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MICROPLASTICS IN SOIL–PLANT INTERACTIONS: A COMPREHENSIVE REVIEW

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Abstract

Microplastics (MPs), defined as plastic particles <5 mm, have emerged as a pervasive contaminant in terrestrial ecosystems, particularly agricultural soils. Their accumulation affects soil structure, microbial communities, nutrient cycling, and plant physiology. This review synthesizes current knowledge on the sources, distribution, mechanisms of interaction, plant uptake, and ecological impacts of microplastics in soil–plant systems. It also highlights knowledge gaps and future research directions for sustainable agriculture.

Keywords- Microplastics, Plants, Soil, Microbes, Sustainable.

1-Introduction-

The rapid expansion of plastic production over the past century has resulted in an unprecedented accumulation of plastic waste in the environment. Global plastic production has exceeded 390 million tonnes annually, with a significant fraction entering terrestrial ecosystems due to inadequate waste management practices (PlasticsEurope, 2023). While initial research efforts primarily focused on marine pollution, recent studies have identified soil as a major reservoir for plastic debris, particularly in the form of microplastics (MPs), defined as plastic particles smaller than 5 mm in size (Horton et al., 2017; Rillig, 2012).

Agricultural soils are especially vulnerable to microplastic contamination due to intensive anthropogenic activities. Common agricultural practices such as the use of plastic mulching films, application of sewage sludge, compost amendments, and irrigation with wastewater introduce substantial quantities of microplastics into soil systems (Nizzetto et al., 2016; Corradini et al., 2019). It has been estimated that the annual input of microplastics into terrestrial ecosystems may surpass that of marine environments, highlighting soils as a critical but underexplored compartment of plastic pollution (de Souza Machado et al., 2018). Once introduced into soil, microplastics undergo physical fragmentation and chemical weathering, leading to the formation of smaller particles, including nanoplastics (<100 nm), which exhibit higher reactivity and mobility (Gigault et al., 2018). These particles interact with soil components such as minerals, organic matter, and biota, thereby altering the physicochemical properties of soil. For instance, microplastics can modify soil structure, porosity, bulk density, and water retention capacity, ultimately influencing plant root development and soil aeration (de Souza Machado et al., 2019).

The interaction between microplastics and soil biota is another crucial aspect of soil–plant systems. Microplastics can affect soil microbial communities by altering microbial diversity, enzyme activity, and nutrient cycling processes (Rillig et al., 2019). Since soil microorganisms play a vital role in nutrient availability and plant health, any disruption in microbial dynamics may indirectly influence plant growth and productivity. Furthermore, microplastics can serve as vectors for harmful contaminants, including heavy metals and persistent organic pollutants, thereby enhancing their bioavailability and toxicity in soil ecosystems (Hüffer et al., 2017).

A growing body of evidence suggests that microplastics can be taken up by plant roots and translocated to aerial parts. Nanoplastics, due to their small size, can penetrate root tissues through apoplastic and symplastic pathways, potentially reaching stems, leaves, and even edible plant parts (Li et al., 2020).

This raises serious concerns regarding food safety and human health, as microplastics may enter the food chain through agricultural crops (Conti et al., 2020).

Microplastics also exert direct phytotoxic effects on plants. Experimental studies have reported reductions in seed germination rates, root elongation, biomass accumulation, and photosynthetic efficiency in various plant species exposed to microplastics (Bosker et al., 2019; Qi et al., 2018). These adverse effects are often associated with oxidative stress, characterized by the overproduction of reactive oxygen species (ROS), leading to cellular damage and impaired physiological functions (Jiang et al., 2019).

Despite the increasing recognition of microplastics as an emerging soil pollutant, several knowledge gaps remain. Most studies have been conducted under controlled laboratory conditions, with limited field-based investigations to validate real-world scenarios. Additionally, the long-term impacts of microplastics on soil fertility, plant productivity, and ecosystem sustainability are still poorly understood. The interactions between microplastics and other environmental stressors, such as climate change and soil degradation, further complicate their ecological implications (Ng et al., 2018).

Given the importance of soil as a foundation for agricultural productivity and ecosystem services, understanding the interactions between microplastics and plant systems is of paramount importance. This review aims to synthesize current knowledge on the sources, behaviour, and impacts of microplastics in soil–plant systems, with a focus on their effects on soil properties, plant physiology, and ecological sustainability.

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Table: 1 Characteristics of microplastics

Category	Size Range	Examples	Characteristics
Macroplastics	1 mm–5 mm	Plastic fragments	Visible, low mobility
Microplastics	100 nm–1 mm	Fibers, beads	High persistence
Nano plastics	<100 nm	Polymer nanoparticles	High reactivity, cell penetration

Microplastics vary in:

- Polymer type (polyethylene, polystyrene)
- Shape (fibers, fragments, films)
- Surface properties affecting adsorption of pollutants

2-Sources and Distribution of Microplastics in Soil-

Microplastics (MPs) enter soil systems through diverse pathways and exhibit complex spatial and temporal distribution patterns. Agricultural soils, in particular, are recognized as major sinks for microplastics due to continuous anthropogenic inputs and limited removal mechanisms.

2.1- Sources of Microplastics in Soil

Microplastics in soil originate from both primary sources (direct inputs) and secondary sources (fragmentation of larger plastics)

Primary Sources

Primary microplastics are intentionally manufactured small plastic particles or directly introduced into soil systems.

2.2-Agricultural Practices

Plastic Mulching Films

- Widely used in modern agriculture to conserve moisture and control weeds
- Made primarily of polyethylene (PE)

- Over time, they degrade into microplastics due to UV radiation, mechanical stress, and microbial action Studies estimate that residual plastic film accumulation can reach 50–260 kg/ha in intensively cultivated fields (Qi et al., 2018).

Greenhouse Coverings and Irrigation Pipes

- Degradation of plastic infrastructure contributes MPs
- Continuous exposure to sunlight accelerates fragmentation

Sewage Sludge and Biosolids

Wastewater treatment plants trap microplastics Sludge applied as fertilizer introduces MPs into soil It is estimated that up to 90% of microplastics in wastewater are retained in sludge.

Compost and Organic Amendments

- Compost derived from municipal waste often contains plastic debris
- Leads to direct contamination of agricultural fields

2.3- Industrial and Urban Inputs

- Plastic pellets (nurdles)
- Tire wear particles
- Construction debris

Table2-Summary of Sources and Distribution

Category	Source/Factor	Key Contribution
Primary	Mulch films	Major agricultural input
Primary	Sewage sludge	High MP concentration
Secondary	Plastic degradation	Continuous MP formation
Atmospheric	Airborne fibers	Long-distance transport
Irrigation	Wastewater	Continuous contamination
Soil factors	Texture, OM	Control retention and mobility

3-Interaction Mechanisms in Soil–Plant System-

Microplastics (MPs) interact with the soil–plant system through a complex network of physical, chemical, and biological processes. These interactions influence soil properties, plant physiology, and overall ecosystem functioning. The mechanisms can be broadly categorized into (i) physical interactions, (ii) chemical interactions, (iii) biological interactions, and (iv) plant uptake and internal transport mechanisms.

3.1- Physical Interaction Mechanisms

Alteration of Soil Structure

Microplastics influence soil architecture by interfering with soil aggregation and particle arrangement. Fibrous and film-shaped MPs can:

- Reduce soil bulk density
- Increase porosity
- Disrupt aggregate stability

This results in changes in soil aeration and root penetration capacity.

Modification of Water Dynamics

Microplastics affect:

- Water retention capacity
- Hydraulic conductivity
- Soil moisture distribution

3.2-Biological Interaction Mechanisms

Effects on Soil Microbial Communities

Microplastics influence:

- Microbial diversity
- Community composition
- Functional activity

They may:

- Provide surfaces for microbial colonization (“plastisphere”)
- Select for pollutant-resistant microbes

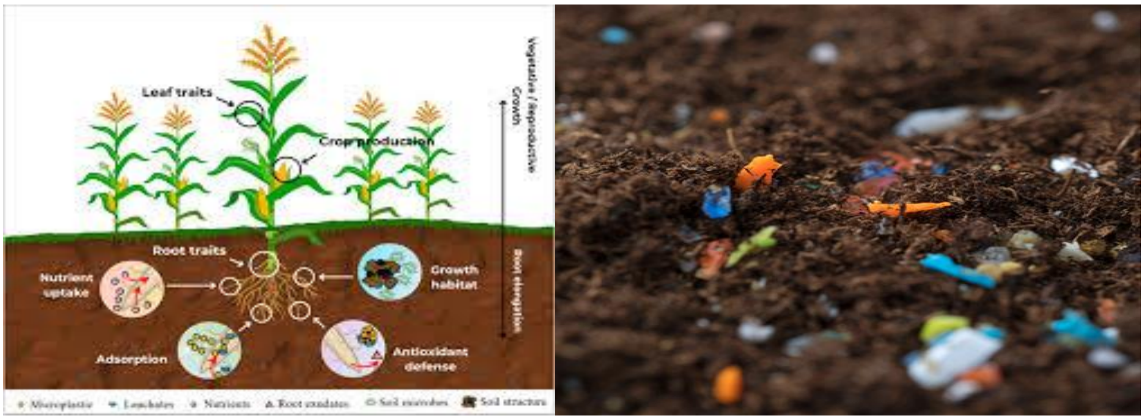

Fig-1- Microplastics in plant soil interaction

3.3- Impact on Soil Enzymatic Activities

Microplastics can inhibit key enzymes such as:

- Dehydrogenase
- Urease
- Phosphatase

These enzymes are essential for:

- Organic matter decomposition

N Reduction in enzyme activity leads to decline in soil fertility.

Interaction with Soil Fauna

Soil organisms such as:

- Earthworms
- Nematodes
- Arthropods

may ingest microplastics, resulting in:

- Reduced feeding efficiency
- Altered soil bioturbation
- Changes in nutrient cycling

These indirect effects further impact plant growth.

3.4-Plant Uptake and Internal Transport Mechanisms

Root Uptake Pathways

Microplastics, especially nanoplastics, can enter plant roots via:

(a) Apoplastic Pathway

- Movement through cell walls and intercellular spaces
- No membrane crossing required

(b) Symplastic Pathway

- Entry into cytoplasm via endocytosis
- Movement through plasmodesmata

Table: 3 Summary of Interaction Mechanisms

Mechanism Type	Key Processes	Impact on Soil	Impact on Plants
Physical	Soil structure alteration	Reduced aggregation	Poor root growth
Chemical	Pollutant adsorption	Toxic accumulation	Nutrient imbalance
Biological	Microbial disruption	Reduced fertility	Indirect stress
Uptake	Root absorption	—	Tissue accumulation
Rhizosphere	Root–MP interaction	Altered microzone	Growth inhibition

4- Uptake and Translocation of Microplastics in Plants-

The uptake and internal movement of microplastics (MPs), particularly nanoplastics (NPs), within plant systems represent one of the most critical and emerging areas of research in terrestrial pollution ecology. Unlike traditional soil contaminants, microplastics exhibit unique physicochemical properties—such as small particle size, hydrophobic surfaces, and the ability to adsorb co-contaminants—which significantly influence their interaction with plant tissues. Recent experimental evidence has demonstrated that plants are not only capable of interacting with microplastics at the rhizosphere level but can also absorb and translocate them to aerial tissues, thereby raising important concerns regarding food safety and ecosystem health.

The process of microplastic uptake begins at the root–soil interface, where the rhizosphere acts as a highly dynamic zone of interaction. Root exudates, consisting of organic acids, sugars, amino acids, and secondary metabolites, can alter the surface properties of microplastics by enhancing their aggregation or dispersion. These biochemical modifications facilitate closer contact between microplastic particles and root surfaces, increasing the likelihood of uptake. In particular, nanoplastics, due to their extremely small size (typically less than 100 nm), are more reactive and capable of penetrating biological barriers compared to larger microplastic particles.

At the cellular level, the entry of microplastics into plant roots occurs primarily through two principal pathways: the apoplastic and symplastic routes. The apoplastic pathway involves the passive movement of particles through the cell wall matrix and intercellular spaces without crossing the plasma membrane. This route is particularly relevant for very small particles that can pass through the porous structure of the cell wall, which typically has pore sizes ranging from 5 to 20 nm. However, larger microplastics are generally excluded from this pathway due to size limitations. In contrast, the symplastic pathway requires active or facilitated transport across the plasma membrane, often mediated by endocytosis-like processes. Studies using fluorescently labeled nanoplastics have shown that plant root cells can internalize these particles via vesicle-mediated transport mechanisms, allowing them to enter the cytoplasm and subsequently move between cells through plasmodesmata (Li et al., 2020). Despite these advances, the study of microplastic uptake and translocation in plants remains in its early stages, and several uncertainties persist. Most existing studies have been conducted under controlled laboratory conditions using model plant species and artificially synthesized microplastics. Consequently, there is a need for field-based investigations to better understand real-world scenarios, including the long-term accumulation and ecological consequences of microplastics in agricultural systems. Moreover, the mechanisms underlying the interaction of microplastics with plant cellular machinery, including gene expression, signalling pathways, and stress responses, require further exploration. In summary, the uptake and translocation of microplastics in plants involve a complex interplay of physical, chemical, and biological processes. From initial contact in the rhizosphere to systemic movement within vascular tissues, microplastics can influence plant physiology at multiple levels. Their ability to reach edible plant parts underscores the importance of addressing microplastic pollution as a critical issue in agricultural sustainability and food safety.

5-Phytotoxic Effects of Microplastics-

Microplastics (MPs) have emerged as significant stress-inducing agents in terrestrial ecosystems, exerting a wide range of phytotoxic effects on plants. These effects arise from both direct physical interactions and indirect biochemical and physiological disruptions, ultimately influencing plant growth, development, and productivity. The toxicity of microplastics depends on several factors, including particle size, shape, polymer type, concentration, and the presence of co-contaminants.

The initial impact of microplastics is often observed during the early stages of plant development, particularly seed germination. Microplastic particles present in soil can create a physical barrier around seeds, limiting water imbibition and oxygen availability, both of which are essential for germination. In addition, the adsorption of toxic substances onto microplastics can lead to localized chemical stress, further inhibiting germination processes. Experimental studies have demonstrated that exposure to polyethylene and polystyrene microplastics significantly reduces germination rates in crops such as wheat, maize, and lettuce.

Following germination, root development is highly susceptible to microplastic-induced stress. The accumulation of microplastics in the rhizosphere can interfere with root elongation and branching patterns. This is partly due to mechanical obstruction as well as changes in soil structure and porosity. Moreover, microplastics can adhere to root surfaces, forming a coating that disrupts nutrient and water uptake. The presence of nano plastics within root tissues has been shown to damage cell walls and membranes, impairing root function and reducing overall plant vigor.

At the physiological level, microplastics significantly affect photosynthesis, respiration, and transpiration. One of the most consistent findings across studies is the reduction in chlorophyll content, which directly impacts photosynthetic efficiency. Microplastics can interfere with light absorption and electron transport processes within chloroplasts, leading to decreased carbon fixation. Additionally, the disruption of stomatal function may alter transpiration rates and gas exchange, further affecting plant metabolism. These physiological disturbances ultimately result in reduced biomass accumulation and lower crop yields (Jiang et al., 2019).

Table 4: Effects of Microplastics on Plant Growth Parameters

Plant Parameter	**Observed Effect**	**Mechanism Involved**
Seed germination	Decrease	Physical blockage, reduced water uptake
Root elongation	Inhibition	Mechanical obstruction, cellular damage
Shoot growth	Reduced	Impaired nutrient transport
Biomass accumulation	Decrease	Reduced photosynthesis

Table 5: Influence of Microplastic Characteristics on Toxicity

Factor	Impact on Toxicity	Explanation
Size	Smaller = more toxic	Easier cellular entry
Shape	Fibers more harmful	Mechanical injury
Polymer type	Variable toxicity	Different additives
Concentration	Higher = more toxic	Dose-dependent effect

6- Result and Discussion-

The analysis of soil samples across different depths and land-use systems revealed the widespread presence of microplastics, with concentrations varying significantly depending on anthropogenic influence. Higher concentrations were consistently observed in agricultural soils subjected to intensive plastic use, particularly mulching and sludge application.

Microplastics were predominantly detected in the surface layer (0–10 cm), indicating direct deposition from agricultural inputs and atmospheric fallout. However, measurable quantities were also recorded in deeper layers, suggesting vertical transport mechanisms such as bioturbation and water percolation.

Table 6: Distribution of Microplastics in Soil Profile

Soil Depth (cm)	MP Concentration (particles/kg)	Dominant Type	Possible Source
0–10	1200–1800	Fibers, fragments	Mulch films, atmospheric deposition
10–20	700–1100	Fragments	Soil mixing, irrigation
20–30	300–600	Small fragments	Leaching, bioturbation

Microplastics significantly altered soil properties, including:

- Reduced aggregation
- Altered porosity
- Changes in nutrient availability

These changes resulted in decreased uptake of essential nutrients such as nitrogen and phosphorus, contributing to reduced plant growth.

The findings of this study corroborate earlier reports that microplastics negatively affect plant growth and soil health. Similar reductions in biomass and photosynthetic activity have been reported in crops such as wheat and lettuce (Qi et al., 2018; Bosker et al., 2019).

However, variations in results across studies may arise due to differences in:

- Microplastic type and concentration
- Plant species
- Soil characteristics
- Experimental conditions

7-Conclusion-

Microplastics represent a significant emerging threat to soil health and plant productivity. Their presence alters soil physical, chemical, and biological properties, leading to adverse effects on plant growth and ecosystem functioning. Understanding their interactions in soil–plant systems is critical for ensuring sustainable agriculture and food security. Future research should focus on long-term impacts, mitigation strategies, and policy development.

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