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Microplastics and plant health: A comprehensive analysis of entry pathways, physiological impacts, and remediation strategies

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Abstract
Microplastics (MPs), tiny plastic particles less than 5 millimeters in size, have become pervasive environmental contaminants with far-reaching implications for ecosystems worldwide. Their infiltration into terrestrial environments, particularly agricultural soils, raises critical concerns about their potential impacts on plant health, ecosystem functioning, and food safety. This review synthesizes current knowledge regarding the multifaceted pathways through which microplastics enter plant systems, their diverse physiological and biochemical effects, and the strategies available or under development to mitigate their adverse impacts. By integrating findings from recent ecotoxicological and agronomic studies, this article aims to highlight critical knowledge gaps, such as the long-term field-scale effects and the risks of co-contaminants, propose future research directions, and inform sustainable management practices to address microplastic pollution's burgeoning threat to global food security and plant ecosystems.

Keywords: Microplastics (MPs), plant health, terrestrial environments, agricultural soils, ecosystem functioning, food safety

1. Introduction

The rapid proliferation of plastics has revolutionized modern life, providing durable, lightweight, and versatile materials for a multitude of applications. However, improper disposal, inadequate waste management, and the persistent nature of plastics have led to widespread environmental contamination. Over time, larger plastic debris undergo photodegradation, mechanical abrasion, and biological processes to form microplastics defined by NOAA as plastic particles less than 5 mm in diameter that are now detected across diverse ecosystems, including oceans, freshwater systems, and soils (Galloway *et al*., 2017; Sharma *et al*., 2020) [18, 17].

Historically, soils were considered a sink rather than a source for microplastic contamination compared to aquatic environments. Nonetheless, recent research indicates that microplastics are increasingly prevalent in terrestrial ecosystems, primarily due to practices such as sewage sludge application, irrigation with contaminated water, atmospheric deposition from urban centers, and the weathering of agricultural plastic mulches (Rillig *et al*., 2019; Zhang *et al*., 2020; Huang *et al*., 2020) [16, 27, 28, 10]. The presence of microplastics in soil environments has raised pressing questions about their interactions with plants, which form the foundation of terrestrial ecosystems and are vital for human food security.

The potential for microplastics to influence plant health is multifaceted and complex. Microplastics may physically interfere with seed germination and root architecture, chemically leach additives (e.g., phthalates, bisphenol A), and act as vectors for heavy metals and pathogens. They may also alter soil physicochemical properties and microbial communities, inducing physiological stresses such as oxidative damage. Furthermore, the translocation of nanoplastics within plant tissues introduces concerns about bioaccumulation and entry into the human food chain. Despite emerging evidence, many aspects of microplastic-plant interactions remain poorly understood, necessitating comprehensive and interdisciplinary research efforts.

This review explores the intricate pathways of microplastic entry into plants, examines their multi-level physiological impacts, and discusses current and emerging strategies for remediation. By critically analyzing recent findings, identifying gaps in knowledge, and proposing future research directions, this article aims to contribute to the development of sustainable solutions to microplastic pollution in terrestrial environments.

2. Entry Pathways of Microplastics into Plants

Understanding how microplastics enter plant systems is fundamental to assessing their ecological and health implications. Multiple pathways facilitate the movement of microplastics from environmental reservoirs into plant tissues, with soil, water, and atmospheric deposition serving as primary vectors.

2.1 Soil and Water Contamination

Microplastics reach soils predominantly through the application of sewage sludge, compost, or biosolids contaminated with plastic debris (Galloway *et al*., 2017; Nizzetto *et al*., 2016) [18, 14]. Sewage sludge, a rich organic fertilizer, can contain alarmingly high quantities of microplastics (up to thousands of particles per kg) derived from synthetic fibers from laundry, microbeads from personal care products, and fragmented plastic waste. When applied to fields, these microplastics become incorporated into the soil matrix, where they can persist for decades due to their chemical inertness and resistance to degradation (Nizzetto *et al*., 2016; Zhang *et al*., 2020) [14, 27, 28].

Irrigation with wastewater or contaminated surface water is a major contributor. A study by Li *et al*. (2020) [11] demonstrated that wastewater irrigation significantly increased the abundance of microfibers in agricultural topsoil. Flooding events can also transport microplastics from rivers and oceans onto floodplains, contaminating previously unaffected soils (Zhao *et al*., 2021; Sharma *et al*., 2020) [29, 17].

Atmospheric deposition is a pervasive and long-range transport mechanism. Microplastics, particularly lightweight fibers and fragments, can be aerosolized by wind erosion of contaminated lands or from urban dust. Brahney *et al.* (2020) [2] found that even remote national parks in the USA receive substantial annual deposition of microplastics via atmospheric fallout. These particles settle onto soil and plant surfaces (Browne *et al*., 2011; Zhang *et al*., 2020) [3, 27, 28], providing a direct pathway for foliar contamination.

2.2 Root Uptake and Soil Interactions

The rhizosphere, the zone of soil surrounding plant roots, is a hotspot for microplastic interaction. The potential for uptake is highly dependent on particle size. While larger microplastics (>1 µm) are generally excluded by the cell wall and Casparian strip, nanoplastics (<100 nm) can potentially penetrate the root epidermis through apoplastic or symplastic pathways, especially at sites of lateral root emergence where the endodermal barrier is compromised (Li *et al*., 2021; Rillig *et al*., 2019; Taylor *et al*., 2020) [12, 16, 21].

Microplastics alter soil physical properties. For instance, polyester fibers can increase soil water holding capacity and aggregation, while polypropylene fragments can decrease soil bulk density and create preferential flow paths, unpredictably altering water distribution (Wang *et al*., 2022; de Souza Machado *et al*., 2018) [23, 17]. This can lead to localized drought stress or waterlogging, indirectly affecting root function. Furthermore, microplastics can cause abrasion and physical damage to root hairs, reducing their absorptive surface area (Sharma *et al*., 2020) [17].

2.3 Foliar Deposition and Uptake

Apart from soil interactions, microplastics can deposit directly onto plant foliage through atmospheric transport. Once on the leaf surface, microplastics may adhere to the cuticular wax or infiltrate through stomata. Zhang *et al.* (2022) [27, 28] provided evidence that nanopolystyrene particles could be taken up through the stomata of lettuce leaves and subsequently translocated to other parts of the plant. The hydrophobicity and surface charge of the particles, as well as environmental conditions like humidity, play a crucial role in this process. This pathway is particularly relevant for leafy vegetables and crops in urban and industrial areas.

2.4 Translocation within Plant Tissues

The translocation of internalized microplastics, primarily nanoplastics, is believed to occur through the vascular system. The xylem stream, which transports water and minerals from roots to shoots, is a likely conduit. Sun *et al.* (2020) [19] demonstrated the upward translocation of fluorescently tagged nanoplastics from roots to shoots in maize plants. Phloem-mediated translocation to sink tissues like fruits and roots is also possible but less documented. This systemic distribution is a critical concern for food crops, as it implies that simply washing produce may not remove internalized plastic particles (Chen *et al*., 2020; Zhang *et al*., 2020) [4, 27, 28].

3. Physiological Impacts of Microplastics on Plants

The presence of microplastics in soils and plant tissues can significantly influence plant physiology, growth, and development. These effects are mediated through physical interactions, chemical toxicity, and induced stress responses.

3.1 Inhibition of Germination and Seedling Development

Seed germination is highly sensitive to its immediate environment. Microplastics can create a physical barrier around the seed, impairing water and oxygen exchange necessary for germination (Li *et al*., 2022) [23]. They can also alter the soil microbiome, potentially reducing the abundance of beneficial bacteria that promote germination. Studies have shown dose-dependent inhibition of germination in plants like wheat (*Triticum aestivum*) and lettuce (*Lactuca sativa*) in the presence of high concentrations of polyethylene and polyester microplastics (Li *et al*., 2022; Sharma *et al*., 2020; Bosker *et al*., 2019) [23, 17, 1]. Seedling growth, particularly root architecture, is often more severely affected than shoot growth, leading to an imbalanced root-to-shoot ratio.

3.2 Disruption of Water and Nutrient Uptake

The alteration of soil hydro-physical properties by microplastics directly impacts plant water relations. Furthermore, direct attachment of particles to roots can block water and nutrient channels. Microplastics can also act as a sink for essential nutrients. For example, Rillig *et al.* (2019) [16] discussed how the high surface area of microplastics can adsorb nutrients like phosphorus and zinc, effectively immobilizing them and making them less available for plant uptake. Conversely, they can also act as vectors for toxic elements like cadmium and lead, increasing their bioavailability and uptake by plants, a phenomenon known as the "Trojan horse" effect (Galloway *et al*., 2017; Wang *et al*., 2020) [18, 22].

3.3 Oxidative Stress and Cellular Damage
The induction of oxidative stress is a primary mechanism of microplastic phytotoxicity. When plants perceive microplastics as a stressor, they trigger a burst of reactive oxygen species (ROS). While low levels of ROS act as signaling molecules, excessive levels cause oxidative damage to lipids (lipid peroxidation), proteins, and DNA (Yin *et al*., 2023; Zhang *et al*., 2020) [27, 28]. This is often compounded by the leaching of plastic additives (e.g., phthalates) or adsorbed pollutants. Plants respond by upregulating their antioxidant defense system, including enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidases, as well as non-enzymatic antioxidants like glutathione. The magnitude of this response is a key indicator of stress levels (Colzi *et al*., 2022) [5].

3.4 Impairment of Photosynthesis and Growth
Reductions in photosynthetic efficiency are a common consequence of microplastic stress. This can be due to:

1. Chlorophyll Degradation: ROS can break down chlorophyll molecules, leading to chlorosis (yellowing of leaves).
2. Stomatal Blockage: Airborne microplastics deposited on leaves can physically clog stomata, reducing gas exchange (CO_2 intake and O_2 release).
3. Damage to Photosynthetic Apparatus: Ultrastructural damage to chloroplasts has been observed in plants exposed to nanoplastics (Zhao *et al*., 2021; Zhang *et al*., 2020) [29, 27, 28].

The resulting reduction in carbon assimilation directly translates to lower biomass accumulation, stunted growth, and ultimately, reduced crop yield (Qi *et al*., 2018) [15].

3.5 Bioaccumulation and Food Safety Concerns
The confirmation that nanoplastics and small microplastics can be translocated to edible tissues like fruits (e.g., apples), vegetables (e.g., lettuce, broccoli), and grains (e.g., wheat) which poses a direct food safety risk (Chen *et al*., 2020; Conti *et al*., 2020) [4, 6]. The health implications of dietary exposure to microplastics in humans are still being unraveled but are a major focus of ongoing research, with concerns ranging from gastrointestinal issues to inflammatory responses and the potential for endocrine disruption from associated chemical additives.

4. Remediation Strategies
Mitigating microplastic contamination in terrestrial ecosystems requires a multi-pronged approach combining prevention, remediation, and sustainable agricultural practices.

4.1 Prevention and Source Control
The most effective strategy is to stop microplastics at their source. This includes:

- Policy Interventions: Banning single-use plastics and microbeads in cosmetics, and implementing Extended Producer Responsibility (EPR) schemes.
- Wastewater Treatment: Upgrading treatment plants with advanced filtration techniques (e.g., membrane bioreactors, disc filters) can capture over 99% of microplastics (Sun *et al*., 2019) [20].
- Sustainable Alternatives: Promoting natural fibers over synthetic textiles and developing truly biodegradable plastics for agricultural use (e.g., mulches).

4.2 Soil Remediation Techniques
- Bioremediation: This approach harnesses plastic-degrading microbes. Bacteria like *Ideonella sakaiensis* (which degrades PET) and fungi like *Aspergillus tubingensis* show great promise (Shen *et al*., 2020; Zhang *et al*., 2023) [18, 26]. Research is focusing on enhancing their activity in complex soil environments through bioaugmentation and biostimulation.
- Organic Amendments: Biochar is highly effective due to its porous structure and large surface area, which can adsorb and immobilize microplastics, reducing their bioavailability to plants (Wang *et al*., 2022; Zhang *et al*., 2021) [23, 21]. The addition of compost can improve soil structure and stimulate microbial communities that may contribute to degradation.
- Phytoremediation: While not yet a proven technology for microplastics, some plants with extensive root systems (e.g., grasses) may help to stabilize soil and prevent the erosion and spread of microplastic particles.

4.3 Agricultural Management Practices
- Reducing Inputs: Avoiding or strictly regulating the use of sewage sludge and untreated wastewater in agriculture.
- Soil Management: Practices like deep ploughing may bury surface microplastics, reducing root zone exposure, but this is a temporary solution. Crop rotation with hyperaccumulator species (if identified) could be a future strategy.

4.4 Innovative Technologies
- Magnetic Extraction: Functionalizing iron nanoparticles to bind to microplastics allows for their magnetic removal from soil or water samples, a technique being explored for remediation (Grbic *et al*., 2019) [9].
- Catalytic Degradation: Advanced Oxidation Processes (AOPs) or photocatalysts that can break down microplastic polymers into harmless molecules are under lab-scale development.

5. Future Perspectives and Research Gaps
Despite progress, significant knowledge gaps remain

- Real-World Exposure Scenarios: Most studies use high concentrations of pristine, spherical microplastics. Research is needed on the effects of environmentally relevant concentrations and shapes (fibers, fragments) under field conditions.
- Long-Term and Multigenerational Effects: The chronic impact of low-dose exposure on soil health and plant fitness over multiple generations is unknown.
- The "Trojan Horse" Effect: More work is needed to understand how microplastics modulate the

bioavailability and toxicity of co-contaminants (pesticides, heavy metals, pathogens).

- Human Health Risks: Quantifying the amount and type of microplastics in various food crops and assessing the associated health risks is a critical priority.
- Standardization: Developing standardized methods for extracting, quantifying, and characterizing microplastics in complex matrices like soil and plant tissue is essential for comparing data across studies.

6. Conclusion

Microplastics represent an insidious and complex threat to plant health, agricultural productivity, and ultimately, human well-being. Their entry into the plant-soil system occurs via a multitude of pathways, and their impacts range from physical obstruction to profound biochemical disruption. Addressing this challenge demands a holistic and concerted effort. This includes robust source reduction policies, innovative remediation technologies like enhanced bioremediation and biochar application, and the adoption of sustainable agricultural practices. Closing the critical research gaps through interdisciplinary collaboration is essential to mitigate microplastic pollution and safeguard the health of our terrestrial ecosystems and food supply for future generations.

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