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The Silent Sink: A Comprehensive Review of Microplastic Accumulation in Agricultural Soils and its Impact on Crop Physiology

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ABSTRACT

The abundance of microplastics (MP) in agricultural soils has launched a "silent sink" of pollution that endangers global food security. Originating from plastics from plasticulture, sewage sludge and irrigation water, MPs are accumulating in arable lands at alarming rates, leading to a fundamental change in the soil biophysical environment. This review performs a critical synthesis of the mechanisms of disruption of the soil-plant continuum by MPs. We highlight that MPs contribute to increasing the porosity and impair aggregate stability of soils, worsening erosion and drought stress. Chemically, they interrupt the cycle of nutrients in a way that the biodegradable plastics have a paradoxical effect of "carbon catabolite repression" that starves plants of nitrogen. Physiologically, below microscopic level value particles enter root tissues and cause oxidation stress, genotoxicity and hormonal imbalances which stunt root growth and reduce the rate of photosynthesis. Furthermore, MPs are vectors for heavy metals, antibiotics and pathogens, which help to transfer them into the food chain. We also point out a "biodegradable paradox", through which environmentally benign alternatives are potentially more phytotoxic than conventional plastics. Finally, we assess new approaches for remediation such as the potential of biochar amendment and microbial bioaugmentation approaches to restoration of soil health. This review highlights the importance of urgent standardization of monitoring and global governance for the reduction of the increasing threat of 'white pollution' in agroecosystems.

INTRODUCTION

The Anthropocene epoch has been irrevocably defined by the proliferation of synthetic polymers, marking the dawn of a "Plastic Age" that has transformed every facet of modern civilization, including agriculture. Since the mid-20th century, the integration of plastics into farming practices, often termed the "White Revolution", has offered unparalleled benefits in terms of crop protection, water conservation, and yield enhancement, particularly in arid and semi-arid regions where resources are scarce. However, this agricultural intensification has birthed an insidious and escalating environmental challenge, the accumulation of microplastics (MPs) in terrestrial ecosystems. While early ecotoxicological research disproportionately focused on marine environments, a growing and compelling body of evidence now confirms that agricultural soils act as a massive, and perhaps larger, sink for plastic debris. Current estimates suggest that terrestrial soils may hold 4 to 23 times more plastic pollution than oceans, yet the implications for soil health, crop physiology, and ultimately food security remain comparatively understudied. Microplastics, defined as plastic particles smaller than 5 mm, have become ubiquitous in arable lands globally, originating from a diverse and continuous array of sources, including plasticulture (mulching films), sewage sludge application, wastewater irrigation, and atmospheric deposition (Tian et al., 2022). These particles are not merely inert bystanders in the soil matrix; they are active physical and chemical agents that fundamentally alter the soil biophysical environment, disrupt nutrient cycling, and impose severe physiological stress on crops, creating a "silent sink" of pollution that threatens the sustainability of global food production.

The widespread adoption of plastic mulching films has been a cornerstone of modern agronomy. These films conserve soil moisture, suppress weed competition, and increase soil temperature, thereby extending the growing season and boosting yields in regions where cultivation would otherwise be marginal. However, the incomplete removal and subsequent fragmentation of these films have led to a legacy of "White Pollution" that is now deeply embedded in the soil profile (Zhang et al., 2022). Mechanical abrasion from tillage, combined with ultraviolet (UV) radiation and biological degradation, fragments macro-plastics into micro- and nano-plastics (NPs), which then persist in the soil matrix for decades or even centuries (Li et al., 2025). This fragmentation process is not uniform; it is influenced by environmental factors such as temperature, rainfall, and soil texture, leading to a heterogeneous distribution of particles that complicates risk assessment. The accumulation is further exacerbated by the application of sewage sludge and organic fertilizers, which, while rich in essential nutrients, act as significant vectors for microplastic entry into agroecosystems. Wastewater treatment plants act as concentrators for microplastics released from domestic and industrial sources, and the subsequent land application of the resulting biosolids transfers these particles directly into the food production system (Yang et al., 2021). Current modeling estimates suggest that without significant intervention, microplastic concentrations in agricultural soils could rise exponentially, potentially reaching levels that severely compromise soil function and food safety within the next century (Meizoso-Regueira et al., 2024).

Once incorporated into the soil, microplastics exert a multifaceted and often deleterious impact on the edaphic environment. Physically, they alter soil bulk density, porosity, and water-holding capacity. While some studies suggest an increase in porosity due to the inclusion of low-density particles, this often comes at the cost of soil aggregate stability. Microplastics can disrupt the binding agents that hold soil particles together, leading to increased erosion risks and reduced hydraulic conductivity, which paradoxically exacerbates drought stress in crops despite the presence of "pores" (Wang et al., 2022). Chemically, microplastics interact dynamically with soil nutrients and contaminants. They can alter soil pH, influence the bioavailability of heavy metals, and disrupt the cycling of carbon and nitrogen. For instance, biodegradable plastics, often touted as eco-friendly alternatives to conventional polyethylene, can induce "Carbon Catabolite Repression." In this scenario, the rapid microbial growth fueled by the labile carbon from the degrading plastic depletes available nitrogen and phosphorus in the rhizosphere, effectively starving the plant of essential mineral nutrients (Han et al., 2024). This highlights a critical "Biodegradable Paradox" where the solution to plastic pollution may inadvertently create new agronomic challenges.

Furthermore, microplastics act as vectors for a wide range of co-contaminants. Their large surface-to-volume ratio and hydrophobic nature allow them to adsorb heavy metals such as cadmium and arsenic, as well as organic pollutants like polycyclic aromatic hydrocarbons (PAHs), pesticides, and antibiotics (Abbasi et al., 2021; Huang et al., 2023). In the complex chemical environment of the rhizosphere, these particles can act as "chemical shuttles," facilitating the transport and uptake of toxic compounds by plant roots. This "Vector Effect" is compounded by the leaching of chemical additives inherent to the plastic manufacturing process, such as phthalates and bisphenols, which can act as endocrine disruptors. The interaction is further complicated by the presence of nanoplastics, which possess a much higher mobility and reactivity than their larger counterparts. Nanoplastics can penetrate cell walls and membranes, carrying adsorbed pollutants directly into the cellular cytoplasm, where they can induce severe oxidative stress and metabolic disruption (Azeem et al., 2021).

The interaction between microplastics and plants extends beyond physical blockage or chemical leaching; it represents a complex physiological disruption that targets the plant at multiple organizational levels. At the seed stage, micro- and nanoplastics can accumulate in the pores of seed coats, creating a physical barrier that inhibits water uptake and gas exchange, thereby delaying germination and reducing seedling vigor (Zhang et al., 2022). Upon germination, sub-micrometer particles can penetrate root tissues via "crack-entry" modes at lateral root junctions or through endocytosis, subsequently translocating to aerial parts via the transpiration stream. This internalization triggers a cascade of stress responses within the plant. Plants exposed to microplastics often exhibit oxidative stress, characterized by the overproduction of Reactive Oxygen Species (ROS) such as hydrogen peroxide and superoxide radicals. This oxidative burst damages cellular lipids, proteins, and DNA, leading to genotoxicity, chromosomal aberrations, and cell cycle arrest (Elbasiouny et al., 2023; Maity et al., 2022). Moreover, microplastics have been shown to impair photosynthesis by damaging chloroplast ultrastructure and reducing chlorophyll content, directly compromising biomass accumulation and yield (Ren et al., 2021; Sun et al., 2023).

The rhizosphere, the critical interface between root and soil, is a primary target of microplastic toxicity. Microplastics disrupt the intricate metabolic coupling between plant roots and the soil microbiome. Plants exude a diverse array of chemical compounds into the rhizosphere to recruit beneficial microbes and modulate soil chemistry; however, microplastics can alter the profile of these root exudates and simultaneously modify microbial consumption patterns (Lebel et al., 2025). This leads to significant shifts in microbial community structure, often suppressing beneficial Plant Growth-Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF) while enriching stress-tolerant or pathogenic taxa (Bouaicha et al., 2022; Zhu et al., 2022). Such dysbiosis not only hampers nutrient acquisition, particularly nitrogen and phosphorus but also weakens the plant's immune defense, making crops more susceptible to soil-borne diseases. Furthermore, the "Plastisphere", the distinct microbial community colonizing plastic surfaces—has been implicated in the horizontal transfer of antibiotic resistance genes (ARGs) within the soil microbiome, posing a broader ecological and public health risk that extends far beyond the immediate crop loss (Maddela et al., 2023).

Despite the growing body of literature, a comprehensive synthesis linking soil physicochemical alterations to detailed crop physiological responses remains fragmented. Most existing reviews focus either on soil properties, ecotoxicology, or polymer chemistry in isolation, often failing to capture the systemic nature of the threat. There is a critical need to integrate findings from soil science, plant physiology, microbiology, and environmental chemistry to construct a holistic understanding of how microplastics reshape the agricultural landscape. This review aims to bridge that gap by providing a comprehensive analysis of the "Soil-Plant-Microplastic" continuum. We critically evaluate the sources, migration, and degradation of microplastics in agricultural soils, decipher the mechanisms of their interaction with soil properties and nutrient cycles, and detail the physiological, biochemical, and molecular responses of crops. Furthermore, we address the controversial "Vector Effect" of co-contaminants, comparing the impacts of biodegradable versus conventional plastics, and discussing the potential implications for food security and human health. Finally, we discuss emerging remediation strategies, such as biochar amendment, microbial bio-augmentation, and phytoremediation, offering a scientific roadmap for sustainable agriculture in a plastic-polluted world. By integrating findings from recent field studies, meta-analyses, and multi-omics research, this review aspires to provide a definitive resource for understanding the "Silent Sink" beneath our feet and the urgent actions required to mitigate its impact.

Dynamics of Microplastic Accumulation in Agricultural Soils

Dominant Pathways of Entry and Accumulation

Agricultural soils have become significant traps for man-made debris, mainly as a result of intensive farming. The extensive use of plasticulture, including the use of mulching films, and the application of sewage sludge and wastewater irrigation, are the dominating entry pathways for MP to the terrestrial environment. I.e., research supports that the origin of contamination determines the morphological nature of the debris, for example, in the application of sewage sludge, soils are likely to accumulate fiber from the effluent of washing machines, while plasticulture residues are likely to accumulate mostly fragments and film (Wang et al., 2022). Furthermore, irrigation with eutrophic water is a "double-edged sword," that simultaneously brings microplastics and biological pollutants, such as cyanotoxins, to the rhizosphere (Maity et al., 2021). This interaction forms a complex pollution matrix where plastics can act as carriers of organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) in a manner that is very similar to the plastic acting as a chemical shuttle before entering the soil system (Abbasi et al., 2021). Moreover, unmanaged continual plastic mulching is leading to indefinite accumulation, as the productive arable land turns into a long-term storage of the recalcitrant polymer residue (Yadav et al., 2022).

Beyond direct agricultural inputs, atmospheric deposition is a pathway that is often overlooked but has a huge reach. Wind-blown dust, synthetic fibers from urban centers, and particles from tire wear settle on the agricultural lands, contributing substantially to the "sink" effect, even for fields that are not directly treated with sludge or plastic mulch (Yu et al., 2021). The "legacy effect" of sewage sludge is particularly pronounced - results from field studies on soils showing a history of repeated sludge application show significant accumulations of microplastics, i.e., up to 1383 items/kg. Notably, while fibers are highly abundant in raw sludge, fragments of polypropylene (PP) and polyethylene (PE) tend to become the predominant shape in the soil over time (42-76%), which suggests that agricultural soils are selective sinks in which specific morphotypes tend to accumulate, or remain for a longer time, than others (Yang et al., 2021). This accumulation is further complicated by the use of biosolids, as the nutrient load can help mask or modify the stress that our metabolic machinery imposes on the rhizosphere due to the plastics (Lebel et al., 2025).

Table 1

Dominant Sources and Characteristics of Microplastics in Agroecosystems

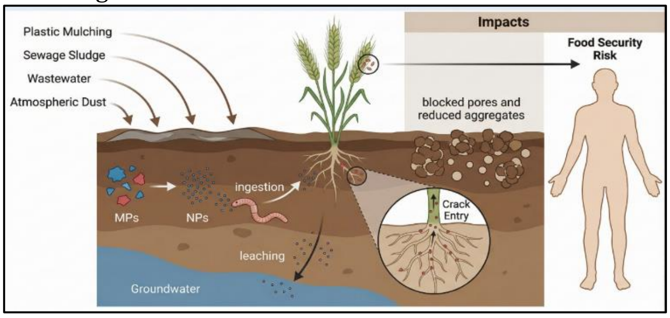
Entry Pathway	Primary Polymer Types	Dominant Shape	Key Mechanism of Entry	References
Plasticulture (Mulching)	Polyethylene (PE), Polypropylene (PP), PBAT	Fragments, Films	Mechanical abrasion of weathered films; incomplete removal after harvest.	(Lebel et al., 2025; Wang et al., 2022)
Sewage Sludge/Biosolids	Polyester, Polyamide, Polyethylene	Fibers, Beads	Land application of wastewater treatment byproducts containing microfibers.	(Lebel et al., 2025; Yang et al., 2021)
Wastewater Irrigation	Polyethylene (PE), Polystyrene (PS)	Fragments, Spheres	Direct irrigation with eutrophic or treated water containing suspended MPs.	(Abbasi et al., 2021; Maity et al., 2021)
Atmospheric Deposition	Synthetic Rubber (Tire wear), PVC	Dust, Particles	Wind-blown dust from urban centers; settling of tire wear particles.	(Tian et al., 2022; Yu et al., 2021)

Fate, Behavior, and Migration in the Soil Matrix

Once deposited, microplastics are not stationary. Vertical migration is caused by bioturbation by soil fauna such as earthworms, and the formation of the "Plastisphere," and so the particles re-distribute in the soil profile. Recent advancements in the field of soil zymography have enabled the visualization of this unique framework of high microbial activity zeumia surrounding plastic particles (Zhou et al., 2021). Microplastics travel through wet-dry cycles and root pathways vertically to reach large concentrations in sub-soil (20-40 cm depth) (Yang et al., 2021; Yu et al., 2021). This downward movement agrees with the conclusion that agricultural topsoil is not a place to put things, but a zone of transit, bringing with it possible risks to groundwater aquifers and deep-rooting crops. Soil macrofauna in particular, anecic earthworms (Lumbricus terrestris) and collembola, play an important role in this transport concerning the feeding and burrowing of soils (Bouaicha et al., 2022).

Horizontal migration is also of great importance, with wind erosion playing a major role in the dispersal of light-density plastics, especially weathered PE mulch films. This transports contamination from the agricultural field to the neighbouring ecosystems, rendering agricultural soils akin to secondary sources of atmospheric microplastics (Tian et al., 2022). Furthermore, the risk is not restricted only to the unsaturated zone as agricultural soils are the temporary sink, micro and nanoplastics (MnPs) are eventually leached into groundwater aquifers. This vertical transport is facilitated by macropores and desiccation cracking, allowing the particles to get around the filtering capacity of the soil matrix during intense rainfall events (Moeck et al., 2023). Soil texture and the method of irrigation have an important role in these dynamics; coarse sandy loams have less abundant nutrient concentrations than do fine clays, and drip irrigation has been found to result in greater MP accumulation compared to sprinkler or surface irrigation (Deng et al., 2024).

Figure 1
The cycle of microplastic accumulation in agroecosystems, highlighting the transition from surface pollution to deep-soil and groundwater contamination.



Degradation, Weathering, and Future Projections

In the case of the terrestrial environment, differentially charged microplastics are formed through weathering (photo-oxidation, mechanical fragmentation). Aging introduces oxygen-containing functional groups (i.e., -COOH, -OH), radically changing the toxicity profile of plastics, compared to their virgin counterparts (Xu et al., 2022). Agricultural practices, especially intensive activities like tillage and harvesting activities, enhance this process through mechanical abrasion, combining the UV irradiation to break down macro-plastics into micro- and nano-plastics at a higher pace than the natural weathering process (Tian et al., 2022). Climatic considerations are also likely to contribute because warmer ambient temperatures and higher rainfall rates are a catalysts for greater rates of fragmentation and migrations (Deng et al., 2024). Microscopically, aged PE and PP gain notable surface roughness as well as cracks that help to increase their adsorptive capacity and interaction with root cell walls (Li et al., 2025).

A critical consensus is emerging concerning the size dependency of the toxicity of these particles. Nanoplastics (<1 μm) are known to cause significantly higher oxidative stress and photosynthetic inhibition than the larger ones because they can enter the cell wall. Conversely, larger microplastics (>200 μm) tend to have more negative effects on plant biomass, which is probably the result of physical processes such as pore blockage and reduced water hydraulic conductivity (Wang et al., 2022; Y. Zhang et al., 2022). In terms of the future, based on the corresponding data in the long term, predictive models indicate an exponential increase in microplastic concentration in agricultural soils, which is strongly amplified by the use of fertilizers. Projections suggest that in just a century, levels could reach values (on the order of 0.1% w/w) similar to those used in current toxicity experiments at high doses: in this case, the validity of the current research is demonstrated for future scenarios (Meizoso-Regueira et al., 2024).

Physico-Chemical Interactions in the Rhizosphere

Alteration of Soil Bulk Properties: The pH Paradox

Microplastics have an overwhelming physical effect on the soil matrix, changing its physical parameters such as bulk density, water holding capacity (WHC), and pH. A comprehensive review concluded that low-density microplastics incorporation generally reduces the soil bulk density and increases the soil porosity, especially the macropores. While this may suggest an increase in aeration, it has often been at the cost of disturbed water stable aggregates and increasing evapotranspiration channels with the concomitant reduction in water retention capacity (Wang et al., 2022; Y. Zhang et al., 2022) . This aggregate unreliability makes agricultural soils far more prone to erosion (Lwanga et al., 2022). However, conflicting evidence exists pointing to the fact that under certain conditions, especially with high-density plastics, bulk density may be increased which will lead to compaction (Hasan & Tarannum, 2025).

Furthermore, the effects of microplastics on the soil pH are a "paradox" that is dependent on soil type and hydrology. In dryland agricultural soils, other materials like PE and PLA have been seen to improve soil pH (Elbasiouny et al., 2023; Wang et al., 2020). On the other hand, in the paddy soils, polymers, such as PS and PTFE, may cause a strong acidification (Dong et al., 2021). This divergent effect has a very important consequence as it essentially determines the solubility and bioavailability of heavy metals and nutrients in cropping systems. Additionally, microplastics made of polystyrene have been found to raise the amount of Dissolved Organic Matter (DOM), which enriches more humic-like substances, possibly affecting the dynamics of carbon cycling (Chen et al., 2024; Ren et al., 2021).

Nutrient Availability and Cycling: The "Starvation" Effect

The input of carbon-based and nutrient-impoverished microplastics can induce a severe stoichiometric imbalance that leads to acute Nitrogen (N) immobilization. Microplastics often suppress the action of other important enzymes (urease and phosphatase) that are important for N and P mineralization, therefore, it decreases the availability of these nutrients in the rhizosphere (Dong et al., 2021; Wang et al., 2022). While common reporting of urease inhibition has been noticed, it is not uncommon to see the opposite reporting, which refers to the activity of enzymes like catalase and sucrase increasing in a parallel way, which could refer to a complex stress response in which N cycling is repressed, but carbon turnover is stimulated (Lai et al., 2025). Moreover, biodegradable plastics such as PBAT can establish "priming effect," a result of microbial decomposition of the native soil organic matter or preferred uptake of the plastic-derived carbon over plants without competition and subsequent decrease of the mineral nutrient uptake of plants from the soil (Han et al., 2024).

Microplastics also have a significant impact on nitrogen cycling dynamics that can increase nitrate and nitrite content and reduce ammonium, caused by changes in the population of nitrifying and denitrifying bacteria (Bouaicha et al., 2022; Lai et al., 2025). Beyond immobilization, microplastics are active disruptors of the nitrogen cycle, which worsens ammonia volatilization and greenhouse gas emissions (methane) during composting and soil incubation (Sarfraz et al., 2025). Furthermore, a 'growth dilution effect' in fertile soils has been identified, in which the stimulation of biomass caused by microplastic exposure results in a decrease in micronutrient concentrations (e.g. Zinc) in plant tissues, at the expense of nutritional quality (Moreno-Jiménez et al., 2022).

Surface Chemistry & The "Vector" Effect

The ability of microplastics to act as vectors for other pollutants is a major concern and interactions are complex and context-dependent. Regarding the heavy metals, a debate is on between the "Vector" and "Sink" hypotheses. Some studies have been conducted that suggest a sink effect, whereby biodegradable MPs increase the pH of soils and bind metals such as Cadmium (Cd), decreasing their concentration in plants (Huang et al., 2023). However, a global meta-analysis shows that, overall, microplastics increase Cd uptake by plants by almost 30%, supporting the vector hypothesis, especially in the case of polyethylene (PE) (Huang et al., 2023). The winner is probably going to be the competition between the adsorption capacity of the plastic and the uptake capacity of the plant root.

Microplastics also work like vectors for organic pollutants. PET microplastics are proven to be able to adsorb and release significant fractions of polycyclic aromatic hydrocarbons (PAHs) from irrigation water into the rhizosphere and can act as "chemical shuttles." (Abbasi et al., 2021). Similarly, they are capable of adsorbing metalloids such as Arsenic (Dong et al., 2021) and antibiotics such as Oxytetracycline, and related to the latter, they may exhibit synergistic toxicity of these contaminants (Guo et al., 2022). Furthermore, microplastics offer hotspots of horizontal transfer of Antibiotic Resistance Genes (ARGs) to and within bacterial communities in the soil (Maddela et al., 2023). While some modeling studies indicate that the kinetics of desorption might potentially limit the long-distance transport of some organic contaminants (Castan et al., 2021). The possibility of facilitated transport through preferential flow paths to groundwater is a major concern (Moeck et al., 2023).

Table 2

Interaction of Microplastics with Co-Contaminants

Co-Contaminant	Interaction Mechanism	Outcome	Reference
Cadmium (Cd)	"Vector Effect": Increased uptake via PE; "Sink Effect": Reduced uptake via PLA (pH rise)	Synergistic toxicity; Reduced biomass; Altered bioavailability; Global uptake increase (+29.4%)	(Huang et al., 2023; Wang et al., 2023)
Antibiotics (e.g., Tetracycline)	Adsorption onto the MP surface; Horizontal gene transfer	Spread of Antibiotic Resistance Genes (ARGs); Enhanced phytotoxicity in wheat	(Guo et al., 2022; Maddela et al., 2023)
Arsenic (As)	Complexation; Redox potential alteration	Variable uptake depending on MP type and soil redox status; Reduced bioavailability in some cases	(Dong et al., 2021; Sun et al., 2023)

Impact on Soil Microbiome and Symbionts

Microplastics apply selective pressure on the soil microbiome that leads to changes in microbiological taxonomy that can lead to soil health. Generally, microplastics favor stress-tolerant taxa such as Acidobacteria and Chloroflexi while cause reduction in Proteobacteria and Plant Growth Promoting Rhizobacteria (PGPR) (Dong et al., 2021; Guo et al., 2022; Zhou et al., 2021). The impact is different between polymer types; PE has been shown to cause the most pronounced reduction in the bacterial richness and diversity compared to PS and PVC, which suggests there may be a hierarchy of toxicity (Zhu et al., 2022). Conversely, in certain situations, PE may select for nitrogen-fixing genera, such as Anaeromyxobacter (Lai et al., 2025). The "Plastisphere" is also a haven for pathogenic fungi and could therefore lead to an increase in the incidence of disease (Bouaicha et al., 2022).

The impact on symbiotic associations, especially Arbuscular Mycorrhizal Fungi (AMF), is subtle. While biodegradable plastics such as PLA often change the selective pressure to a greater extent than PE (Wang et al., 2020). Evidence from extremely fertile soils indicates that the colonization of AMF may be stable to MP exposure (Moreno-Jiménez et al., 2022). Importantly, amendment with biochar has been shown to ameliorate the shift in the microbial consortium and also restore diversity and recruit beneficial genera of the nitrogen cycle (Elbasiouny et al., 2023; Yang et al., 2024). Furthermore, the influence of microplastics on the stability of the soil carbon pool through changing the contribution of microbial necromass can be opposing for conventional plastics and biodegradable plastics (Chen et al., 2024).

Disruption of Element Cycling Genes (Metagenomics)

Metagenomic analyses have demonstrated that microplastics essentially alter the functional potential of the microbiome. Biodegradable plastics like PBAT have been shown to cause dose-dependent depletion of genes with respect to the carbon and nitrogen cycles (Han et al., 2024). The impact is polymer specific, and polystyrene (PS) specifically reduces genes for metabolism, effectively stopping the metabolic engine of the rhizosphere, while PE and PVC may increase the level of some categories as a stress response (Zhu et al., 2022). This genetic disruption offers some mechanistic explanation for the effects on nutrient cycling and soil fertility.

Mechanisms of Plant Uptake and Translocation

Root Interception and Adsorption

The main interaction between the plants and microplastics takes place at the surface of the root. Microplastics, and especially nanoplastics, deposit in the pores of the seed coat, thereby physically obstructing water and gas exchange, which has a drastic effect on germination delay (Z. Zhang et al., 2022). Size is a crucial factor in deciding, and particles below micrometers can enter root tissues (Mészáros et al., 2023). This accumulation, at the root surface, can also act as a physical barrier preventing the absorption of nutrients. For example, adsorbent effects-the adsorption of microplastics onto root hairs by the plant can clog the uptake of important minerals such as nitrate and phosphate, causing nutrient deficiencies even in rich soils. Furthermore, the hydrophobic property of countless plastics can alter the wettability of the root surface, and this could potentially interfere with the root-soil contact necessary for efficient water uptake (Wang et al., 2022).

Cellular Internalization

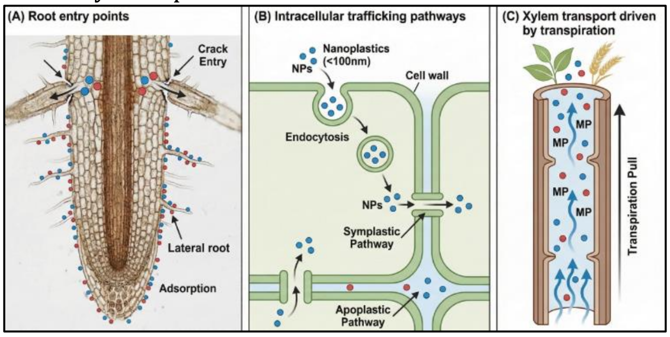
Internalization takes place through different pathways according to the particle size. Sub-micrometer plastics mainly enter roots through the so-called "crack-entry" mode at the sites of lateral root emergence, where the Casparian strip is disrupted. Nanoplastics (<100 nm) are directly enterable through the epidermis cells through endocytosis (Li et al., 2020; Bandmann et al., 2012). While plant cell walls usually contain particles larger than 5 - 20 nm, root secretion can change surface charges, which may open up larger pores or enable uptake (Azeem et al., 2021). Once inside the root cells, the nanoplastics can travel through the symplastic pathway, via plasmodesmata, that link the cytoplasm of cell neighbors. This intercellular transport occurs to get plastics past cell walls and move deeper into the plant tissue, eventually finding their way into the vascular cylinder. The efficiency of this internalization is also dependent on the surface properties of the plastics, meaning the positively charged particles are more likely to bind to the negatively charged cell membrane, increasing their uptake (Xu et al., 2022).

Transpiration Pull and Transport

Once internalized, due to the flowing transpiration current, the microplastics are forced to move upward through the xylem to the stem and fruits (Deng et al., 2024). The Translocation Factor (TF) is a measure of this risk and whilst it would be generally low for cereal crops, the higher transpiration rates of leafy vegetables could mean that the TF's are higher and there is a higher risk of food safety. The Translocation Factor (TF) is a measure of this risk and whilst this would be generally low for cereal crops, as the leafy vegetables have higher transpiration rates, there is potentially a higher risk from food safety when its TF is also high (Azeem et al., 2021). Nanoplastics have much greater potential for systemic translocation to edible tissues than microplastics (Boctor et al., 2025).

Figure 2

Mechanisms of microplastic internalization and translocation in plants. (A) Root entry points; (B) Intracellular trafficking pathways; (C) Xylem transport driven by transpiration.



The movement of plastics through the xylem is a passive process due to the water potential induced by the evaporation from leaves. However, this transport may be impeded by the physical dimensions of the xylem vessels and by the presence of perforation plates. Accumulation of plastics in the xylem can cause embolisms and a reduction of hydraulic conductivity, forcing the plant in a further state of water stress. Additionally, there exists evidence of redistribution of some nanoplastics by means of the phloem, thus reaching seeds and fruits during the formation stage (Maity et al., 2022).

Differential Uptake based on Surface Charge

Surface chemistry is very important in uptake. Positively charged particles (-NH2) adsorb strongly to the negatively charged cell wall and can therefore lead to blockage, whereas hydrophilic or negatively charged particles (-SO3H) can pass through the cell membrane more readily and therefore result in severe intracellular toxicity (Xu et al., 2022). The interaction between the surface of the plastic and the cell wall components, including pectin and cellulose, is the determining factor in the amount of adsorption and internalization. Modifications on the plastic surface through weathering or through the adsorption of biomolecules (forming an "eco-corona") can greatly change its absorption behaviour. For example, weathered plastics with greater surface roughness and the presence of functional groups with oxygen may have enhanced the interactions between the plastics and root exudates as well as the transport of root exudates into the root tissues (Li et al., 2025). This differential uptake has profound implication on the toxicity and bioaccumulations for microplastics for different plant species and environmental conditions.

Physiological Responses and Biotic Interactions

Oxidative Stress and Antioxidant Defense

Microplastic exposure consistently induces production of Reactive Oxygen Species (ROS) that lead to oxidative damage of lipids, proteins and DNA. This oxidative burst frequently occurs at the nano-bio interface, where interaction of the particle surfaces with each other disrupts the electron transport chain in mitochondria and chloroplasts (Azeem et al., 2021; Maity et al., 2022). The type of polymer is important; PET is a particularly potent stressor, resulting in huge increases in hydrogen peroxide levels (Wang et al., 2023). In addition, aged plastics are even worse than their original counterparts because of the occurrence of oxygen-containing functional groups in the plastics (Li et al., 2025). Antioxidant strategies of plants are divergent, dependent on the kind of polymer (biochar being efficient in the part of buffering this oxidative shock; (Sun et al., 2023; Yang et al., 2024). The amount of ROS is responsible for lipid peroxidation, membrane damage, and triggering of programmed cell death pathways. To counteract this a process called "voltage up- regulation" of the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD) is induced by plants. However, if the stress becomes too much for the antioxidant system, severe cell damage and cell growth inhibition occur.

Table 3

Summary of Microplastic Effects on Soil Properties and Plant Physiology

Polymer Type	Soil Effect	Plant Physiological Impact	Reference
Polyethylene (PE)	Reduced bulk density; Altered microbial diversity (reduced richness)	Inhibited root growth; Reduced biomass; Increased Cd uptake (Vector effect)	(Huang et al., 2023; Wang et al., 2020; Zhu et al., 2022)
Polystyrene (PS)	Increased dissolved organic matter (DOM); Acidification in paddy soils	Oxidative stress; Photosynthetic inhibition (Chlorophyll a > b); Metabolic disruption	(Dong et al., 2021; Ren et al., 2021)
Biodegradable (PLA/PBAT)	Increased soil pH; Nutrient immobilization (N starvation); Carbon Catabolite Repression	Severe phytotoxicity; Reduced leaf area; "Biodegradable Paradox"; "Sink effect" for Cd	(Han et al., 2024; Sun et al., 2023; Wang et al., 2023)
Polypropylene (PP)	Increased soil porosity; Reduced aggregate stability; Modified enzyme activity	Imbalanced antioxidant system; Reduced root viability; Altered respiration profiles	(Lebel et al., 2025; Lian et al., 2024)
Polyethylene Terephthalate (PET)	No significant pH change; Adsorbs organic pollutants	High ROS generation (H_2O_2); Synergistic toxicity with PAHs	(Abbasi et al., 2021; Wang et al., 2023)

Photosynthetic Inhibition

Microplastics affect the functioning of the photosynthetic process, where surface functional groups and the type of polymer used affect the severity of the impact. Positively charged nanoplastics lead to a severe dose of PSII reaction center shutdown (Xu et al., 2022). Biodegradable plastics have also been shown to cause catastrophic declines in photosynthetic capacity (Sun et al., 2023). Specifically, Chlorophyll a seems more sensitive to the stress of microplastics than Chlorophyll b, which disrupts the ratio of both pigments and adversely affects the light-harvesting efficiency (Ren et al., 2021). The chlorophyll decrease is often accompanied by thylakoid membrane damage as well as a decline in the efficiency of electron transport. This causes a decrease in the rate of CO2 assimilation and a decrease in the production of photosynthates, ultimately stunting plant growth and the yield amount. Furthermore, the microplastics can also disrupt the stomatal conductance, restricting the amount of gas that can pass through the leaf, which further limits photosynthesis.

Genotoxicity and Cytotoxicity

Microplastics have a genetic toxicity effect which causes chromosomal cleavage (e.g. micronuclei, stickiness) and low mitotic index in root tips (Elbasiouny et al., 2023; Z. Zhang et al., 2022). This is associated with the repression of cell cycle regulator genes such as cdc2 and the activation of stress-responsive genes, which results in cell cycle arrest (Mészáros et al., 2023). Cytoprotective effects resulting from biochar amendment, mitigating such genotoxic effects, have been presented (Elbasiouny et al., 2023). For example, the physical interaction of internalized nanoplastics with the cytoskeleton and genetic material can interfere with cell division and the segregation of chromosomes. This could result in the formation of micronuclei and other sorts of nuclear abnormalities, which are indicative of genotoxicity. The blocking of cell division in root tips directly correlates to decreased root elongation and branching, which compromises the plant's ability to explore the soil for water and nutrients.

Metabolic Alterations and Root Exudation

Microplastics cause metabolic reprogramming of the body. Plants redistribute resources away from growth to that of defense, and change the balance of root exudate (e.g., reduced indoleacetic acid, increased stress signals such as ABA) (Han et al., 2024; Li et al., 2025). This hormonal imbalance leads to a "hormonal blockade" and stunts root developments (Jia et al., 2023). Furthermore, microplastics affect microbial consumption of these exudates so that their metabolic coupling to the rhizosphere microbiome is disrupted (Lebel et al., 2025). Carbon metabolism is also inhibited, which leads to an energy deficit (Maity et al., 2022). The change in metabolism often includes the building up of compatible solutes such as proline and soluble sugars that help to keep osmotic balance and prevent damage to cellular structures. However, this drawing away of energy and carbon from primary growth processes causes lower biomass accumulation. The change in root exudates may lead to the disruption of the recruitment of beneficial microbes, which may further reduce plant health.

Impact on Soil Fauna and Trophic Interactions

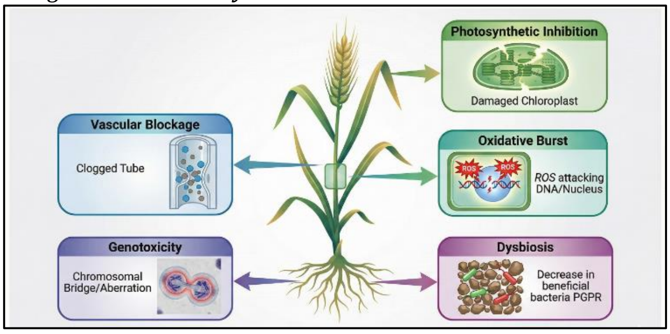
The effects of microplastics do not stop with just the soil food web. MPs cause direct toxicity to soil fauna such as earthworms, springtails, and snails, affecting their behaviour and ecosystem services (which are often beneficial) (Bello et al., 2025; Bouaicha et al., 2022). Furthermore, ultraviolet rays in the environment have been found to use MPs as vectors to enable trophic transfer and biomagnification up the food chain (Athulya et al., 2024). Earthworms, as ecosystem engineers, play an important role in the aeration of soil and decomposition of organic matter. Microplastics can cause damage to their digestive system, lower their growth and reproduction rates and change their burrowing activity level. This in turn, has impacts on soil structure and nutrient cycling. In addition, microplastics may be transferred from soil fauna to predators (birds, small mammals) and will therefore lead to the accumulation of plastics and high associated contaminants in higher trophic levels.

Multi-omics Insights into Molecular Mechanisms

Recent multi-omics studies have shown that MP exposure causes a massive reprogramming of gene expression with the up-regulation of genes involved in the oxidative stress response, the synthesis of secondary metabolites, and hormone signaling. Metabolomic profiles reveal a balance towards defense-related metabolites (e.g., proline, flavonoids) at the expense of primary growth metabolites, explaining the existence of a trade-off between survival and accumulation of biomass (Farooq et al., 2025). Transcriptomic analysis has defined the gene set involved during the plant response to microplastic stress, such as genes implicated in cell wall modification, transporters, and signal transduction. Proteomic studies have identified alterations in the abundance of proteins associated with photosynthesis, energy, and stress. By integrating data from transcriptomics, proteomics, and metabolomics, researchers could acquire a more holistic view of the molecular mechanisms responsible for the toxicity of microplastics and pinpoint possible targets to prioritise potential solutions that can be used to make plants more resilient.

Figure 3

Systemic physiological disruption caused by microplastics, ranging from rhizosphere dysbiosis to organelle damage and genetic instability.



Impact on Agronomic Traits and Food Security

Seed Germination and Root Architecture

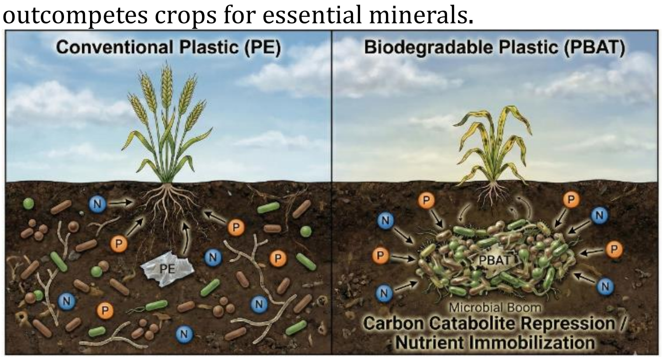
Microplastics accumulate in the pores of the seed coat and prevent water uptake and gas exchange physically as it delays germination (Z. Zhang et al., 2022). While in hydroponic studies, severe toxicity is often shown, for soil culture studies, it is seen that there is a buffering effect(Li et al., 2022). Nevertheless, plants are often observed to have significant phytotoxicity in the roots such as a decrease in length and biomass, but the biochar can mitigate this effect (Elbasiouny et al., 2023). Importantly, small-sized microplastics critically threaten the filling and quality of grain (Xiang et al., 2024). The microplastics can negatively affect imbibition delay, germination rate, and consequently, poor stand establishment due to the physical obstruction of seed pores. Once germinated the young roots are subject to physical resistance from the soil particles interspersed with plastics which can potentially alter root architecture. Microplastics may result in the inhibition of primary root elongation and lateral root development, which is a common stress response to maximize soil exploration. However, this altered root system may prove less efficient in water and nutrient uptake and thus eventually affect the crop's yield.

Yield Penalties and The Biodegradable Paradox

A surprisingly startling "Biodegradable Paradox" has come to light - biodegradable plastics, which are supposed to be 'environmentally friendly', are often found to be more phytotoxic than conventional plastics because of the degradation product and immobilization of nutrients. This is observed in crops such as Pakchoi, Maize, and Wheat (Han et al., 2024; Zhou et al., 2021). However, some studies indicate a resource allocation shift with the biodegradable MPs increasing root biomass and restricting the shoot growth (Wang et al., 2023). Global analyses confirming synergistic toxicity in the case of co-occurrence of MPs and heavy metals. Broad phytotoxicity of different polymer types (Huang et al., 2023; Lian et al., 2024).

Figure 4

The Biodegradable Paradox. While conventional plastics persist, biodegradable plastics can induce acute nutrient starvation by stimulating rapid microbial growth that outcompetes crops for essential minerals.



A "hormesis effect" has also been reported, in which low concentrations of MP stimulate growth, and higher concentrations reliably inhibit growth (Mészáros et al., 2023). The breakdown of biodegradable plastics produces monomers and oligomers which can be toxic for plants and soil microbes. Additionally, the speed at which the plastic is broken down by microbial means can lead to a resulting nitrogen immobilization and thus a lack of this crucial plant nutrient. This reveals the importance of conducting a thorough assessment of the environmental consequences of the use of biodegradable plastics in the agricultural sector prior to their widespread adoption.

Plant Community Dynamics and Weed Competition

Microplastics can change the interspecific competition and the community structure, which might benefit robust and stress-tolerant weed species to the detriment of sensitive crops. This accumulation could lead to an imbalance in the agroecosystem competition process, altering the course of succession, and demanding new approaches to weed management (Yu et al., 2021). Weeds tend to be more phenotypically plastic and stress-tolerant than are cultivated crops. In the presence of microplastics, weeds may be able to better sustain growth and reproduction, and outcompete crops for resources. This could result in a change in weed community composition and an increase in weed pressure, requiring farmers to change their weed management practices. Furthermore, microplastics can also modify soil microbial communities in a way that differentially impacts crops and weeds and may also contribute to competitive imbalances.

Comparative Crop Sensitivity

All crops are not equally vulnerable. There is a clear hierarchy of sensitivity; Maize, Garden Cress, and Water Spinach are highly sensitive, Rice and Tomato are moderately sensitive and Wheat and Lettuce are somewhat resistant (Bello et al., 2025; Wang et al., 2023; Y. Zhang et al., 2022). Certain hyperacculators such as Sedum alfredii, may even have an increased biomass and show an opportunity for phytoremediation. The sensitivity of crops to microplastics is reliant on numerous aspects such as the root morphology, growth rate, physiological stress tolerance, etc. Crops with large root systems might face a higher number of microplastics, thus a higher exposure. Similarly, the fast-growing crops may be more susceptible to nutrient limitation due to microplastics. Understanding these responses among species is important when developing targeted mitigation strategies and a strategy for selecting resilient crop varieties for use in plastic-contaminated soils.

Securing Food Safety and Human Health

The accumulation of MPs in the edible tissue is a direct threat to the safety of the food. There is an urgent need to shift towards a functional trait-based framework to identify MP- resistant genotypes as well as to establish regulatory thresholds (Chen et al., 2025). Drawing parallels from recent advancements in wheat breeding, where integrated approaches combining phenotypic screening with molecular markers (e.g., GWAS, QTL mapping) have successfully identified drought-tolerant genotypes (Bibi et al., 2025), similar "pheno-genomic" strategies should be adapted to screen for crops capable of withstanding the osmotic and oxidative stresses imposed by microplastics. The bioaccumulation of MPs allows a pathway for "bio-toxification," where the MP and pollutants adsorbed on it bio-magnify via the food chain (Okeke et al., 2023). Consumption of contaminated produce is associated with different human health risks, ranging from liver damage to inflammation and potential neurotoxicity. MPs are also known to be vectors of endocrine disrupters and antibiotic resistance genes and so the problem becomes a public health issue (Bello et al., 2025; Tariq et al., 2024). The ingestion of microplastics through the consumption of food can result in the accumulation of microplastics in human tissues and organs. The potential health effects are chronic inflammation, oxidative stress and disruption of the endocrine system. Furthermore, microplastics may transport harmful bacteria and antibiotic resistance genes, which may be transferred to the human gut microbiome and create a risk of infection and antibiotic resistance. Ensuring the safety of agricultural produce in an era of microplastic pollution is a large challenge in the 21st century.

Emerging Remediation Strategies

Microbial and Chemical Remediation

The complexity of microplastic pollution has an urgent need for innovative and multi-pronged approaches to remediation. Bio-augmentation, or the addition of certain strains of microorganisms or combinations of microorganisms, has shown great potential. Studies have shown that sowing degrading bacteria like Stenotrophomonas, Bacillus and Acinetobacter on soil can not only reverse the effects of microplastics on crop yield, that have been observed in Highland Barley, but also actively degrade the polymer matrix (Xiang et al., 2024). Specificity is the key to this; recent reviews describe the efficiency of Ideonella sakaiensis for PET degradation, Pseudomonas for polyphenylene sulfide (PPS), and Amycolatopsis for polylactic acid (PLA) (Yadav et al., 2022). To overcome the instability of free enzymes in soil environments, sophisticated methods on immobilized enzyme complexes, in which various enzymes, such as cutinases and lipases, are anchored on stable supports, are developed to improve durability and catalytic efficiency under field environment (Okeke et al., 2023). Chemical means of remediation are also evolving, with bio-surfactants being investigated to make the plastic surfaces more hydrophilic in order to make them more accessible to microbial degradation.

Table 4

Emerging Remediation Strategies

Strategy	Mechanism	Target Pollutant/Effect	References
Bio-augmentation	Inoculation with specific degrading bacteria (Ideonella, Pseudomonas, Stenotrophomonas)	Polymer degradation; Restoration of microbial diversity; Yield recovery	(Xiang et al., 2024; Yadav et al., 2022)
Biochar Amendment	Adsorption of toxins; Improvement of soil structure; Transcriptomic rescue	Reduced ROS; Restoration of nutrient uptake genes; Reduced NH3 volatilization; Cytoprotection	(Elbasiouny et al., 2023; Sarfraz et al., 2025; L. Yang et al., 2024)
Phytoremediation	Phytoextraction (uptake) and Phytostabilization (immobilization via exudates)	Removal of small MPs/NPs; Reduced migration to groundwater; Soil stabilization	(Jia et al., 2023; Tariq et al., 2024)
Enzymatic Degradation	Immobilized enzyme complexes (cutinases, lipases)	Cleavage of ester bonds in polyesters; Enhanced stability in soil environment	(Okeke et al., 2023)

Source Control and Policy Implementation

While remediation is focused on existing pollution, good governance is the key to stopping the tide of new accumulation. Global frameworks are taking shape for implementation, including the UNEP Global Plastics Treaty that is currently being negotiated to create legally binding agreements that may change the use of plastic in farming. Regionally, the EU Green Deal and Farm to Fork Strategy are setting ambitious targets for plastic footprint reduction and nationally, such policies as the UK's Agricultural Transition Plan are giving incentives for practicing sustainable soil management (Chen et al., 2025; Z. Zhang et al., 2022). An important component of such policies is tight management of inputs. This includes regulating the quality of sewage sludge used for land applications to ensure microplastic loads to the land are minimized and mandating that fully biodegradable mulch films are used, which have been verified for non-toxicity to soil biota (Boctor et al., 2025). Furthermore, an overhaul from voluntary guidelines to enforceable rules, related to "Zero Plastic to Landfill" and extended producer responsibility (EPR) of agricultural plastics are crucial to long term mitigation.

Phytoremediation and Rhizosphere Engineering

Phytoremediation is a sustainable, solar-based process that exploits the natural resources of plants. Phytoextraction is the process of using hyperaccumulator plants to absorb and compartmentalize small micro and nanoplastics in their aboveground tissues, and subsequently to harvest them and subject them to treatment. While this study is limited in its smaller particle size, this method has the potential application in the cleanup of "hotspots" of contamination (Jia et al., 2023). Alternatively, Phytostabilization is focused on the immobile and in the root zone. Plants emit exudates from their roots, such as mucilage and organic acids, which hold the potential to bind Soil particles and microplastics together to form stable aggregates. This limits the availability of the plastics and stops them from flowing into the groundwater or being taken up by food crops. Future attempts to explore rhizosphere engineering (optimization of plant-microbe interaction to boost degradation of the plastic) could potentially boost these vegetative strategies even further (Tariq et al., 2024).

Analytical Challenges and Methodologies

The "invisible" nature of microplastic pollution in soil is an analytical challenge. Quantification of such particles in complex ag matrices is surrounded by difficulties that often result in data underestimation or incomparability. One of the main challenges is the separation of plastics from soil organic matter, which has similar density ranges. While traditional density separation using NaCl is common, for heavier polymers, it is often not enough. Several recent reviews strongly suggest the implementation of high-density solutions such as $ZnCl_2$ or NaI for better recovery rates despite their higher cost and potential toxicity (Athulya et al., 2024). Chemical methods of digestion using hydrogen peroxide or Fenton's reagent are standard methods of removing organic matter, but the protocols have to be carefully optimized to ensure that the plastic polymers do not themselves become degraded, which would throw off results.

Identification is a challenge. Spectroscopic techniques such as FTIR and Raman are the gold standards but tend to be affected by biofilms, clay particles, or iron oxide sticking to the plastic surface, and therefore need to perform thorough sample cleaning. Furthermore, these methods can be time-consuming and are usually only possible to explore a small subsample. To solve this, though, Pyrolysis-GC/MS Thermal Degradation Methods are picking up momentum. These techniques offer precise identification of polymers and mass-based quantification with the limitation of not providing a bias of the particle counting at the cost of a destroyed analyzed sample and also without any morphological information (Athulya et al., 2024). A key area of missing information with cross-matrix detection is that currently, the same study method is unable to move from soil to root and shoot tissue without missing some tracking of the microplastics, impeding on an accurate understanding of translocation factors and food safety concerns (Chen et al., 2025).

Emerging technologies are offering new prospects of overcoming these bottlenecks. The unification of Artificial Intelligence (AI) and Machine Learning and Spectroscopic Imaging is disrupting the world as far as detection is concerned. Convolutional Neural Networks (CNNs) can be used to train models that can quickly detect and classify microplastics in hyperspectral images with a much higher throughput and accuracy compared to manually counting the microplastics in an image (Okeke et al., 2023). However, one critical "Concentration Gap" tends to dominate the literature. Many laboratory studies use elevated concentrations of microplastics (up to 50% w/w) to induce acute toxicity in comparison to what is found in the field (generally low - < 0.1% w/w). This disagreement is a cautionary note that direct extrapolation of the laboratory measuring data to the field situation should be avoided without taking into account long-term, chronic exposure. Finally, a lack of standardized global protocols for sampling, extraction of samples and reporting is the single biggest incurred barrier to meta-analysis and global risk assessment.

Future Research Priorities

Despite the considerable progress, the scientific understanding of microplastics in agroecosystems is currently in the infancy stage and there are still a number of critical knowledge gaps that need urgent attention. First of all is the need for Long-term Field Monitoring. The available information is mainly from short-term laboratory/experimental/vehicle-based studies or greenhouse experiments, which do not reflect the slow cumulative impacts of microplastics on soil stability, carbon sequestration and ecological functions over decades. The establishment of long-term ecological research (LER) sites in a manner specific to plastic pollution is necessary to aid in the comprehension of the path forward of "soil plastification." (Gao et al., 2025).

Secondly, there is an important need to redress the Geographical Bias of current Literature. Most research is heavily concentrated in China and Europe, leaving huge gaps in data for tropical, arid, and developing regions in Africa and South America. These regions are often exposed to different climatic drivers (e.g., extreme heat, monsoon rains) and agricultural practices (e.g., intensive plastic mulching with no removal infrastructures) that could cause vastly different dynamics of soil-plastic interaction (Sa'adu & Farsang, 2023).

Finally, we need a better mechanistic understanding of Nanoplastic Toxicity and Carbon Dynamics. The mechanisms of penetration of nanoplastics into plant cells and the disruptions to molecular pathways remain for the most part black boxes. Advanced imaging and omics technologies are required to trace the intracellular trafficking of these. Furthermore, as pointed out by (Chen et al., 2024). The influence of microplastics on the microbial necromass, which is the animportant component of stable soil carbon, remains poorly quantified. Determination of whether or not microplastics destabilize this long-term carbon pool is important in understanding the implications of plastic pollution on the global carbon cycle and climate change mitigation.

CONCLUSION

The conversion of agricultural soils into a "Silent Sink" for microplastics is a highly significant paradigm shift in environmental toxicology. This review has demonstrated that microplastics are powerful physical and chemical stressors that fundamentally change the soil-plant continuum, ranging from seed germination to harvest. We revealed a worrying "Biodegradable Paradox" where environmentally friendly substitutes might be inducing high phytotoxicity via nutrient immobilization to the extent that they hinder their sustainability. Furthermore, the contradictory "Vector" vs. "Sink" role of microplastics illustrates the complexity of the soil interaction with important implications for the bioaccumulation of heavy metals and organic pollutants in the food chain. Addressing this crisis requires an approach of synergies. Scalable remediation approaches, biochar amendment, and microbial bioaugmentation have a very large potential to restore soil health. However, these have to be coupled with strong governance, moving from voluntary guidelines through enforceable international regulations (for example, UNEP Global Plastics Treaty). Future research needs to favor long-term field monitoring that helps bridge the "Concentration Gap" between lab and field, and is geographically broader, covering less studied tropical and arid areas. Ultimately, decoupling agricultural productivity from plastic pollution is imperative in order to ensure food security in the world in the "Plastic Age."

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