa, et al., 2023)

(Source, Jadhav, et al., 2024)

4.1 Bulk Density and Porosity

Unlike the mineral particles, microplastics have different density, shape and structural features. These properties may lead to changes in soil bulk density and porosity characteristics. Fibers and irregularly shaped particles may provide extra space in the soil matrix, while other shapes may block soil pores. Direction of the effect will depend on the type of polymer, shape of the particle, amount of particles and soil texture. Decrease in bulk density has been shown in some experiments, but it is not a common effect, (Hui, et al., 2024).

4.2 Soil Aggregation and Structural Stability

Aggregation of soil is important for maintaining good soil structure, its infiltration and resistance to erosion. Microplastics may affect soil aggregation and stability by affecting the processes of interaction between mineral particles, organic matter and biological binders, (Liu, et al., 2021). Changes in aggregate stability may influence soil aeration, root growth and the availability of water and nutrients. De Souza Machado et al. (2018) demonstrated that microplastics can influence the biophysical environment of soil, indicating their potential to affect important soil structural processes.

4.3 Water Retention Capacity of Soil

The addition of microplastics may have an effect on the ability of the soil to retain and infiltrate water. The fibrous material will enhance water retention in some soils while the shape of other plastics may lower the hydraulic conductance or affect the water distribution. It largely depends on the nature of soil composition, the type of polymer, and the quantity of plastics present in the soil mixture, (Mondol et al., 2025).

4.4 Temperature and Evaporation

Plastic mulching films are added to soil for the purpose of changing its temperature and evaporation process. However, plastic fragments that remain in the soil after mulching can have various impacts on heat conductivity, moisture in the soil, and evaporation process (Aminzadeh, et al., 2025). These impacts depend on the color and surface properties of plastic fragments as well as moisture content in the soil. Thus, the long-term impact of plastics on the thermal properties of soil needs to be explored further.

Table 3. Effects of microplastics and nanoplastics on agricultural soil properties and crop production

Soil/crop parameter	Major effects	Possible agricultural consequences
Bulk density	Alteration of soil density	Changes in root penetration
Soil porosity	Modification of pore distribution	Changes in aeration and water movement
Aggregate stability	Changes in soil aggregation	Soil structural degradation
Water-holding capacity	Altered soil water retention	Changes in plant water availability
Soil pH	Possible changes depending on plastic type	Altered nutrient availability
Organic carbon	Changes in decomposition processes	Disturbance in carbon cycling
Nitrogen cycling	Changes in microbial nitrogen transformations	Altered nitrogen availability
Microbial diversity	Changes in microbial abundance and composition	Disturbance in soil biological functions
Enzyme activities	Changes in urease, phosphatase and dehydrogenase	Altered nutrient mineralization
Crop growth	Effects on roots, shoots and photosynthesis	Variable biomass and yield responses

Source: Compiled from de Souza Machado et al. (2018, 2019), Zhu et al. (2022), Astner et al. (2023) and Bethanis and Golia (2024).

5. Impact on Soil Chemical Characteristics and Nutrient Dynamics

The impact of microplastics and nanoplastics can be manifested directly via interaction with soil elements and indirectly due to alterations of microbial activity.

5.1. Soil pH and Electrical Conductivity

The soil pH and electrical conductivity may change as a result of the leaching of additives and surface oxidation products as well as associated chemicals. This impacts the availability of nutrients and soil microbial activity, (Hossain, et al., 2020).

However, such effects vary depending on the type of soil, plastic material, and conditions of polymer aging, plastic concentration, and soil chemical properties.

5.2. Soil Organic Carbon

Microplastics may impact the decomposition and mineralization of organic matter in soils. They may impact the activity of microbes, the accessibility of organic matter, and the interaction of organic matter compounds with mineral surfaces, (Basumatary, et al., 2025).

5.3 Nitrogen Cycling

Nitrogen availability is essential for plant growth and agricultural productivity. Microplastic contamination may influence nitrogen transformation processes, including ammonification, nitrification and denitrification, through changes in microbial community structure and activity.

Zhu et al. (2022) reported that PVC microplastics and their associated plasticizer could alter soil microbiome composition and nitrogen cycling. Changes in ammonium and nitrate concentrations may consequently affect nitrogen availability to crops.

5.4 Phosphorus and Potassium Availability

Microplastics may influence phosphorus availability by modifying soil microbial activity, phosphatase enzyme activity and interactions between nutrients and soil particles (Zhang, et al., 2026). Similar indirect effects may occur in potassium dynamics through changes in soil structure and microbial processes. However, the available evidence regarding phosphorus and potassium is comparatively limited, and responses vary with soil type and plastic characteristics.

5.5 Adsorption and Transport of Other Contaminants

Microplastic surfaces may interact with pesticides, heavy metals and other organic contaminants. Their weathered surfaces can provide sites for adsorption, potentially modifying the mobility, persistence and bioavailability of associated contaminants, (Prajapati, et al., 2022). Such interactions may influence the movement of contaminants through soil–plant systems and create additional ecological risks. However, whether microplastics increase or decrease contaminant availability depends on the properties of the plastic, contaminant and surrounding soil environment.

6. Effects on Soil Microbiological Communities

Microorganisms in the soil are very important parts of agricultural ecosystems, since they control nutrient cycling, decomposition of organic matter, soil fertility, and plant-microorganism associations (Hao, et al., 2024). Microplastics and nanoplastics can affect soil microbiological communities by changing the physical environment, creating a substrate for microbial colonization, and releasing chemical additives.

6.1 Microbial Diversity and Community Structure Alterations

Microplastics may serve as an artificial substrate for microbial habitats which are called plastisphere. Microorganisms such as bacteria and fungi can colonize plastic surfaces and form specific microbial communities. But the presence of plastic particles can affect the number and diversity of indigenous soil microorganisms; some microbial populations may be stimulated, while other microorganisms may be inhibited depending on the type of plastic, its concentration, and environmental conditions.

Shi et al. (2022) found out that microplastics made soil microbial networks less complex and affected ecological selection processes. Also, Gao et al. (2021) found out that the presence of microplastics changed microbial communities in vegetable-growing soil.

6.2 Effects on Soil Enzyme Activities

Soil enzymes play important roles in organic matter decomposition and nutrient mineralization. Important enzymes include:

- Dehydrogenase: An indicator of overall microbial oxidative activity.
- Urease: Involved in the conversion of urea into ammonium.
- Phosphatase: Associated with organic phosphorus mineralization.
- β-glucosidase: Involved in carbon cycling and cellulose decomposition.
- Catalase: Helps microorganisms manage oxidative stress.

Microplastic contamination may increase or decrease the activities of these enzymes depending on the soil environment, polymer type and exposure concentration (Russo et al., 2023). Inhibition of important enzyme activities may disturb nutrient cycling and reduce the efficiency of biological soil processes.

6.3 Effects on Beneficial Microorganisms

Beneficial soil microorganisms, including Rhizobium, Azotobacter, phosphate-solubilizing bacteria, mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), contribute significantly to sustainable crop production, (Khan et al., 2026). Microplastic contamination may influence their abundance, colonization and functional activities. Changes in microbial communities may affect biological nitrogen fixation, phosphorus solubilization, nutrient acquisition and plant growth promotion.

6.4 Effects on Carbon and Nitrogen Cycling

Microplastics can modify microbial processes associated with carbon decomposition and nitrogen transformations. Changes in bacterial community composition may influence soil respiration, organic carbon mineralization, nitrification and denitrification. Xiao, et al. (2022) demonstrated that microplastics influenced bacterial community succession and organic matter decomposition in paddy soil. Similarly, Zhu et al. (2022) highlighted the role of plastic-associated chemicals in altering microbial communities and nitrogen cycling.

7. Impact on Crop Growth and Productivity

Productivity of crops is determined through the interaction of soil physical properties, nutrient availability, root development, microbial activities and physiology of plants (Jadhav, et al., 2024). The impacts of microplastics and nanoplastics can affect some of these factors, (Hui, et al., 2024).

7.1 Seed Germination and Establishment

Seed germination is affected by soil conditions such as moisture content, contact of seed with the soil and nutrient availability. Microplastic contamination could affect soil moisture content, contact of seed with the soil and nutrient availability, (Li, et al., 2023). Nanoplastics can interact with seeds and impact seed germination process and establishment of seedlings. These interactions can enhance or inhibit the germination depending on the size and concentration of particles.

7.2 Root Growth and Development

Roots are the first organs of plants to interact with soil that is contaminated with microplastics. The presence of microplastic particles in the soil can affect root zone structure, soil aeration and water availability, (Chen, et al., 2022).

Because of small sizes of nanoplastics, they can interact with root surface and enter roots in certain experimental conditions. Interaction of nanoplastics can impact root growth, lateral root development and nutrient uptake. It depends on the particle characteristics and experimental conditions, (Roy et al., 2023).

7.3 Nutrient Uptake and Plant Nutrition

Healthy root systems and beneficial soil microorganisms are essential for the uptake of nitrogen, phosphorus, potassium and micronutrients. Microplastic-induced changes in soil nutrient availability and microbial activity may disturb nutrient acquisition. Consequently, plants may experience nutrient imbalances, which can affect vegetative growth, flowering, fruit development and yield formation, (Arshad, et al., 2026).

7.4 Photosynthesis and Oxidative Stress

Exposure to microplastics and nanoplastics may influence chlorophyll content, photosynthetic efficiency and antioxidant defence mechanisms. Some experimental studies have reported increased production of reactive oxygen species (ROS), which may cause oxidative damage to cellular membranes, proteins and other cellular components, (Liu, et al., 2022).

Plants may respond by activating antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), (Gao, et al., 2023). The intensity of these responses depends on crop species, particle characteristics and exposure levels.

7.5 Plant Biomass and Crop Yield

Microplastics and nanoplastics may affect shoot biomass, root biomass, plant height, leaf area and final crop yield. The response varies considerably among crops and experimental conditions.(Nath, et al., 2024). reported that microplastic and nanoplastic exposure significantly affected root and shoot growth, with differences among crop species.

Lettuce showed comparatively high sensitivity, while wheat exhibited greater resistance under the conditions evaluated. These findings indicate that crop responses cannot be generalized across all agricultural species. More field-based research is needed to establish the actual consequences for commercial crop productivity, (Jadhav, et al., 2024).

8. Crop Species-Specific Impacts of Microplastic and Nanoplastic Pollution

There are various impacts of plastic pollution on different crops depending on the differences in root architecture, plant physiology, duration of growth and nutrient needs.

8.1 Cereals: The main crops which can suffer from plastic pollution are wheat, rice, and maize. These food crops can suffer from changes in root growth, nutrient absorption and microbial processes in soil.

8.2 Vegetables: Vegetables, including lettuce, spinach, cabbage, tomato, and cucumber may suffer from changes in root zone and nutrient content. The special attention should be paid to leafy vegetables because of the possibility of soil particles to affect their edible part through direct contacts and other pollution sources.

8.3 Fruiting Crops: The long-term soil pollution may affect root formation, nutrient uptake and rhizosphere microbial activity in fruiting crops. There is not enough knowledge about the impact of microplastics on perennial fruiting crops production, quality and performance.

8.4 Leguminous Crops: Legumes need symbiotic relations with nitrogen-fixing bacteria for nitrogen nutrition. It is possible that root nodule formation and microbial processes will change.

8.5 Tuber and Root Crops: Potato, radish, carrot and other underground crops develop edible organs within the soil environment. Consequently, the interaction of plastic particles with roots and edible storage organs deserves particular attention, although particle detection in edible tissues must be supported by reliable analytical evidence.

Table 4. Reported internalization of micro-/nanoplastics in plants.

Exposure environments	Plant	Type of MNPs	Size (μm)	Location	Detection device	Ref.
Soil	Thale cress (*Arabidopsis thaliana*)	PS	0.04	Root tips	TEM LCSM	(Sun et al., 2020)
Hydroponics Sand matrices Sandy soil	Wheat (*Triticum aestivum*) Lettuce (*Lactuca sativa*)	PS PMMA	0.2 2.0	Root Stem Leaf	SEM With fluorescence labelling	(Li et al., 2020a)
Agar growth media	Thale cress (*Arabidopsis thaliana*) Wheat (*Triticum aestivum*)	PS	0.04 1	Root tips	LCSM	(Taylor et al., 2020)

Hydroponics	Faba bean *(Vicia faba)*	PS	0.15	Root	LCSM	(Jiang et al., 2019)
Hydroponics	Maize (*Zea mays* L.)	PS	0.2 2.0	Root	LCSM SEM	(Li et al., 2023a)
Hydroponics	Lettuces (*Lactuca sativa* L.)	PS	0.2	Root Stem Leaf	LCSM	(Li et al., 2019)
Hydroponics	Wheat (*Triticum aestivum* L.)	PS	0.2	Root Shoot	Hyperspectral-enhanced-dark field microscopy SEM	(Li et al., 2023b)
Hydroponics	Cucumber (*Cucumis sativus*)	PS	0.1	Root Stem Leaf	SEM	(Li et al., 2021)
Foliar spray	Lettuces (*Lactuca sativa* L.)	PS	0.0936	Leaf Stem Root	TEM SEM	(Lian et al., 2021)
Foliar spray	Maize (*Zea mays* L.)	PS-NH_2 PS-COOH	0.022 0.024	Leaf Stem Root	Micro-photoluminescence-spectra SEM	(Sun et al., 2021)

(Source., Seo et al., 2024)

Note. SEM: scanning electron microscopy, TEM: transmission electron microscopy, LCSM: laser scanning confocal microscopy.

9. Microplastics, Nanoplastics and Food Security

The presence of plastic particles in agricultural soils raises concerns regarding soil health, crop quality, food contamination and long-term agricultural sustainability.

Potential transfer of plastic particles from soil to plants has attracted considerable research attention. Smaller particles may interact with root tissues, while larger particles may remain associated with external plant surfaces (Chen et al., 2022). However, the extent of internal uptake, translocation and accumulation in edible plant tissues remains uncertain.

Plastic additives and associated contaminants may also contribute to ecological risks. Their potential transfer through soil–plant systems requires systematic investigation, (Mithun, et al., 2024). It is important to distinguish between the detection of plastic particles in soil, their uptake by plants and their actual accumulation in edible tissues. These are separate scientific questions and require validated analytical methods.

Maintaining soil health and minimizing plastic contamination are therefore important components of sustainable agriculture and long-term food security.

10. Detection and Characterization of Microplastics and Nanoplastics in Agricultural Soil

Accurate detection and characterization of plastic particles is required to understand the distribution and effects of micro/nano plastics. The common analysis methods include:

10.1 Visual Sorting and Microscopic Analysis: Stereo and optical microscopy are used for preliminary detection and sorting of plastic-like particles based on their colour, shape, and size. Nevertheless, visual detection is not enough for confirmation of polymer types.

10.2 Fourier Transform Infrared Spectroscopy (FTIR): FTIR spectroscopy detects specific infrared absorption pattern that determines the type of plastic polymer. Micro-FTIR can be applied to identify relatively small particles.

10.3 Raman Spectroscopy: Raman spectroscopy determines the information about vibrations of molecules and polymer composition. It can be useful for identification of small plastic particles; nevertheless, fluorescence and interferences from samples can hinder the process.

10.4 Scanning Electron Microscopy (SEM): SEM provides data about surface morphology, cracks, weathering, and structural properties of particles. Usually this method is used together with chemical analysis.

10.5 Pyrolysis-Gas Chromatography–Mass Spectrometry (Py-GC-MS): This method allows the determination of polymer types and their quantity according to thermal decomposition products. Nevertheless, it cannot give data about number, shape, and size of particles.

10.6 Nanoplastic Detection: Nanoplastic analysis is particularly challenging because of extremely small particle dimensions and the difficulty of separating them from natural soil colloids and organic matter. Advanced imaging and spectroscopic approaches, together with appropriate analytical controls, are required. Standardized sampling, contamination prevention, recovery tests, blank controls and reference materials are essential for producing reliable results.

11. Management Strategies for Reducing Plastic Contamination in Agricultural Soil

Effective management requires a combination of preventive measures, improved agricultural practices, waste management and scientific monitoring.

11.1 Proper Collection and Disposal of Plastic Mulch

Farmers should remove used plastic mulch films after crop harvesting and ensure their proper collection, segregation and recycling. Burning or indiscriminate disposal of agricultural plastic waste should be avoided.

11.2 Use of Biodegradable Mulch Films

Biodegradable mulch films may provide an alternative to conventional plastic materials. However, their degradation depends on polymer composition, soil temperature, moisture, microbial activity and environmental conditions.

Their actual biodegradability under field conditions must be verified before large-scale adoption. Biodegradable plastics should not automatically be considered free from environmental risks.

11.3 Improved Quality of Compost and Organic Amendments

Municipal compost, sewage sludge and other organic amendments should be screened for plastic contamination before agricultural application. Source segregation and improved waste treatment can reduce the entry of plastic particles into farmland.

11.4 Safe Irrigation Practices

The quality of irrigation water should be monitored, particularly when treated wastewater is used. Improved wastewater treatment and filtration technologies may help reduce the transport of plastic particles into agricultural soils.

11.5 Sustainable Plastic Management Policies

Agricultural institutions, policymakers and farmers should work together to promote plastic collection, recycling, responsible product use and awareness programmes.

11.6 Biological and Emerging Remediation Approaches

Certain microorganisms have demonstrated the ability to colonize and modify the surfaces of specific plastic polymers. Microbial degradation, enzymatic treatment and other biological approaches are being investigated as potential remediation technologies.

However, the complete removal or mineralization of microplastics and nanoplastics from agricultural soils has not yet been established as a practical, widely applicable field solution.

12. Research Gaps

Though there has been an increase in the research related to it, there is still a lot that remains to be explored in terms of the impact of microplastic and nanoplastic particles on the environment and their behaviour.

Field studies: Most of the current studies have been carried out in laboratory and greenhouse conditions. There is a need for field-based studies to be conducted.

Detection of nanoplastics: Analytical methods need to be improved to detect nanoplastics effectively.

Microbes in the soil: Research can be carried out further in the area of the impact of plastics on soil microbes including mycorrhiza, biological nitrogen fixation and enzymes present in the soil.

Studies related to different crops: Studies on cereal crops, pulses, vegetables, fruits and medicinal plants need to be done to know how susceptible and tolerant different crops are to plastics.

Soil fertility and nutrient cycling: Impact of plastics on soil fertility needs to be studied thoroughly.

Bioaccumulation within food chain: Studies need to determine if plastic fragments are ingested by plants and move from root into edible plant parts in amounts that affect food safety.

Biodegradable plastic polymers: These need to be studied to find out their breakdown products and persistence in various soil types and climates.

Indian agricultural environment: More research needs to be done on plastic pollution in Indian agricultural soils, especially in areas with heavy usage of plastic mulch, vegetables farming, wastewater irrigation and repeated application of organic amendments.

Combination technologies: Researches in future can focus on possible combination of source reduction, waste segregation, good irrigation practices, biological treatment and use of alternative to regular agricultural plastic polymers.

13. Challenges Linked to Micro- and Nanoplastic Contamination in Agricultural Soils

While research on this topic is rapidly growing, assessing and managing plastic pollution in agricultural soils still poses many challenges due to their complexity, persistence and interactions with biological and chemical soil components.

Challenges with Detection and Quantification

One of the problems is accurate detection and quantification of plastic in the soil. Agricultural soils contain organic matter, mineral particles, roots, and other soil organic materials that can complicate plastic identification. Despite the fact that FTIR and Raman spectroscopies are helpful for polymer identification, detection of nanoparticles still remains challenging. The lack of standardized methods also hinders comparison of the results across studies.

Lack of Field-Based Research Over Time

The significant amount of research done is based on laboratory or greenhouse experiments with known concentrations of plastics. Nevertheless, agricultural soils are constantly undergoing temperature changes,

precipitation, tillage, irrigation, and microbial activities. Thus, results obtained from laboratory experiments may not be entirely representative of reality.

Complexity of Soil-Plastic-Microorganism Interactions

Interactions between microplastics and soil minerals, soil organic matter, microorganisms and plant roots are known. Such interactions might affect colonization, transformation of nutrients and activity of enzymes in soil. Nevertheless, the mechanisms that control these responses remain unknown. The effect of various polymers, particle morphology, sizes and aging processes makes the problem even more complex for environmental evaluation.

Uncertainty about Crop Uptake and Food Safety

The potential mobility of micro- and nanoplastics from soil into plants' bodies is an issue of serious concern. However, the information on their uptake, transportation and accumulation in plants' organs that might be used for food is limited. The contamination during analysis and limitations of methodology can cause uncertainties in results. Therefore, standard experimental approach should be developed.

Absence of Efficient Soil Remediation Technologies

It is very difficult to clean microplastics and nanoplastics from the soil due to their small size, extensive distribution and interaction with soil particles. Physical approaches will damage soil structure, while chemical treatment may create new risks for environment. Biological degradation looks perspective; however, it is limited due to low degradation rate of polymers and inability to reach mineralization.

Economic and Policy Constraints

Farming communities might rely on plastic-based agricultural technologies owing to their low cost and efficiency. Switching from conventional plastics to sustainable alternatives can incur extra expenses. Besides, lack of adequate collection facilities, recycling facilities and awareness campaigns might contribute to accumulation of plastic wastes in agriculture.

Table 5. Major challenges and proposed research approaches

Research challenge	Existing limitation	Suggested future approach
Detection of nanoplastics	Difficulty in identifying extremely small particles	Advanced spectroscopy and imaging
Long-term soil impacts	Limited multi-season field data	Long-term field experiments
Microbial interactions	Incomplete understanding of microbial responses	Metagenomics and microbial functional analysis
Crop-specific effects	Limited information across crop species	Comparative crop experiments
Food-chain transfer	Uncertainty about uptake and translocation	Validated root-to-edible-tissue studies
Soil remediation	Lack of scalable removal technologies	Integrated biological and physical approaches
Biodegradable plastics	Variable degradation under field conditions	Soil-based biodegradation assessment
Agricultural monitoring	Lack of standardized protocols	Harmonized sampling and analytical methods

14. Prospects for Future Research

Further research efforts should be devoted to finding scientific, technological and management-based approaches for solving the problem of plastic contamination without hampering agricultural production.

Development of Advanced Analytical Techniques

Better analytical tools need to be devised for identifying, characterizing and quantifying micro- and nanoplastics in agricultural soils. Application of micro-FTIR, Raman spectroscopy, electron microscopy, Py-GC-MS, and other nanoscale analytical techniques might result in improved reliability of plastic detection. Standard procedures of quality control need to be developed in order to facilitate comparison of findings in various geographical locations.

Long-Term Field Studies

Future studies will have to investigate cumulative effects of plastic contamination in different types of soils, under different climatic and cropping regimes. Multi-location and multi-seasonal studies might prove useful in revealing information concerning soil structure, nutrient turnover, microbial biodiversity and crop yield greater attention should be given to Indian agricultural conditions, especially intensively cultivated vegetable-growing areas and regions using plastic mulch and wastewater irrigation.

Use of Molecular and Metagenomic Methods

More advanced molecular techniques, such as 16S rRNA sequencing, ITS sequencing, metagenomics, and metatranscriptomics, may be used to elucidate the changes in soil microbial diversity and activity. These methods could also reveal potentially harmful or beneficial microbial taxa associated with the pollution of soils with plastic

materials. They might improve understanding of the microbial genes responsible for carbon, nitrogen, and phosphorus cycles.

Development of Environmentally Sustainable Plastics for Agriculture

Development of biodegradable and bio-based plastics is another promising research direction. Plastic materials produced from starch, cellulose, polylactic acid, and other renewable resources will decrease the use of conventional non-biodegradable petroleum-based plastics. However, further investigation of the degradation properties of the new materials, their ecotoxicity and influence on the soil microorganisms are needed.

Biological Remediation and Enzymatic Techniques

Microorganisms that can degrade some types of plastics and enzymes of the organisms represent a promising area for future research. Further research should be devoted to the search for appropriate strains of microorganisms and characterization of plastic-degrading enzymes and creation of biologically safe remediation techniques. The actual polymer degradation and mineralization should be demonstrated.

Precision Agriculture and Digital Monitoring

Remote sensing, geographic information systems, and artificial intelligence and machine-learning methodologies might assist in locating areas with higher risks of plastic contamination on agricultural lands. The combination of field surveys, soil analysis, land usage and environmental monitoring could assist in enhancing contamination monitoring and implementing targeted management practices. However, remote sensing detection of microplastics is still an unresolved problem.

Sustainable Soil Health Management Practices

In the future, plastic waste management should be incorporated into conservation agriculture, organic matter management, sustainable nutrient application and protection of beneficial microorganisms inhabiting soils. Continuous soil monitoring and improvement of waste management practices in agriculture could assist in lowering the amount of plastic entering soils.

Guidelines for National and International Level

There is a necessity to develop standard procedures for soil sampling, identification of plastics, risk assessment and environmental monitoring. Research facilities of agriculture, environmental agencies and policymakers should collaborate to produce guidelines for sustainable plastic usage, gathering, recycling and disposal. Training programmes for farmers will also be essential in lowering plastic contamination in fields.

15. CONCLUSION

Microplastics and nanoplastics appear to be new environmental threats to agricultural soils and sustainable agriculture. The constant influx of them through plastic mulches, irrigation waters, sewage sludge, composts and other agricultural inputs can potentially impact soil physical, chemical and biological properties. Soil aggregation, porosity, water retention, nutrients supply, and enzyme activity can potentially affect soil fertility and plant growth.

Microplastics and nanoplastics pollution can also change soil microbial communities' diversity, structure and nutrient cycling. As soil microorganisms perform many important ecological roles, any disruptions in their function can have important consequences for soil health and sustainability of agriculture in the long term.

In plants, plastic particles can potentially impact seed germination, root growth, nutrient uptake, photosynthetic activity, oxidative stress, and biomass accumulation. However, these impacts strongly depend on properties of the particles, concentrations, soil properties and crops type. Therefore, one has to treat current experimental findings very carefully, especially in terms of extrapolation of laboratory results to real yield loss at the field level.

Integrated management involving proper agricultural plastic disposal, improved organic amendment quality, safe irrigation practices, responsible use of biodegradable materials and long-term soil monitoring is essential. Future research should prioritize standardized analytical methods, realistic field experiments and crop-specific investigations. Reducing plastic contamination in agricultural soils will be an important step towards maintaining soil biodiversity, protecting agricultural productivity and ensuring sustainable food systems.

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