



Microplastics in Agricultural Soils: An Emerging Threat to Soil Health, Microbial Ecology, Crop Productivity, and Food Safety

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ABSTRACT

Microplastics have emerged as a pervasive environmental pollutant, infiltrating terrestrial ecosystems, including agricultural soils. These tiny plastic particles (<5 mm) originate from various sources, such as plastic mulching, sewage sludge application, and atmospheric deposition. Their persistence in soils poses significant risks to soil microbial communities, plant health, and ultimately human wellbeing through the food chain. This review synthesizes current knowledge on the sources, distribution, and fate of microplastics in agricultural soils, their effects on soil microbial diversity and function, and the potential implications for human health. We also discuss mitigation strategies and future research directions to address this growing environmental concern.

Keywords: Microplastics; agricultural soils; soil microbiology; human health; plastic pollution; biodegradation.

1. INTRODUCTION

In recent decades, the proliferation of plastic waste has emerged as a critical global environmental challenge, with microplastics—defined as plastic particles smaller than 5 millimeters—becoming a particularly insidious form of pollution. Historically, marine ecosystems have been the primary focus of microplastic research, given their visible accumulation in oceans and the observable impacts on marine life. However, the attention is shifting to terrestrial ecosystems, especially agricultural soils, which are increasingly recognized as significant, yet often overlooked, sinks for microplastic accumulation (Rillig, 2012; Wang et al., 2022). Studies indicate that agricultural soils may receive microplastic loads comparable to or even exceeding those found in marine environments due to the widespread use of plastic-based products in modern agricultural practices (Nizzetto et al., 2016).

The implications of microplastic contamination in agricultural soils extend well beyond the physical presence of plastic debris. Microplastics can profoundly alter the physicochemical properties of soils, disrupt the structure and function of soil microbial communities, impair plant health, and facilitate the spread of pathogenic microorganisms. This multifaceted disruption poses a substantial risk to global food security, ecosystem health, and public safety (Rillig et al., 2019; Machado et al., 2018). The global plastic pollution crisis is alarming, with an estimated 10 million tons of plastic waste entering the oceans

annually (Jambeck et al., 2015). However, terrestrial ecosystems, particularly agricultural soils, are also major sinks for microplastics (MPs) (Rillig et al., 2017).

Microplastics originate from a wide array of sources, including agricultural practices such as the use of plastic mulching films, the application of sewage sludge, composting practices, and atmospheric deposition (Ng et al., 2018). Agricultural soils are particularly vulnerable due to the prevalent use of plasticulture—practices involving plastic materials such as mulch films, irrigation pipes, and greenhouse covers—and the widespread application of biosolids contaminated with synthetic fibers (Weithmann et al., 2018). These microplastics undergo slow degradation once they enter the soil, leaching toxic additives such as phthalates and bisphenol A (BPA) while adsorbing persistent organic pollutants (POPs), which further complicates the environmental and ecological risks associated with their presence (Hüffer et al., 2019).

Microplastics not only persist in the soil but also interact with soil components and organisms, exacerbating soil degradation, hindering plant growth, and introducing potentially harmful pollutants into the food chain. The spread of these contaminants poses a significant threat to soil health, crop productivity, and human health, raising concerns about the long-term sustainability of agricultural practices and food security in the face of growing plastic pollution.

2. SOURCES OF MICROPLASTIC CONTAMINATION IN AGRICULTURAL SYSTEMS

The infiltration of microplastics (MPs) into agricultural ecosystems has emerged as a pressing environmental concern due to their persistence, bioaccumulation potential, and adverse impacts on soil health and crop productivity. Microplastics are defined as synthetic polymer particles smaller than 5 mm in diameter and can originate from both primary sources (designed at micro-size) and secondary sources (resulting from the breakdown of larger plastic debris). In agricultural systems, microplastics infiltrate soils via a multitude of anthropogenic and environmental pathways, which can be broadly categorized as direct and indirect sources.

2.1 Plastic Mulching Films

One of the most prominent direct sources of microplastics in agricultural soils is the widespread use of plastic mulch films, predominantly composed of polyethylene (PE) and polypropylene (PP). These films are integral to modern cultivation systems, especially in horticultural crops, protected cultivation, and intensive monocultures, where they serve multiple agronomic functions: increasing soil temperature, reducing evaporative water loss, suppressing weed emergence, and enhancing nutrient retention (Steinmetz et al., 2016).

However, despite these benefits, mulch films pose a latent environmental risk. Due to continuous exposure to ultraviolet (UV) radiation, mechanical stress from tillage, and microbial colonization, these films undergo progressive fragmentation. The degradation pathways result in the formation of micro- and nanoplastics that become embedded within the soil matrix, where they persist for extended periods. Even after mechanical removal of the mulch at the end of a cropping season, residual plastic fragments are commonly left behind, contributing to long-term soil contamination.

2.2 Controlled-release Fertilizers and Pesticide Coatings

Another direct, but often overlooked, contributor to microplastic pollution in agricultural fields is the use of polymer-coated agrochemical

formulations. Many modern fertilizers and pesticides utilize synthetic polymeric shells, such as polyurethane, polyacrylonitrile, or polylactic acid-based coatings, to facilitate controlled or slow release of active ingredients (Corradini et al., 2019).

While this delivery strategy optimizes the timing and efficacy of nutrient and pesticide application, the degradation of these polymer coatings in soil leads to the steady accumulation of microplastic residues. Depending on soil conditions — including moisture, pH, microbial activity, and temperature — the rate and extent of microplastic release can vary significantly, raising concerns about both localized and diffuse contamination.

2.3 Sewage Sludge Application

The land application of treated sewage sludge, or biosolids, is a common agricultural practice worldwide, valued for its high content of organic matter, nitrogen, phosphorus, and trace elements essential for plant growth. However, this practice also serves as a significant vector for microplastic contamination.

Wastewater treatment plants are generally not designed to filter out microplastics efficiently, leading to their enrichment in the solid fraction during the treatment process (Nizzetto et al., 2016). As a result, biosolids applied to croplands often contain substantial concentrations of microplastic particles, which, once incorporated into the soil, become difficult to remove or degrade. The continuous application of such biosolids leads to the cumulative buildup of microplastics in agricultural soils over time, altering soil structure, permeability, and potentially impacting soil microbial communities (Corradini et al., 2019).

2.4 Irrigation with Contaminated Water

Water used for irrigation, particularly from surface water bodies, reclaimed wastewater, or treated effluents, can serve as a significant source of microplastic input into agricultural soils. The degree of contamination depends on the source of water and the efficiency of the water treatment facilities involved. For instance, reclaimed municipal wastewater and effluents from industrial sources are often laden with microplastics, including synthetic fibers, fragments, and beads (Lv et al., 2019).

Over the course of multiple irrigation cycles, microplastics accumulate in the topsoil layer, where they can be incorporated into soil aggregates or transported vertically via soil water movement. This route of contamination is especially concerning in regions that rely heavily on wastewater reuse for irrigation, a common practice in water-scarce agricultural regions (Tang, 2020).

2.5 Atmospheric Deposition

Microplastics are not confined to aquatic environments or soil amendment inputs; they also enter agricultural ecosystems through atmospheric deposition. Airborne microplastic particles, including synthetic fibers and fragmented debris, are disseminated by wind transport and atmospheric turbulence from urban centers, roads, and industrial zones to adjacent agricultural landscapes (Brahney et al., 2020).

These particles can settle onto soil surfaces either via dry deposition (gravity and wind settling) or wet deposition (precipitation events). Once deposited, microplastics can be incorporated into the soil during tillage operations or washed into the soil profile via rainwater infiltration, adding another diffuse pathway of soil contamination that is difficult to quantify or control.

2.6 Secondary Sources of Microplastic Pollution

In addition to the direct pathways described above, microplastics can also infiltrate agricultural soils through a range of secondary sources, typically resulting from the fragmentation of macroplastic debris already present in the environment. Key examples include:

- a) **Weathering and mechanical breakdown of macroplastics:** Larger plastic items, such as packaging waste, silage wrap, greenhouse covers, irrigation pipes, and discarded containers, can degrade under environmental stressors like UV radiation, temperature fluctuations, and physical abrasion, progressively releasing microplastic particles into the surrounding soil.
- b) **Runoff from urban and industrial areas:** Agricultural fields located downstream of urban catchments or near landfills are at risk of receiving microplastics via surface

runoff. Rainwater can transport microplastic-laden sediments and litter from impervious surfaces into adjacent agricultural landscapes, especially during heavy precipitation events.

- c) **Tire wear particles and road dust:** Fields adjacent to highways and rural roads are particularly susceptible to contamination from tire-derived microplastics — one of the largest unregulated sources of microplastic pollution worldwide. Wind, water runoff, and soil erosion can mobilize these particles and deposit them onto agricultural soils.

Once deposited, these microplastics undergo gradual degradation but rarely complete mineralization, leading to long-term persistence in soil ecosystems (Rillig et al., 2017).

3. IMPACT OF MICROPLASTICS ON SOIL PHYSICO-CHEMICAL PROPERTIES

The incorporation of microplastics into soil ecosystems has emerged as a significant driver of alterations in soil physical structure, chemical composition, and biological activity. These changes can have cascading effects on soil fertility, plant growth, and the overall resilience of agroecosystems. Due to their diverse shapes, sizes, polymer types, and surface properties, microplastics interact with soil constituents in complex and often unpredictable ways, challenging traditional assumptions about soil stability and nutrient dynamics.

3.1 Effects on Soil Structure and Aggregation

Soil structure, particularly the formation and stability of soil aggregates, is a critical determinant of soil health, influencing water infiltration, aeration, root penetration, and microbial habitat quality. The introduction of microplastics—especially fibrous, fragmentary, and film-like particles—can significantly disrupt these natural aggregation processes.

Studies have demonstrated that microplastics physically interfere with soil particle cohesion, leading to both the destabilization of macroaggregates and the formation of atypical soil microstructures (de Souza Machado et al., 2018). These disruptions alter the distribution of soil pore sizes and reduce the mechanical strength of soil aggregates, increasing susceptibility to erosion, compaction, and surface

crusting. Moreover, microplastics can change soil bulk density — either increasing it by clogging pore spaces or decreasing it when fibrous particles create artificial voids — depending on the microplastic type, concentration, and the existing soil texture (Lozano et al., 2021).

3.2 Influence on Water Infiltration and Retention

Water dynamics in soil systems are heavily dependent on pore structure, surface tension, and capillary forces. Microplastic contamination can significantly alter these parameters by modifying the physical architecture of soil. For example, microplastics may block micropores and macropores, thus impeding water infiltration rates and increasing surface runoff potential.

Conversely, some forms of microplastics, such as synthetic fibers, can artificially enhance short-term water retention by physically absorbing and retaining water within their polymer matrix. However, this effect is often localized and inconsistent, sometimes leading to heterogeneous soil moisture distribution that can exacerbate plant water stress during dry periods (Wang et al., 2021). Changes in infiltration and retention also have downstream consequences for soil aeration, root respiration, and microbial activity, thus influencing overall soil-plant-water relations.

3.3 Disruption of Nutrient Cycling and Chemical Availability

Beyond their physical impact, microplastics can also exert profound effects on soil chemical processes, particularly nutrient cycling. Their presence has been associated with shifts in the abundance and diversity of soil microbial communities, which play a fundamental role in nutrient transformations such as nitrogen mineralization, phosphate solubilization, and organic matter decomposition (Lehmann et al., 2021).

Microplastics can serve as novel surfaces for microbial colonization, creating "plastisphere" microbial communities that differ markedly from those associated with soil mineral particles. These shifts can reduce the efficiency of key nutrient pathways, leading to imbalances in nutrient availability for crops. Furthermore, microplastics may act as adsorption surfaces for heavy metals, organic pollutants, and agricultural chemicals, altering their bioavailability and

mobility within the soil profile. Such interactions can disrupt plant nutrient uptake and pose indirect toxicological risks to both soil organisms and crops.

4. EFFECTS OF MICROPLASTICS ON BENEFICIAL SOIL MICROORGANISMS

Soil microbial communities are fundamental to the maintenance of soil health and agricultural productivity. These microorganisms facilitate organic matter decomposition, nutrient mineralization, nitrogen fixation, phosphate solubilization, soil structure formation, and plant-pathogen suppression. However, the introduction of microplastics into soil ecosystems presents a significant ecological disturbance that can impair the diversity, abundance, and functionality of these microbial consortia. Microplastics affect soil microorganisms both directly, through physical interactions and chemical leaching, and indirectly, by altering soil physicochemical properties such as aggregation, aeration, and moisture availability.

4.1 Community Composition Shifts

The introduction of microplastics into soil systems has been shown to cause substantial shifts in microbial community composition, often favoring organisms capable of colonizing plastic surfaces while suppressing functionally critical microbial groups. Microplastics act as novel ecological niches, creating the so-called "plastisphere" — a distinct microhabitat on plastic surfaces that selects for specific microbial taxa, including plastic-degrading bacteria and opportunistic species (McKay et al., 2022).

However, this selective colonization frequently comes at the expense of beneficial soil organisms such as arbuscular mycorrhizal fungi (AMF), nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azospirillum*), and phosphate-solubilizing bacteria, whose population densities tend to decline in microplastic-contaminated soils (Fei et al., 2020). The result is often a reduction in microbial biodiversity and the loss of functional redundancy, which in turn weakens the soil's resilience against environmental stressors.

4.2 Reduction in Soil Enzyme Activity

Soil enzymes, produced by microorganisms and plant roots, are critical mediators of biogeochemical processes such as nutrient cycling and organic matter decomposition.

Microplastic contamination has been observed to significantly reduce the activities of key soil enzymes including:

- a) Dehydrogenase — an indicator of overall microbial oxidative activity,
- b) Urease — crucial for nitrogen cycling via urea hydrolysis,
- c) Phosphatase — responsible for releasing bioavailable phosphorus from organic compounds (Huang et al., 2019).

The suppression of these enzymes is indicative of both microbial stress and metabolic dysfunction, suggesting that microplastics impair not only the size but also the metabolic vitality of soil microbial communities. The precise mechanisms may involve physical inhibition of microbial colonization sites, leaching of toxic additives (such as phthalates and bisphenols) from plastics, and the indirect effects of altered soil moisture and aeration.

4.3 Disruption of Plant-microbe Symbioses

One of the most ecologically significant consequences of microplastic contamination is the disruption of mutualistic plant-microbe interactions, which are essential for nutrient acquisition, plant growth promotion, and abiotic stress mitigation.

Studies indicate that arbuscular mycorrhizal fungi (AMF), which form symbiotic associations with the roots of over 80% of terrestrial plant species, exhibit reduced colonization rates and impaired hyphal growth in the presence of microplastics. Similarly, rhizobia-legume symbioses, which are central to biological nitrogen fixation, are highly sensitive to microplastic-induced soil alterations (Lehmann et al., 2021). The weakening or loss of these beneficial interactions can severely limit plant nutrient uptake, reduce resilience to drought and pathogen attacks, and ultimately diminish agricultural yields.

5. MICROPLASTICS AS VECTORS FOR PATHOGENIC MICROORGANISMS

Beyond their direct physical and chemical impact on soil properties and biota, microplastics pose an insidious biological threat through their role as vectors for pathogenic microorganisms. Increasing evidence suggests that microplastics not only offer surfaces for microbial colonization but also facilitate the persistence, transport, and

horizontal gene exchange of plant, animal, and human pathogens in terrestrial environments.

5.1 The Plastisphere: A Novel Ecological Niche

Microplastics in the soil environment provide a durable, hydrophobic substrate that fosters the establishment of complex and often pathogenic microbial assemblages, collectively termed the “plastisphere” (Zettler et al., 2013). These biofilm-rich microhabitats are distinct from the surrounding soil microbial communities in both taxonomic composition and functional potential. The plastisphere not only enhances microbial survivability by offering protection from environmental stresses such as desiccation, UV radiation, and predation but also promotes interactions among different microbial taxa, including potential pathogens.

Recent studies have shown that both opportunistic and obligate pathogens — including genera such as *Pseudomonas*, *Vibrio*, *Salmonella*, and certain phytopathogenic fungi and bacteria — can persist longer and at higher densities on microplastic surfaces than in surrounding soil matrices (Frontiers in Environmental Science, 2022). This reservoir function raises serious concerns about the role of microplastics in enhancing pathogen persistence and facilitating outbreaks in agroecosystems (Gupta et al., 2024).

5.2 Pathogen Mobility and Amplification

Microplastics also facilitate the spatial dispersal of pathogens within and beyond soil systems. Their low density and resistance to degradation allow them to be easily mobilized by surface water runoff, irrigation flows, wind erosion, and even soil fauna activity. As microplastics move through soil profiles, they can physically transport attached pathogens to previously uninfected sites, amplifying the scale and severity of contamination (Rochman et al., 2014).

Furthermore, the hydrophobic nature of plastic surfaces encourages the adsorption of co-contaminants such as heavy metals, pesticides, and persistent organic pollutants. The resulting chemical-biological complexes not only increase the stability of pathogenic cells in the environment but may also enhance their virulence and stress tolerance, creating a multidimensional threat to crop health, food safety, and human well-being.

5.3 Hotspots for Antibiotic Resistance Gene Transfer

A particularly alarming consequence of the plastisphere's formation is its facilitation of horizontal gene transfer (HGT), especially the dissemination of antibiotic resistance genes (ARGs). Recent studies have documented that the microbial communities associated with microplastic surfaces exhibit elevated rates of gene exchange compared to those found in bulk soil, primarily due to the high cell density and biofilm-forming conditions on plastics (Wang et al., 2023).

This phenomenon has serious implications for both environmental and public health, as soil serves as a critical reservoir for ARGs that can be transferred to pathogens infecting humans, livestock, and crops. The coupling of microplastics with antibiotic residues — commonly found in wastewater-irrigated soils or sewage-sludge-amended fields — creates a feedback loop that accelerates the spread of antimicrobial resistance, further complicating disease management in agricultural and natural systems.

6. IMPLICATIONS FOR CROP PRODUCTION AND FOOD SECURITY

The infiltration of microplastics into agricultural soils introduces a significant and emerging abiotic stressor that holds profound implications for both the productivity of cropping systems and the safety of agricultural produce. Microplastics exert multifaceted effects on soil-plant interactions, affecting soil physical integrity, microbial ecology, nutrient dynamics, and plant physiological responses. These disruptions can cumulatively compromise crop performance, reduce arable land productivity, and raise new concerns for global food security.

6.1 Microplastics as an Emerging Abiotic Stressor in Agriculture

Microplastics, when embedded in the soil matrix, fundamentally alter the physical structure and functional dynamics of agricultural soils. Their presence has been shown to reduce soil aggregate stability, diminish soil porosity, and impair water infiltration and gas exchange, thereby limiting the availability of oxygen and moisture at the root-soil interface (de Souza Machado et al., 2018). These physical alterations directly restrict root system development, impede

nutrient acquisition, and contribute to drought-like conditions even in otherwise well-irrigated soils.

Moreover, the surface properties of microplastics allow them to adsorb and concentrate a variety of environmental contaminants, including heavy metals, pesticide residues, and persistent organic pollutants. These adsorbed compounds can desorb under changing soil conditions, creating chemically enriched microsites in the rhizosphere that elevate the risk of phytotoxicity and potentially harm soil biota (Hodson et al., 2017).

6.2 Disruption of Soil Microbial Functions and Nutrient Cycling

The presence of microplastics has been shown to disrupt the balance and functioning of soil microbial communities, which are vital to nutrient turnover, soil organic matter decomposition, and plant health (Rillig et al., 2019). The suppression of soil microbial enzyme activity, particularly enzymes such as dehydrogenase, urease, and phosphatase, leads to delayed nutrient mineralization and reduced nutrient availability for plants (Huang et al., 2019). Over the long term, this impairment of biogeochemical cycling can degrade soil fertility and diminish the productive capacity of agricultural systems.

6.3 Plant Physiological Responses to Microplastic Exposure

Microplastics also directly affect plant growth and development, with numerous studies reporting a range of morphological, physiological, and biochemical stress responses. These include:

- a) **Inhibition of Seed Germination and Root Growth:** Microplastic particles can physically obstruct pore spaces within the soil, limiting water availability and oxygen diffusion to germinating seeds and emerging roots. As a consequence, both seedling establishment and subsequent root elongation are adversely affected, with cascading impacts on nutrient uptake and plant vigor (Boots et al., 2019; Lozano et al., 2021).
- b) **Reduction in Photosynthetic Efficiency and Biomass Accumulation:** Plants grown in microplastic-contaminated soils often exhibit stunted growth, reduced leaf area, and diminished chlorophyll content, which collectively impair photosynthetic capacity and lower biomass production

(Bosker et al., 2019). The severity of these effects is often correlated with microplastic concentration, particle size, and polymer type.

- c) **Translocation of Microplastics and Associated Chemicals:** Microplastics and their chemical additives, including endocrine-disrupting compounds such as phthalates and bisphenol A, have been shown to be absorbed by plant roots and translocated to aerial tissues, including leaves and edible parts (Li et al., 2020; Wang et al., 2023). This phenomenon poses a direct threat to food safety and human health, introducing new pathways for the dietary exposure of plastic-associated pollutants.

6.4 Yield Reductions and Food Security Implications

The cumulative effect of these physical, chemical, and biological disruptions can result in significant declines in crop yields. Experimental studies have consistently demonstrated reductions in plant biomass and reproductive output in microplastic-contaminated soils, particularly for species with delicate or fine root systems (Bosker et al., 2019). Such productivity losses, if mirrored in field conditions, could undermine efforts toward sustainable intensification and threaten food security, especially in regions already grappling with soil degradation and climate variability.

Furthermore, the contamination of food crops with microplastic particles or their chemical additives raises critical food safety concerns for both local and global food supply chains, necessitating robust monitoring and regulatory interventions.

7. DETECTION METHODS FOR MICROPLASTICS IN SOIL

The identification and quantification of microplastics in agricultural soils present substantial analytical challenges, primarily due to the wide diversity in polymer types, particle sizes (from millimeters to sub-micrometer scale), morphologies (fibers, fragments, films, spheres), and the complex nature of soil matrices, which often contain a mixture of organic matter, minerals, and biogenic particles. As such, multiple complementary detection techniques are employed to achieve reliable and reproducible results.

7.1 Fourier-Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy is one of the most commonly employed techniques for microplastic identification due to its capacity to detect polymer-specific molecular vibrations. When infrared light interacts with a microplastic particle, characteristic absorbance bands are produced that correspond to the chemical bonds within the polymer, allowing qualitative identification of the plastic type (Pérez-Reverón et al., 2022).

FTIR can be applied in transmission, reflection or attenuated total reflectance (ATR) modes, depending on particle size and sample preparation. While the method is highly reliable for particles larger than ~20 µm, its sensitivity decreases for smaller particles due to diffraction limitations.

7.2 Raman Spectroscopy

Raman spectroscopy is a complementary vibrational spectroscopy technique that excels in the analysis of microplastics, particularly at the lower end of the particle size spectrum (down to 1 µm or even sub-micron scale). Unlike FTIR, Raman spectroscopy is less affected by water content and offers high spatial resolution, making it well-suited for the detection of microplastics embedded in soil particles or biofilms (Löder et al., 2015).

Moreover, Raman spectroscopy allows for the differentiation of chemically similar polymers, including distinguishing between polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), which is critical for detailed environmental assessments.

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

Py-GC-MS represents a powerful destructive analytical method that enables both the identification and quantification of microplastics at a molecular level. During pyrolysis, the sample is thermally decomposed into its monomeric or fragmentary components, which are then separated via gas chromatography and identified through mass spectrometry (Pérez-Reverón et al., 2022).

This technique offers high sensitivity and polymer-specific identification, even for extremely small or degraded particles that might elude

optical or spectroscopic detection. However, it is incapable of providing morphological information and requires labor-intensive sample preparation to remove non-plastic organic matter.

7.4 Nile Red Fluorescence Microscopy

Nile Red staining has emerged as a rapid, cost-effective screening tool for the visualization of microplastics, especially in complex organic matrices such as soil and compost. Nile Red is a lipophilic fluorescent dye that preferentially binds to hydrophobic plastic surfaces, enabling their detection under fluorescence microscopy (Erni-Cassola et al., 2017).

While this technique allows for fast, semi-quantitative assessment and particle visualization, it lacks the ability to determine polymer type, and false positives are possible due to staining of other hydrophobic materials, such as waxes or organic residues. As such, it is typically used as a pre-screening method, followed by spectroscopic confirmation.

7.5 Nuclear Magnetic Resonance (NMR) Spectroscopy

Nuclear Magnetic Resonance (NMR) spectroscopy offers a non-destructive and highly precise approach for elucidating the chemical composition of polymeric materials and their associated additives in environmental samples. Although less commonly applied in microplastic soil research compared to spectroscopic or thermal decomposition methods, NMR is particularly useful for detailed molecular characterization and the identification of specific chemical signatures of plasticizers, flame retardants, and stabilizers embedded in or adsorbed onto microplastic particles (Du et al., 2022).

7.6 Integrated Analytical Approaches

Given the inherent limitations of individual methods—whether in size detection thresholds, chemical resolution, or sample throughput—multi-method workflows are increasingly recommended to ensure reliable microplastic detection in soil environments. Typically, optical microscopy or fluorescence staining is used for initial screening, followed by FTIR or Raman spectroscopy for chemical identification, and Py-GC-MS for quantitative confirmation.

Developing standardized, reproducible protocols remains a critical need in the field, as cross-study comparability is often hindered by variations in sample pre-treatment, extraction efficiency, and detection limits.

8. IMPLICATIONS FOR HUMAN HEALTH

The accumulation of microplastics in agricultural soils represents not only an emerging threat to ecosystem stability and crop productivity but also a growing public health concern. Microplastics in agroecosystems can enter the human body through various pathways, including the consumption of contaminated food crops, exposure to polluted water, and inhalation of airborne plastic particles. Once internalized, microplastics can exert a combination of physical, chemical, and biological effects that are increasingly associated with adverse human health outcomes.

8.1 Dietary Intake Via Contaminated Crops

One of the most significant pathways for microplastic exposure in humans is through the ingestion of contaminated agricultural produce. Studies have demonstrated that microplastic particles present in the soil can be absorbed by plant root systems and translocated to above-ground tissues, including leaves, stems, fruits, and grains (Li et al., 2020). Root vegetables and leafy greens are particularly vulnerable due to their direct soil contact and extensive surface area. As microplastic contamination of soil intensifies, the likelihood of human exposure through the diet is expected to rise, especially in regions where reclaimed wastewater or biosolid-amended soils are used for crop production (Wang et al., 2023).

8.2 Chemical Leachates and Endocrine Disruption

Beyond the physical hazard posed by microplastic particles themselves, these materials act as carriers for a complex cocktail of chemical additives, including phthalates, bisphenol A (BPA), polybrominated flame retardants, and heavy metals. These compounds are known endocrine-disrupting chemicals (EDCs) capable of mimicking or blocking hormonal signaling pathways at extremely low concentrations (Galloway, 2015).

Once leached into soil and water or absorbed by plant tissues, these chemicals can bioaccumulate along the food chain, increasing the risk of chronic health effects such as developmental abnormalities, reproductive disorders, metabolic syndromes, and even certain cancers (Prata et al., 2020). Long-term, low-level exposure to such contaminants is especially concerning for sensitive populations, including pregnant women and young children.

8.3 Microplastics as Vectors for Pathogenic Microorganisms

Microplastics serve as ideal substrates for microbial colonization, forming microhabitats known as the "plastisphere" (Zettler et al., 2013). Within these plastispheres, pathogenic bacteria — including antibiotic-resistant strains — can not only survive but proliferate. When crops grown in microplastic-contaminated soils are consumed raw or inadequately washed, these pathogens can be directly transferred to humans, potentially leading to foodborne illnesses and amplifying the risk of antimicrobial resistance (Frontiers in Environmental Science, 2022; Wang et al., 2023).

Moreover, the persistence of microplastics in soil and water allows for the long-distance transport and dissemination of pathogens beyond the initial contamination site, raising broader concerns for both local and global food safety.

8.4 Systemic Health Effects of Chronic Microplastic Exposure

Emerging research has identified several mechanisms through which microplastics may harm human health after ingestion, inhalation, or dermal absorption. These include:

- a) Physical tissue irritation and inflammation caused by particle deposition.
- b) Oxidative stress and immune system dysregulation due to the interaction of microplastic surfaces with biological tissues.
- c) Bioaccumulation of adsorbed pollutants (such as heavy metals and persistent organic pollutants), which may amplify toxicity beyond the plastic particles themselves.
- d) Potential genotoxic and carcinogenic effects arising from both chemical leachates and persistent physical irritation (Prata et al., 2020).

Although the full extent of microplastics' health impact on humans remains an active area of investigation, preliminary evidence indicates that chronic exposure — especially through contaminated food and water — is likely to have far-reaching consequences for public health.

9. MITIGATION STRATEGIES FOR MICROPLASTIC CONTAMINATION IN AGRICULTURAL SYSTEMS

The mitigation of microplastic contamination in agricultural systems requires a coordinated and holistic approach, incorporating technological innovations, sound policy frameworks, and farmer education. Given the complexity of microplastic sources and their pervasive environmental impacts, addressing this issue requires action at multiple levels, from individual farming practices to national and global regulatory measures.

9.1 Adoption of Biodegradable Alternatives

One of the most promising strategies to reduce microplastic pollution is the transition from conventional petroleum-based plastics to biodegradable alternatives. For example, the use of biodegradable polymers for plastic mulching films, fertilizer coatings, and agricultural packaging has the potential to mitigate long-term microplastic accumulation in soils. These biodegradable materials, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), can break down more readily under natural environmental conditions, thereby minimizing persistence in soil ecosystems (Bandopadhyay et al., 2018). Moreover, they often have reduced toxicity profiles, making them safer for both soil organisms and human health. However, the development and widespread adoption of these materials require further research to ensure they do not create unintended environmental consequences, such as incomplete degradation or the introduction of new pollutants.

9.2 Sustainable Waste Management Practices

A key element in mitigating microplastic contamination is the enhancement of waste management practices at the farm level and throughout the agricultural supply chain. Improved recycling programs, coupled with the reduction of single-use plastics in agricultural operations, can significantly reduce the amount

of plastic waste entering the environment. On-farm waste audits can identify plastic-related practices that contribute to contamination, such as improper disposal of plastic mulch or pesticide containers (Bouwmeester et al., 2015). Furthermore, reducing the use of plastic packaging and switching to alternative materials — such as paper or glass — can prevent the introduction of microplastics into soils and water bodies. Establishing comprehensive farm-level waste management protocols and incentivizing sustainable practices through financial or regulatory mechanisms will help mitigate plastic waste at its source.

9.3 Policy Intervention and Regulatory Frameworks

Policy interventions at both national and international levels are crucial in curbing the widespread use and mismanagement of plastics in agriculture. Governments should implement regulations that mandate the reporting of plastic usage in agricultural operations and establish clear guidelines for the reduction of plastic waste. This may include the phasing out of non-essential single-use plastics, the introduction of bans or limitations on certain plastic products, and the regulation of microplastic emissions from wastewater treatment facilities (de Souza Machado et al., 2018). Furthermore, national and regional bodies should establish routine monitoring and reporting requirements to assess microplastic concentrations in agricultural soils, water systems, and food products. By enforcing stricter regulations and providing incentives for research into alternative materials, policymakers can create an environment conducive to sustainable agricultural practices.

9.4 Farmer Education and Outreach

To successfully mitigate microplastic pollution in agriculture, it is essential to foster a culture of awareness and responsibility among farmers. Agricultural extension services play a critical role in educating farmers about the risks posed by microplastics, including their impact on soil health, crop productivity, and food safety. Extension programs should focus on promoting sustainable farming practices that reduce plastic use, such as adopting biodegradable alternatives, recycling plastics, and managing plastic waste responsibly (Bläsing & Amelung, 2018). Providing farmers with access to training on alternative farming technologies, such as precision agriculture and organic farming, can

further reduce reliance on plastic-based inputs. Additionally, supporting farmer cooperatives and networks focused on plastic-free farming initiatives could accelerate the transition towards more sustainable agricultural practices.

9.5 Integrated Approach for Long-Term Sustainability

Ultimately, a sustainable and integrated approach to mitigating microplastic contamination must involve collaboration across multiple sectors — from research institutions and industry stakeholders to farmers, policymakers, and environmental organizations. Multidisciplinary research efforts focused on understanding the long-term effects of microplastics on soil ecosystems and developing scalable alternatives will be essential in advancing this agenda. Moreover, a proactive approach to managing plastic pollution will require international cooperation, as microplastics do not respect national boundaries. Shared monitoring frameworks, international agreements on plastic reduction, and global standards for plastic waste management are needed to address the global nature of this issue.

10. CONCLUSION

The presence of microplastics in agricultural soils poses a significant threat to soil health, microbial ecology, crop productivity, and food safety. These tiny plastic particles can alter soil structure, affect microbial communities, and potentially impact human health through food contamination. As microplastics persist in soils, they can disrupt nutrient cycling, reduce soil fertility, and influence crop growth. Moreover, the transfer of microplastics through the food chain raises concerns about human consumption and potential health risks. To mitigate these risks, it's essential to address microplastic pollution in agricultural soils through sustainable practices. Strategies include reducing plastic use, promoting organic farming, and implementing effective waste management systems. Further research is needed to understand microplastic behavior, fate, and effects in agricultural ecosystems. Policymakers, farmers, and consumers must collaborate to develop and implement effective solutions. By prioritizing soil health and adopting eco-friendly practices, we can minimize microplastic contamination and ensure sustainable agriculture. Protecting soil health is crucial for maintaining ecosystem services, promoting food security, and

safeguarding human health. Addressing microplastic pollution in agricultural soils requires a collective effort to preserve soil integrity and ensure a healthier environment for future generations. By working together, we can mitigate the impacts of microplastic pollution and foster a more sustainable agricultural system.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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