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Microplastics in Agricultural Soils: Emerging Challenges for Soil Health and Food Security

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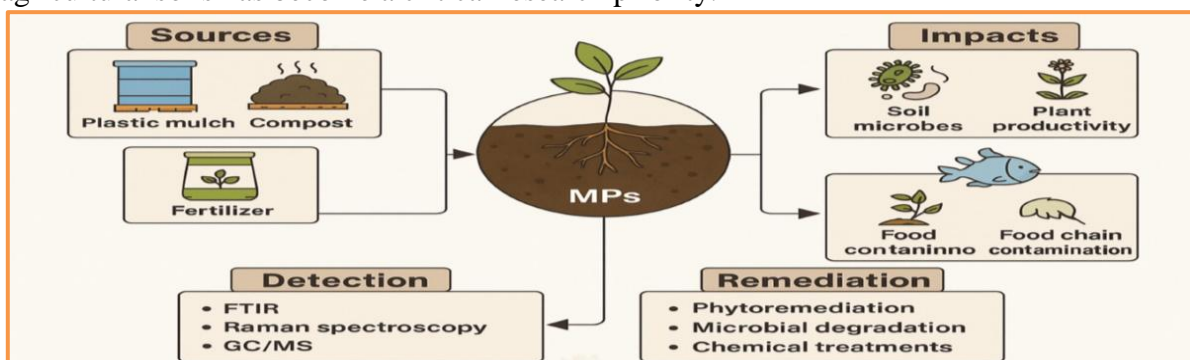
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Microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged as pervasive contaminants in terrestrial ecosystems, particularly agricultural soils. While considerable attention has been devoted to marine plastic pollution, agricultural lands are increasingly recognized as significant reservoirs of microplastics due to intensive farming practices, sewage sludge application, wastewater irrigation, and atmospheric deposition. The accumulation of microplastics in soil can alter physicochemical properties, disrupt soil microbial communities, impair nutrient cycling, and negatively affect plant growth and crop productivity. Furthermore, microplastics serve as carriers of toxic chemicals, pathogens, and antibiotic resistance genes, posing potential risks to food safety and human health. This review examines the major sources of microplastics in agricultural systems, their impacts on soil properties and beneficial microorganisms, implications for crop production and food security, current detection techniques, and potential mitigation strategies. Addressing microplastic contamination is essential for ensuring sustainable agriculture, environmental protection, and long-term food security.

Introduction

Plastic production has increased exponentially over the past decades, exceeding 400 million tonnes annually worldwide. A substantial proportion of plastic waste eventually fragments into microplastics (MPs), which are now detected in virtually every environmental compartment, including agricultural soils. Recent studies suggest that terrestrial ecosystems may accumulate greater quantities of microplastics than marine environments due to continuous inputs from agricultural activities and land-based waste sources. Agricultural soils receive microplastics through multiple pathways, including plastic mulching, sewage sludge application, wastewater irrigation, polymer-coated fertilizers, and atmospheric deposition. Once introduced into the soil environment, these particles persist for long periods because of their resistance to degradation. Their presence can modify soil structure, interfere with microbial processes, reduce nutrient availability, and potentially enter the food chain through crop uptake. As concerns about sustainable agriculture and food security intensify, understanding the occurrence, behavior, and ecological consequences of microplastics in agricultural soils has become a critical research priority.



Sources of Microplastic Contamination in Agricultural Systems



Plastic Mulching Films

Plastic mulching is widely used to improve soil temperature, moisture retention, and weed control. However, prolonged exposure to ultraviolet radiation and mechanical stress causes mulch films to fragment into microplastics that remain in the soil.

Polymer-Coated Fertilizers and Pesticides

Controlled-release fertilizers and pesticide formulations often utilize synthetic polymer coatings. As these coatings degrade, they release microplastic residues into the soil environment.

Sewage Sludge Application

Biosolids from wastewater treatment plants frequently contain high concentrations of microplastics. Repeated land application contributes significantly to microplastic accumulation in agricultural soils.

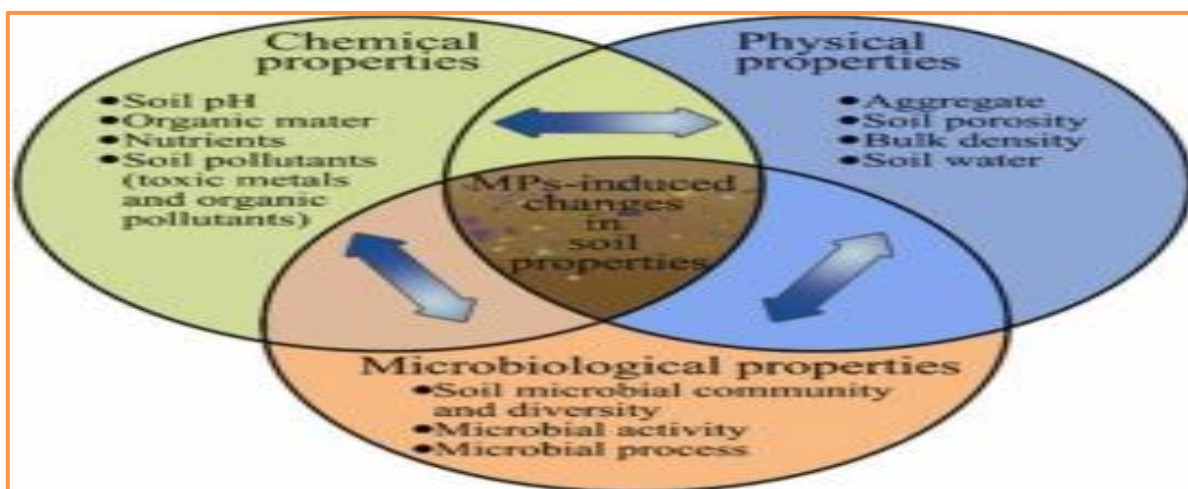
Wastewater Irrigation

Irrigation using reclaimed wastewater introduces synthetic fibers, fragments, and other microplastic particles into agricultural fields, particularly in water-scarce regions.

Atmospheric Deposition

Airborne microplastics originating from urban, industrial, and transportation sources can be transported over long distances and deposited onto agricultural lands.

Impact of Microplastics on Soil Physicochemical Properties



Soil Structure and Aggregation

Microplastics can alter soil aggregation, porosity, and bulk density. Their presence disrupts natural soil particle interactions and may increase susceptibility to erosion and compaction.

Water Retention and Infiltration

Changes in pore structure caused by microplastics affect water infiltration, retention, and distribution within the soil profile. These modifications can influence plant water availability and root development.

Nutrient Cycling

Microplastics interfere with nutrient transformations by altering microbial activity and adsorption processes. They can affect nitrogen, phosphorus, and carbon cycling, reducing nutrient-use efficiency.

Effects on Soil Microbial Communities

Changes in Microbial Diversity

Microplastics create novel microbial habitats known as the "plastisphere." These habitats often favor opportunistic microorganisms while reducing beneficial soil microbes.

Reduction in Enzymatic Activity

Studies have reported decreased activities of soil enzymes such as urease, phosphatase, and dehydrogenase, indicating reduced microbial functionality.

Disruption of Plant–Microbe Interactions

Microplastics negatively affect arbuscular mycorrhizal fungi and nitrogen-fixing bacteria, reducing nutrient acquisition and plant resilience.

Microplastics as Carriers of Pathogens and Antibiotic Resistance

Microplastics provide surfaces for microbial colonization and biofilm formation. These biofilms may harbor pathogenic bacteria and fungi, increasing disease risks in agricultural systems. Moreover, microplastic-associated biofilms facilitate the transfer of antibiotic resistance genes, posing environmental and public health concerns.

Implications for Crop Production and Food Security

Microplastic contamination affects plant growth through:

- Reduced seed germination.
- Inhibited root development.
- Altered nutrient uptake.
- Lower photosynthetic efficiency.
- Decreased biomass accumulation.

Recent evidence indicates that nano- and microplastic particles may be absorbed by plant roots and transported to edible tissues, creating potential food safety concerns.

Detection and Characterization of Microplastics in Soil

Several analytical techniques are employed for microplastic detection:

Fourier Transform Infrared Spectroscopy (FTIR)

Used for polymer identification based on molecular vibrations.

Raman Spectroscopy

Provides high-resolution identification of smaller particles.

Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS)

Enables accurate quantification and polymer characterization.

Fluorescence Microscopy

Useful for rapid screening and visualization.

Emerging AI-Assisted Detection Methods

Recent advancements integrate machine learning and hyperspectral imaging for automated microplastic identification and classification.

Human Health Implications

Microplastics can enter the human body through contaminated food, drinking water, and airborne exposure.

Potential health effects include:

- Oxidative stress

- Inflammation
- Endocrine disruption
- Immune dysfunction
- Increased exposure to toxic additives and heavy metals

Although long-term impacts remain under investigation, growing evidence suggests a need for precautionary management.

Mitigation Strategies

Biodegradable Agricultural Plastics

Replacing conventional plastics with biodegradable alternatives can reduce long-term contamination.

Improved Waste Management

Enhanced recycling and responsible disposal of agricultural plastics can minimize environmental leakage.

Sustainable Agricultural Practices

Reduced plastic dependency, conservation agriculture, and organic farming approaches may help limit microplastic inputs.

Policy and Regulatory Measures

Governments should establish standards for monitoring, reporting, and reducing microplastic contamination in agricultural environments.

Research and Innovation

Development of eco-friendly materials, improved detection technologies, and soil remediation strategies is essential.

Conclusion

Microplastics have emerged as a significant environmental contaminant in agricultural soils, with far-reaching implications for soil health, microbial diversity, crop productivity, food safety, and human well-being. Their persistence and complex interactions within soil ecosystems necessitate immediate scientific attention and policy intervention. Sustainable agricultural practices, improved waste management, technological innovation, and stronger regulatory frameworks are critical for mitigating microplastic pollution and protecting future food systems. Continued interdisciplinary research is essential to better understand the long-term ecological and health consequences of microplastic contamination and to develop effective mitigation strategies.

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