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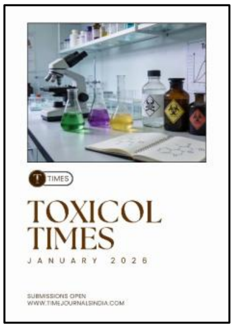

Microplastic Phytotoxicity in Plants: Uptake Mechanisms and a PICO-Based Evidence Framework for Mitigation Strategies

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ABSTRACT

Microplastics have emerged as persistent contaminants of increasing concern in terrestrial ecosystems, particularly in agricultural soils where plastic residues accumulate through mulching films, compost amendments, sewage sludge, irrigation water, and atmospheric deposition. Recent studies indicate that plants can interact with microplastics through both below-ground and above-ground pathways, leading to adhesion to root and leaf surfaces, partial internalization of nanoscale particles, and limited translocation to aerial tissues under certain conditions. Once associated with plant systems, microplastics can impair root and shoot growth, disturb nutrient uptake, induce oxidative stress, alter soil physicochemical properties, and disrupt rhizosphere microbial communities. At the molecular level, microplastic exposure can influence gene expression related to antioxidant defense, energy metabolism, cell-cycle regulation, and photosynthesis, ultimately affecting plant productivity. In addition to these direct phytotoxic effects, microplastics indirectly affect plants by modifying soil structure, enzymatic activities, microbial dynamics, and nutrient cycling within the rhizosphere. Recent research has identified potential mitigation strategies, including biochar amendments, beneficial microbial inoculation, silicon and selenium supplementation, and antioxidant or hormonal priming. These interventions may alleviate microplastic-induced stress by restoring rhizosphere functioning, stabilizing redox homeostasis, improving nutrient availability, and enhancing plant physiological resilience. This review provides a systematic synthesis of current knowledge using a PICO-based evidence framework, in which the population/problem involves plants exposed to microplastic contamination; interventions include biological and physicochemical mitigation strategies; comparisons involve untreated microplastic-exposed systems; and outcomes relate to improvements in plant growth, physiology, soil health, and stress tolerance. By integrating mechanistic evidence from recent experimental studies, the review highlights emerging mitigation pathways. It identifies key research gaps, particularly the need for standardized exposure methodologies, long-term field validation, and deeper mechanistic understanding of plant–microplastic interactions in agroecosystems

KEYWORDS: Microplastics; Plants; Phytotoxicity; Uptake and translocation; Oxidative stress; Rhizosphere; Gene expression; Mitigation strategies

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1. INTRODUCTION

Plastic pollution has emerged as one of the most critical environmental challenges of the modern era. Progressive fragmentation of plastic waste leads to the formation of microplastics (particles <5 mm), which are now widely distributed in terrestrial and aquatic environments. Although early research primarily focused on marine ecosystems, terrestrial environments, particularly agricultural soils, are increasingly recognized as major reservoirs of microplastics due to inputs from plastic mulching films, sewage sludge application, compost amendments, irrigation water, atmospheric deposition, and degradation of larger plastic residues (de Souza Machado et al., 2019; Tariq et al., 2024; Tayyab et al., 2024). Because of their persistence and heterogeneous physicochemical properties, microplastics are capable of interacting with soil particles, microorganisms, plant roots, and other components of the soil ecosystem, thereby raising significant concerns regarding their ecological impacts and potential entry into food chains (Jia et al., 2023; Banerjee et al., 2025).

Experimental evidence shows that microplastics can adhere to root surfaces, penetrate root tissues under specific conditions, and undergo limited vascular translocation to aerial plant organs (Li et al., 2020; Sun et al., 2020). The uptake and internal distribution of these particles are influenced by factors such as particle size, polymer type, surface charge, plant species, and surrounding environmental conditions (Azeem et al., 2021; Yu et al., 2024). In addition to root-mediated uptake, foliar exposure has also been proposed as a potential entry route, whereby nanoscale plastics may enter leaf tissues through stomatal openings or cuticle-associated transport mechanisms (Eichert et al., 2008; Guo et al., 2023). Microplastic exposure can impair plant growth, disrupt nutrient uptake, induce oxidative stress, and alter gene expression associated with photosynthesis and antioxidant defence pathways (Ma et al., 2022; Zhang et al., 2021; Teng et al., 2022). Furthermore, microplastics can modify soil physicochemical properties and microbial communities, thereby indirectly influencing plant health and productivity (de Souza Machado et al., 2019; Wang et al., 2020). Emerging mitigation approaches including biochar amendments, beneficial microbes, and nutrient-based protectants offer promising strategies to alleviate microplastic-induced phytotoxicity, although mechanistic understanding and field validation remain limited.

Despite the rapid expansion of research on microplastic–plant interactions, existing reviews often focus primarily on describing toxicity mechanisms or environmental distribution patterns, while systematic evaluation of mitigation strategies remains limited. To address this gap, the present review adopts a PICO-based evidence synthesis framework, commonly used in systematic environmental and biomedical research to evaluate intervention effectiveness. In this framework, the Population/Problem (P) represents plants exposed to microplastic contamination in soil or environmental matrices; Intervention (I) includes mitigation strategies such as biochar amendments, microbial inoculation, nutrient-based protectants, and antioxidant or hormonal priming; Comparison (C) refers to microplastic-exposed plants without mitigation treatment; and Outcome (O) represents improvements in plant growth, physiological performance, soil microbial stability, and stress tolerance. By applying this structured approach, the review systematically integrates experimental evidence on mitigation mechanisms and provides a more rigorous understanding of potential strategies to alleviate microplastic-induced phytotoxicity in agricultural ecosystems.

2. ABSORPTION OF MICROPLASTICS IN PLANTS

2.1 Absorption of microplastics through roots

The interactions between plant roots and microplastics have been the emphasis of various research investigations, with particular focus on elucidating the physicochemical and biological mechanisms that govern microplastic adhesion to root surfaces, potential uptake across root tissues, and subsequent translocation within plant systems. Plant roots secrete a diverse array of exudates, which mediate particle-root interactions, and owing to their relatively large surface area, microplastics adhere firmly to root epidermal surfaces under certain environmental conditions (Taylor et al., 2020; Zhou et al., 2021). Such adhesion represents the initial step facilitating further interaction between microplastics and plant tissues. Experimental studies further suggest that small-sized microplastics, particularly nano- and submicron-scale particles, may penetrate root tissues depending on plant species, particle characteristics, and environmental conditions. Several possible pathways for entry have been proposed, including apoplastic pathways, symplast pathways, cracks at sites of lateral root emergence, or endocytosis-like processes (Li et al., 2016; Li et al., 2020; Dong et al., 2021; Rong et al., 2024). Once internalized within root tissues, microplastics may be transported to aerial parts of the plant through the transpiration stream via xylem. This vascular transport mechanism enables the movement of small particles from roots to stems and leaves (Lv et al., 2019). For instance, studies in cucumber (Cucumis sativus) suggest that 100 nm polystyrene nanoplastics can be absorbed by roots and subsequently translocated to aerial tissues through xylem-mediated transport driven by root pressure and transpiration pull (Li et al., 2020). Comparable observations have also been reported in Arabidopsis thaliana, where polystyrene nanoplastics (<100 nm) enter root tissues and accumulate within other plant organs. Moreover, the uptake efficiency and distribution of nanoplastics appear to be influenced by particle surface charge, as positively and negatively functionalized particles exhibit different transport behaviors and interaction patterns with plant tissues (Sun et al., 2020). Recent advancements in analytical and imaging techniques have improved the detection and characterization of microplastics within plant systems, thereby enhancing the understanding of their uptake mechanisms. For example, in maize (Zea mays), microplastic beads ranging from 0.2–2.0 µm have been observed to adhere to the root epidermis and enter root tissues, likely through apoplastic pathways and intercellular spaces. In contrast, larger particles are generally retained on the root surface with limited internalization (Li et al., 2023). Microscopic analyses, including scanning electron microscopy (SEM), have further revealed the presence of microplastic particles in stems and leaves of plants grown in contaminated soils. These observations provide experimental evidence that certain microplastics, after entering the root system, can be transported to aboveground tissues and accumulate in different plant organs under controlled exposure conditions (Azeem et al., 2021). These findings collectively indicate that absorption of microplastics through plant roots represents a complex process influenced by particle size, surface characteristics, plant species, and surrounding environmental conditions.

2.2 Absorption of Microplastics Through Foliage

In higher plants, the outer epidermis of leaves is covered by a cuticle of variable thickness and composed primarily of cutin and waxes. This cuticular layer forms a hydrophobic barrier that limits non-stomatal water loss, reduces uncontrolled diffusion of solutes, and provides protection against pathogen invasion and herbivory. At the same time, it regulates interactions between the leaf surface and external environmental factors while enabling regulated gas exchange primarily through stomata (Mostafa et al., 2022). Due to these protective properties, the leaf cuticle represents the first structural barrier that can restrict the adhesion and direct penetration of microplastics and nanoplastics into aerial plant tissues, thereby potentially limiting their entry via foliar pathways (Arya et al., 2021). Transport across the cuticle occurs mainly through two pathways: a lipophilic pathway through the cuticular wax matrix and a hydrophilic pathway mediated by aqueous pores within the cuticle. The lipophilic pathway facilitates the diffusion of small non-polar molecules, whereas the hydrophilic pathway enables the movement of polar solutes through aqueous pores (Schönherr, 2006). Although these pathways are primarily associated with the transport of small molecules, recent studies suggest that nanoscale particles may also exploit these routes under certain conditions. Stomata represent another potential entry point for nanoscale particles. Stomatal apertures typically range from 3–10 µm in width and 20–30 µm in length, depending on plant species and environmental conditions. Experimental studies indicate that nanoparticles suspended in aqueous media can traverse the stomatal pathway under favourable physicochemical conditions (Eichert et al., 2008). Supporting this mechanism, recent scientific evidence shows that nanosized plastic particles (~80 nm) can penetrate maize leaves through stomatal and cuticle-associated pathways (Guo et al., 2023). Following entry into the leaf apoplast via stomatal openings, nanoscale particles may access vascular tissues and undergo internal translocation. The vascular system consists of xylem and phloem tissues, which mediate long-distance transport within the plant. Xylem primarily facilitates upward movement of water and solutes from roots to aerial tissues driven by transpiration, whereas phloem transport is source-to-sink dependent and can occur bidirectionally depending on physiological gradients. Although most evidence for vascular translocation derives from studies on metal-based nanoparticles, similar transport mechanisms may potentially apply to nanoscale plastic particles (Lv et al., 2019). Following foliar exposure, nanoplastics accumulate around stomatal apertures and subsequently enter internal leaf tissues. Experimental evidence demonstrates that these particles can undergo leaf-to-root translocation via vascular tissues, with the extent of movement influenced by surface charge and other physicochemical properties (Sun et al., 2021). These findings indicate that foliar uptake represents a potential pathway for nanoplastics to enter plants and distribute throughout plant tissues.

2.3 Absorption of Microplastics Through Flowers and Fruits

The internal distribution of microplastics within plants is largely influenced by their movement through the vascular system, which facilitates transport between different plant organs. Evidence suggests that microplastics taken up either through roots or leaves may undergo translocation within the plant via vascular tissues, contributing to their redistribution among above- and below-ground parts. Such vascular transport mechanisms are well documented for engineered nanoparticles and other particulate contaminants, suggesting that similar processes may potentially influence the internal mobility of microplastics within plants. However, the detailed organ-specific transport mechanisms of microplastics at the whole-plant level remain insufficiently characterized. In particular, limited studies have examined the potential uptake, accumulation, and distribution of microplastics in reproductive organs, including flowers and fruits (Conti et al., 2020; Nassar et al., 2025). This knowledge gap is particularly important because the presence of microplastics in reproductive tissues could represent a pathway for their entry into plant-derived food products, thereby raising concerns regarding food safety and human exposure.

3. EFFECT OF MICROPLASTICS ON PLANTS

3.1 Effect of Microplastics on Root Growth and Development

Several studies have demonstrated that microplastics can accumulate in plant root systems and adversely affect root morphology and physiological performance. These effects may alter important growth parameters, including root length, relative root elongation, metabolic activity, and both fresh and dry root biomass. For instance, in soils contaminated with poly(butylene adipate-co-terephthalate), soybean plants exhibited substantial reductions of approximately 34–58% in root length, 34–54% in root surface area, and 25–40% in root biomass. Even stronger inhibitory effects were reported in maize, where root length declined by 37–71% and root biomass decreased by 24–64% compared with control plants (Yu et al., 2023). Similarly, exposure to polystyrene and polyvinyl chloride microplastics significantly affects root growth and development in rice (Oryza sativa). Microplastic contamination reduces root biomass and disrupts root physiology by interfering with nutrient uptake, ionic balance, and metabolic processes, ultimately impairing root development and overall plant growth (Ma et al., 2022). Comparable inhibitory effects have also been reported in several other plant species, including Triticum aestivum, Arabidopsis thaliana, Hordeum vulgare, and Phaseolus vulgaris (Meng et al., 2021; Iqbal et al., 2023; Yu et al., 2024; Alhaithloul et al., 2024).

At the cellular level, microplastics can induce oxidative stress through excessive production of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. Under normal conditions, plants maintain ROS homeostasis through an antioxidant defense system consisting of enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD), as well as non-enzymatic antioxidants. However, when ROS production exceeds the detoxification capacity of these systems, oxidative damage occurs. This imbalance leads to lipid peroxidation of cellular membranes, often indicated by increased malondialdehyde (MDA) levels, resulting in membrane disruption and impairment of cellular metabolism. In root tissues, microplastic-induced oxidative stress may also alter cellular ultrastructure and interfere with cell-cycle processes in meristematic cells, thereby reducing mitotic activity and cell elongation. Consequently, these disturbances inhibit root development, reduce root biomass, and suppress overall plant productivity (Giorgetti et al., 2020; Yu et al., 2024).

3.2 Effect of Microplastics on Shoot Growth and Development

Microplastics have also been reported to negatively influence shoot growth and development in plants. One of the primary mechanisms involves disruption of root physiological functions, which subsequently affects the transport of water, nutrients, and signalling molecules from roots to shoots. Microplastics may interfere with nutrient translocation and cell-to-cell connectivity within root tissues, impairing vascular transport and reducing the availability of essential resources required for shoot growth (Jiang et al., 2019). As a result, plants exposed to microplastics often exhibit reduced shoot elongation, limited leaf expansion, and decreased above-ground biomass accumulation. Experimental studies have demonstrated these effects in several crop species. In Cucurbita pepo, exposure to polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) microplastics significantly reduced shoot growth, leaf lamina size, and photosynthetic performance. Among these polymers, PVC exhibited the highest phytotoxicity (Cozi et al., 2022). Similarly, in common bean (Phaseolus vulgaris L.), soil contamination with low-density polyethylene microplastics produced relatively minor effects on shoot growth. However, biodegradable plastics composed of polylactic acid mixed with poly-butylene-adipate-co-terephthalate significantly reduced shoot biomass and leaf area when present at concentrations ≥1.5% in soil (Meng et al., 2021). In rice (Oryza sativa L.), exposure to polystyrene and polyvinyl chloride microplastics markedly inhibited shoot growth. Increasing microplastic concentrations resulted in reduced plant height and decreased shoot biomass, with the strongest inhibition observed at 3 mg L^{-1} (Ma et al., 2022). Similar dose-dependent inhibitory effects have been reported in lentil (Lens culinaris) seedlings exposed to polyethylene microplastics, where shoot length and biomass declined progressively with increasing concentrations (De Silva et al., 2022). Collectively, these findings indicate that microplastic contamination can impair shoot growth across different plant species by disrupting nutrient transport, altering physiological processes, and reducing photosynthetic efficiency.

3.3 Effect of Microplastics on Plant Gene Expression

Microplastics can significantly influence plant physiology by altering gene expression and disrupting essential cellular and metabolic pathways. One of the vital targets of microplastic stress is the regulation of genes associated with cell-cycle progression. For example, exposure to polystyrene microplastics has been reported to affect the expression of the cdc2 gene, which encodes a cyclin-dependent kinase responsible for controlling the transition from G2 phase to mitosis during cell division. In onion (Allium cepa) root cells, cdc2 expression was significantly downregulated in microplastic-treated samples compared with the control, and the reduction occurred in a dose-dependent manner. Significant reductions were observed at concentrations of 25 mg L^{-1} and 100 mg L^{-1}, while the maximum suppression occurred at 400 mg L^{-1}. The downregulation of cdc2 suggests that polystyrene microplastics interfere with cell-cycle regulatory mechanisms, potentially delaying mitotic progression and leading to cytotoxic effects in meristematic root cells (Maity et al., 2020). Microplastic exposure can also modify the expression of genes involved in oxidative stress regulation. In rice plants, transcriptomic analysis revealed that polystyrene microplastics significantly influence the expression of antioxidant-related genes associated with hydrogen peroxide metabolism and detoxification pathways. Several genes linked to antioxidant enzyme activity have been downregulated under microplastic stress, which may contribute to the accumulation of reactive oxygen species (ROS), including superoxide radicals and hydrogen peroxide in root tissues. The disruption of antioxidant gene expression weakens the plant’s oxidative defence system and interferes with the normal functioning of enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). Consequently, microplastic-induced modulation of antioxidant genes plays an important role in ROS accumulation and oxidative stress responses in plants exposed to microplastic contamination (Zhang et al., 2021). Microplastic stress has also been shown to alter gene expression in plant roots, leading to molecular changes associated with the cytotoxic and genotoxic effects during root development (Jia et al., 2023). In particular, exposure to polystyrene microplastics significantly influences root and overall plant growth by altering the expression of genes involved in major metabolic pathways. Transcriptomic studies indicate that polystyrene microplastics downregulate genes associated with nitrogen metabolism and linolenic acid metabolism, which are essential for nutrient assimilation and lipid signalling processes (Zhang et al., 2021). Furthermore, polystyrene exposure also modifies the expression of genes encoding proteins involved in the tricarboxylic acid (TCA) cycle, thereby disrupting cellular energy metabolism (Wu et al., 2022). Such dysregulation collectively impairs metabolic activity and contributes to growth inhibition in plants exposed to microplastics. Microplastic stress also affects the regulation of genes associated with photosynthesis. Photosynthetic efficiency in plants depends on the coordinated expression of genes involved in chlorophyll biosynthesis, carbohydrate metabolism, and ATP generation within chloroplasts. Disruption of these genes by microplastic exposure can impair chlorophyll formation, reduce efficiency of carbon fixation and energy metabolism, and ultimately decrease photosynthetic activity in plants. For example, Liu et al. (2022) reported that exposure to poly (butylene adipate-co-terephthalate) (PBAT) microplastics significantly impaired photosynthesis in Arabidopsis thaliana. This effect was associated with the downregulation of genes encoding light-harvesting chlorophyll a/b-binding (LHCB) proteins, which are essential components of the photosystem II antenna complex responsible for capturing and transferring light energy during photosynthesis. In addition to their role in light harvesting, LHCB proteins are involved in plant stress responses. Their downregulation can influence cellular redox homeostasis and modulate stomatal sensitivity to abscisic acid (Chen et al., 2023b). Consequently, PBAT microplastic–induced alterations in photosynthetic gene expression may also be linked to ABA-mediated stomatal regulation, suggesting that microplastics can indirectly affect photosynthetic efficiency through hormone-dependent control of stomatal behaviour (Liu et al., 2022; Chen et al., 2023b). Similar transcriptomic responses have been observed in tobacco (Nicotiana tabacum L.) exposed to polyethylene microplastics. Studies have shown that PE exposure led to downregulation of genes associated with photosynthetic processes. More than 80% of the differentially expressed genes related to the chloroplast electron transport chain (ETC), photosystem I (PSI), photosystem II (PSII), and light-harvesting complexes were suppressed. This transcriptional repression suggests that microplastics can severely disrupt photosynthetic electron transport and light energy capture, leading to reduced photosynthetic efficiency and plant growth (Teng et al., 2022). Overall, these findings indicate that microplastics can profoundly affect plant growth and physiological processes by altering the expression of genes associated with cell-cycle regulation, antioxidant defense, metabolic pathways, and photosynthesis. Such molecular disruptions represent a key mechanism underlying the phytotoxic effects of microplastic contamination in terrestrial ecosystems.

3.4 Other Effects on Plants

Microplastic contamination can also exert indirect effects on plant growth by altering the physicochemical properties of soil and microbial communities. These changes in soil conditions subsequently influence both root and shoot development. For example, the presence of microplastics in soil can modify the structure and composition of soil bacterial communities, which play an essential role in nutrient cycling, organic matter decomposition, and maintenance of overall soil fertility. In addition, microplastic contamination has been reported to reduce soil organic matter content and alter soil bulk density, thereby affecting soil structure and water-holding capacity. Such modifications can influence nutrient availability, root penetration, and microbial activity in the rhizosphere. Consequently, these indirect effects of microplastics on soil properties and microbial dynamics may impair plant growth and productivity. In this context, microplastics can influence plant performance not only through direct physiological stress but also through their impact on soil fertility and ecosystem functioning (Jia et al., 2023). Microplastics can also significantly alter soil enzymatic activities and disrupt microbial functioning in soil ecosystems. For example, the addition of fibrous polypropylene (PP) microplastics has been reported to markedly reduce the activity of soil enzymes involved in nutrient cycling. Specifically, fluorescein diacetate hydrolase activity decreased by approximately 38%, while urease activity declined by about 41% following PP microplastic application (Yi et al., 2021). In addition, plastics generally possess a lower density than most soil mineral particles, which can modify important physical properties of soil such as bulk density, porosity, and aeration. For example, de Souza Machado et al. (2019) reported that the incorporation of different types of microplastics into soil significantly reduced soil bulk density. Although reduced bulk density may sometimes improve soil aeration, it can also disrupt normal soil aggregation and water retention, ultimately influencing root growth, microbial activity, and overall soil functioning (Jia et al., 2023).

Uzamurera et al. (2023) reported that biodegradable microplastic residues reduced soil bulk density, plant height, water-use efficiency, and grain yield compared with soils containing polyethylene microplastics. These findings indicate that different types of microplastics can exert distinct impacts on soil–plant interactions, suggesting that biodegradable plastics may not always be environmentally benign and can adversely affect crop performance and agricultural productivity. Microplastics can also influence soil water dynamics and plant responses under fluctuating moisture conditions. By modifying soil structure and pore distribution, microplastics may alter soil water retention and water movement within the rhizosphere.

For example, Zhang et al. (2023) demonstrated that microplastic contamination, in combination with dry–wet cycles, altered lettuce antioxidant activity and reshaped rhizospheric bacterial communities, indicating that microplastics can modify plant physiological responses to soil moisture stress. These findings suggest that microplastics may disrupt soil–plant water relations and indirectly affect plant growth and productivity. Furthermore, microplastics can also modify soil microbial communities and nutrient cycling processes.

For example, exposure to low-density polyethylene microplastics has been shown to alter the structure and turnover of soil microbial communities within 90 days (Wang et al., 2020). Similarly, polyethylene microplastic contamination has been shown to modify soil bacterial community structure and the abundance of microbial taxa involved in nitrogen transformation processes. In acidic agricultural soils, Fei et al. (2020) demonstrated that PE microplastic accumulation significantly altered soil enzyme activities and bacterial community composition, suggesting potential disturbances in nitrogen cycling pathways that may influence ammonium availability, soil pH, and overall soil fertility. Collectively, these findings demonstrate that microplastics can influence plant growth not only through direct physiological and molecular effects but also by altering soil properties, microbial communities, and nutrient cycling processes. Such soil-mediated impacts can disrupt the delicate balance of the soil–plant–microbe system, ultimately affecting plant productivity and ecosystem stability. Therefore, understanding these indirect pathways is essential for accurately assessing the ecological risks of microplastic contamination in agricultural soils and for developing sustainable management strategies to mitigate their impacts.

4. MITIGATION STRATEGIES FOR MICROPLASTIC TOXICITY IN PLANTS

4.1 PICO-Based Systematic Overview

The PICO-based systematic overview is shown in Table 1. The PICO framework incorporates the P (Population/Problem): Plants grown in microplastic-contaminated soil; I (Intervention): Soil amendments, nutrients, microbes, or plant regulators; C (Comparison): Plants exposed to microplastics without mitigation; O (Outcome): Improvement in plant growth, physiology, soil health, and stress tolerance.

Table 1. PICO-based systematic overview of mitigation strategies for microplastic toxicity in plants

Strategy	P Population/ Problem	I Intervention	C Comparison	O Outcomes	Mechanistic insight	Reference
Biochar-based mitigation	Root–rhizosphere system under MP stress	Biochar amendment	MP-exposed treatment without biochar	Relief of toxicity in root–rhizosphere soil system; altered root expression profiles; improved microbial diversity and functions	Biochar mitigated MP toxicity by changing root transcript profiles and reshaping microbial diversity/function in the rhizosphere, consistent with adsorption/buffering plus rhizosphere restoration.	Yang et al. (2024)
	Paddy soil with MP toxicity affecting plant growth	Biochar preloaded with beneficial bacteria	MP-stressed soil without bacterial-charged biochar	Enhanced plant growth; mitigation of MP toxicity; altered microbial communities	Combined amendment effect: carrier-mediated microbial establishment plus reprogramming of soil metabolic and	Afzal et al. (2025)

				and soil metabolism	community profiles	
Microbial mitigation	Plants under raw and aged MP stress	Beneficial microbial inoculation	MP stress without inoculation	Improved plant health and oxidative balance	Microbe-mediated mitigation of MP injury through regulation of oxidative balance and plant stress responses	Khan et al. (2025)
	Plant stress under combined MP + Cd toxicity	Combined plant growth-promoting bacterial consortia	Combined pollution without consortia	Alleviated plant stress; improved soil inorganic nutrients; changed bacterial functional composition	Consortium-driven restructuring of bacterial community function and nutrient status under mixed pollution	Zhang et al. (2025)
Silicon and selenium as nutrient-based protectants	Kale exposed to polyethylene microplastics	Silicon supplementation	PE-MP exposure without silicon	Higher shoot and root biomass; restored enzyme activity; rhizosphere microbiota shifts	Si alleviated PE-MP-induced phytotoxicity through plant–microbe linked mechanisms, including soil enzyme recovery and rhizosphere microbiota changes.	Wang et al. (2025)
	Kale under MP stress	Selenium supplementation	MP exposure without selenium	Improved photosynthesis, redox homeostasis, secondary metabolism, and hormonal status	Se-mediated mitigation through ROS control, photosynthetic protection, and hormone/metabolite regulation	Tong et al. (2024)
	Highland barley/soil system under MP pollution	Selenium supplementation	MP exposure without selenium	Reduced toxicity; trophic restructuring of soil nematodes; biochemical regulation	Se mitigation beyond plant physiology to soil food-web reorganization, suggesting ecosystem-level buffering of MP stress	Zaman et al. (2026)
Anti-oxidant and hormonal priming	Rice under MP stress	Exogenous glutathione (GSH) treatment	MP exposure without GSH	Suppressed adverse effects of MPs; improved growth/productivity	Antioxidant-based mitigation, with GSH improving plant performance under MP stress via redox-related protection	Chen et al. (2023a)
	Edible plants, especially tomato, under polystyrene nanoplastic stress	Brassinosteroid application	Nanoplastic exposure without brassinosteroids	Reduced accumulation, reversed phytotoxicity, improved growth	Hormonal mitigation: BRs activated antioxidant defenses and suppressed nanoplastic uptake, partly through aquaporin-related regulation	Gao et al. (2023)
Source-control / broader agroecosystem mitigation	Agricultural soils contaminated by MPs	Policy, substitution, source reduction, sustainable interventions	Business-as-usual input of plastic residues	Reduced exposure risk at the system level	These reviews support mitigation at the agroecosystem scale, but they are not direct plant intervention trials.	Tariq et al. (2024); Tayyab et al. (2024); Banerjee et al. (2025)

4.2 Mechanistic Insights and Discussion

4.2.1 Biochar-based mitigation

Biochar is one of the most well-supported interventions because it has direct proof that it lowers MP pollution at the plant-soil interface. Yang et al. (2024) showed that growth was improved and specifically showed that the roots–rhizosphere soil system was less affected, along with changes in root expression patterns and microbial diversity and function. This means that biochar is important because it works on both plants and soil, not just on plant tissue.

Bacterial-charged biochar is a stronger version of this method. In this case, the amendment acts as both a sorptive matrix and a way to deliver beneficial microbes. Adding microbial species to biochar can change how soil works, which assist plants grow better if they are under MP stress and supports the notion of rhizosphere modelling (Afzal et al., 2025).

4.2.2 Microbial mitigation

There is now enough proof to show that helpful microorganisms can help with the adverse effects of microplastics. Khan et al. (2025) undertook direct testing of bacterial inoculation on new and older microplastics. They discovered that the plants' health and oxidative balance enhanced. This is essential since older microplastics are more accurate at showing what the environment is truly like than new ones.

Zhang et al. (2025) found that when microbial consortia cooperate together, they can lessen the negative aspects impacts of microplastics and cadmium. The inorganic nutrients in the soil and the kinds of bacteria that reside there are what cause these impacts. The study has a lot of potential because it shows that mixed pollution, not simply MPs, may need to be the focus of mitigation in real life.

4.2.3 Silicon and selenium as nutrient-based protectants

The silicon paper is especially useful for mitigation strategies from the perspective of plants and microbes. In kale subjected to polyethylene microplastics, silicon enhanced biomass, mitigated enzyme inhibition, and modified rhizosphere microbiota. Thus, the supported interpretation transcends the notion of Si as an antioxidant aid, indicating that Si also helps to stabilize the soil–plant–microbe interface under microplastic stress (Wang et al., 2025).

Selenium has been proved useful in two complementary systems. Tong et al. (2024) found a direct link between selenium mitigation and the restoration of photosynthesis, redox homeostasis, secondary metabolism, and hormonal balance in kale. Zaman et al. (2026) applied that framework to the soil ecological context in highland barley, demonstrating that the trophic restructuring of nematode communities in soil interacts with biochemical regulation to potentially mitigate MPs. These studies substantiate Se as a multilevel intervention influencing both plant functionality and the organization of soil organisms.

4.2.4 Antioxidant and hormonal priming

The research directly substantiates antioxidant priming techniques with glutathione as a potential mitigating strategy. Chen et al. (2023a) demonstrated that exogenous GSH mitigates detrimental MP effects in rice and enhances growth/productivity, aligning with the reinstating of redox buffering mechanisms under MPs induced oxidative stress.

Gao et al. (2023) provide one of the clearest hormone-based (brassinosteroids) mitigation demonstrations in edible plants. Their study showed not only reduced phytotoxicity but also lower nanoplastic accumulation, and the mechanism was tied to antioxidant defense activation and suppression of nanoplastic uptake, including aquaporin-related regulation. This makes BRs more than a generic stress hormone treatment; they appear to affect both damage control and particle entry. The strongest direct experimental evidence currently supports biochar-based amendments, beneficial microbes/microbial consortia, silicon, selenium, glutathione, and brassinosteroids as mitigation tools for MP-induced plant stress. However, the evidence base is still dominated by species-specific, short-term, controlled studies, often using a single polymer type or relatively high exposure scenarios. Reviews such as Tariq et al. (2024), Tayyab et al. (2024), and Banerjee et al. (2025) are useful for framing mitigation pathways and research gaps, but these literatures are not primary evidence for a specific experimental mechanism unless the underlying primary studies are also evident.

5. CONCLUSION

Terrestrial ecosystems and agricultural soils are increasingly impacted by microplastics. Growing data shows that microplastics can interact with plants through root absorption, surface adhesion, and limited internal translocation, depending on particle size, polymer type, and plant species. Microplastics can impact photosynthetic and metabolic activities, root and shoot development, gene expression, and oxidative stress once in plant tissues. Besides phytotoxicity, microplastics can indirectly affect plant performance by changing soil physicochemical qualities, microbial populations, enzyme activity, and rhizosphere nutrient cycling.

Recently studied mitigation methods include charcoal additions, beneficial microbial inoculation, silicon and selenium supplementation, and antioxidant or hormonal priming. These treatments may reduce microplastic-induced stress by increasing rhizosphere function, antioxidant defense, and plant physiological processes. However, field-scale data is few and most understanding comes from controlled laboratory investigations.

Long-term trials under realistic climatic circumstances, consistent microplastic exposure methods, and a mechanistic knowledge of particle properties and plant responses are needed for future study. Mechanistic knowledge of plant–microplastic interactions is needed to appropriately estimate ecological hazards and design sustainable methods to reduce microplastic contamination in agricultural environments.

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