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Review

Microplastics in Soil–Plant Systems: Current Knowledge, Research Gaps, and Future Directions for Agricultural Sustainability

Zhangling Chen [1,2,*], Laura J. Carter [2], Steven A. Banwart [1,†] and Paul Kay [2]

[1] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[2] School of Geography, University of Leeds, Leeds LS2 9JT, UK; l.j.carter@leeds.ac.uk (L.J.C.); p.kay@leeds.ac.uk (P.K.)
* Correspondence: chenzhangling1101@gmail.com
† Deceased.

Abstract

With the increasing accumulation of plastic residues in agricultural ecosystems, microplastics (MPs) have emerged as a novel and pervasive environmental risk factor threatening sustainable agriculture. Compared to aquatic systems, our understanding of MP dynamics in agricultural soils—particularly their transport mechanisms, bioavailability, plant uptake pathways, and ecological impacts—remains limited. These knowledge gaps impede accurate risk assessment and hinder the development of effective mitigation strategies. This review critically synthesises current knowledge in the study of MPs within soil–plant systems. It examines how MPs influence soil physicochemical properties, plant physiological processes, toxicological responses, and rhizosphere interactions. It further explores the transport dynamics of MPs in soil–plant systems and recent advances in analytical techniques for their detection and quantification. The role of plant functional traits in mediating species-specific responses to MP exposure is also discussed. In addition, the review evaluates the ecological relevance of laboratory-based findings under realistic agricultural conditions, highlighting the methodological limitations imposed by pollution heterogeneity, complex exposure scenarios, and detection technologies. It also examines existing policy responses at both regional and global levels aimed at addressing MP pollution in agriculture. To address these challenges, we propose future research directions that include the integration of multi-method detection protocols, long-term and multi-site field experiments, the development of advanced risk modelling frameworks, and the establishment of threshold values for MP residues in edible crops. Additionally, we highlight the need for future policies to regulate the full life cycle of agricultural plastics, monitor soil MP residues, and integrate MP risks into food safety assessments. This review provides both theoretical insights and practical strategies for understanding and mitigating MP pollution in agroecosystems, supporting the transition toward more sustainable, resilient, and environmentally sound agricultural practices.

Keywords: microplastics; soil–plant interactions; transport mechanisms; ecotoxicology; detection methods; agricultural sustainability

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1. Introduction

Microplastics (MPs), typically defined as plastic particles smaller than 5 mm in diameter, originate from the breakdown of larger plastic debris (secondary MPs) or are manufactured at microscopic scales (primary MPs) [1,2]. These particles are now recognised as a class of emerging contaminants that are ubiquitously distributed across various ecosystems. Due to their small size, large surface area, and persistent nature, MPs can interfere with biological functions, disrupt ecological processes, and potentially pose risks to human and environmental health [3,4].

In recent years, significant progress has been made in understanding the sources, distribution, and ecological toxicity of MPs in aquatic environments. This has led to the rapid advancement of detection technologies and the establishment of preliminary risk assessment frameworks [5,6]. However, research on MPs in terrestrial ecosystems lags behind, particularly in the soil–plant interface of agricultural systems. This gap is especially concerning given the scale and importance of agricultural land, which accounts for approximately 38% of the global land area and is essential for food security and sustainable development [7]. Agricultural soils are becoming major sinks for MPs due to widespread plastic mulch, sewage sludge application, wastewater irrigation, and atmospheric deposition [8–11]. Quantitative data indicate that plastic residues from mulch films in China average 83.6 kg/ha across 19 provinces [12]. In the United Kingdom, agricultural soils contain approximately 3680 $\pm$ 129.1 items/kg, largely attributed to the extensive use of plastic crop covers [13]. Similarly, in Canada, mean microplastic concentrations in agricultural soils have been reported to reach up to 1.4×10^4 items/kg, closely linked to the application of recycled biosolids [14].

Plants are vital components of agroecosystems and play a central role in soil–plant–MP interactions, particularly within the rhizosphere. This region serves as a key interface where MPs can be retained, absorbed, and transformed [15,16]. While several studies have demonstrated the uptake of nano- and submicron-sized MPs by plants via crack-entry or endocytosis, these experiments are mostly conducted under hydroponic conditions, using a single MP type (polystyrene microsphere, PS-MPs) and unrealistically high exposure levels [17,18]. Such limitations hinder our ability to extrapolate findings to real-world agricultural systems, where MPs occur as complex mixtures and interact with dynamic biotic and abiotic factors. Moreover, MPs may affect agroecosystem health not only through direct plant uptake but also by altering soil physicochemical properties, disturbing microbial communities, and inducing toxicological effects in crops [19,20]. In this context, soil and plants should be examined as an integrated system rather than in isolation [21]. Moreover, plant functional traits, such as root morphology and antioxidant capacity, may serve as key mediators of MP sensitivity and help explain the species-specific variations observed in plant responses to MP exposure [22].

To gain a clearer understanding of the current research landscape and future directions regarding the behaviour and impacts of MPs in soil–plant systems, this review synthesises approximately 170 peer-reviewed articles published primarily between 2020 and 2025. This time frame was selected for two main reasons. First, research on MPs in agroecosystems has expanded significantly during this period, reflecting growing global attention and a rapid accumulation of empirical data. Second, as the objective of this review is to synthesise recent advances rather than provide a historical overview, focusing on the most recent five years offers a more accurate representation of current research priorities, evolving methodologies, and emerging knowledge gaps related to soil–plant–MP interactions. Literature was identified through databases, including Web of Science, Scopus, and Google Scholar, using search terms such as "microplastics," "agricultural soil," "plant uptake," and "soil–plant system." This review focuses on four core areas: (1) the sources, migration, and transformation of MPs in agricultural soils; (2) their ecological effects on soil–plant systems; (3) current detection and quantification techniques in soil and plant matrices; and (4) critical knowledge gaps and future research priorities. Unlike previous reviews that focus on MP pollution in isolated environmental compartments, this work emphasises the soil–plant system as a dynamic and interactive interface. Particular attention is given to the migration and transformation of MPs within soil matrices and the deep biochemical interactions between MPs and plants. By integrating these cross-disciplinary perspectives, the review aims to enhance MP monitoring and contribute to the development of more sustainable and pollution-resilient agricultural management practices.

2. Sources, Migration, and Transformation of Microplastics in Agricultural Soils

2.1. Major Sources, Types, and Sizes of Microplastics in Agricultural Soils

(1) Degradation of agricultural mulch films and greenhouse covers: plastic mulch films and greenhouse covers are widely applied to conserve soil moisture, regulate temperature, and promote crop growth [23]. However, prolonged exposure to ultraviolet (UV) radiation, temperature fluctuations, and mechanical disturbance leads to their gradual breakdown into MP fragments. This degradation process is considered one of the primary sources of MPs in agricultural soils [24].

(2) Application of sewage sludge (biosolids): municipal sewage sludge, which is frequently reused as an organic fertiliser in farmland, contains a high load of MPs, especially microfibers. These microfibers originate mainly from domestic and industrial laundry wastewater [25]. Studies have shown that microfibers account for approximately 89.4–97.2% of the MPs present in sludge [26].

(3) Wastewater irrigation: reclaimed municipal or industrial wastewater is often used for agricultural irrigation. If inadequately treated, such water can contain microbeads, microfibers, and fragments that settle directly into the topsoil, resulting in localised point-source MP contamination [27].

(4) Leachate from landfills: MP fragments from packaging materials and other plastic waste may infiltrate farmland through landfill leachate, surface runoff, or subsurface water migration, contributing to diffuse pollution across rural landscapes [28].

(5) Improper disposal of plastic waste: during agricultural operations, improper disposal of pesticide containers, seed bags, fertiliser packaging, and other plastic debris can result in long-term pollution. These items degrade under environmental exposure into persistent MP contaminants [29].

(6) Atmospheric deposition: due to their low density, MPs (e.g., microfibers and fragments) can become airborne and deposit over long distances. Atmospheric deposition has been recognised as a key non-point source of MPs in farmland [30,31]. Recent studies have also shown that deposited MPs can adhere to leaf surfaces and be internalised through foliar uptake pathways, increasing the potential for plant exposure [11].

Recent studies have characterised the prevalent sizes, forms, and polymer types of MPs found in agricultural soils. Most commonly detected MP particles range in size from 10 to 500 μm, with two dominant morphological types: film-like and fibres/fragment-like structures [32]. Film-type MPs, primarily composed of polyethylene (PE), are widely associated with plastic mulch applications and can account for up to 88.2% of the total MP content in certain fields [33]. In contrast, fibres and fragments, primarily originating from sludge, compost, and atmospheric fallout, are the most frequently observed MP forms in agricultural soils, often exceeding 90% of the total count. These particles are typically composed of polyester (PES), polypropylene (PP), and polyvinyl chloride (PVC) polymers [25]. An overview of the sources, environmental transformation processes, and migration pathways of MPs in agricultural soils is illustrated in Figure 1, which provides a conceptual framework for understanding the subsequent sections.

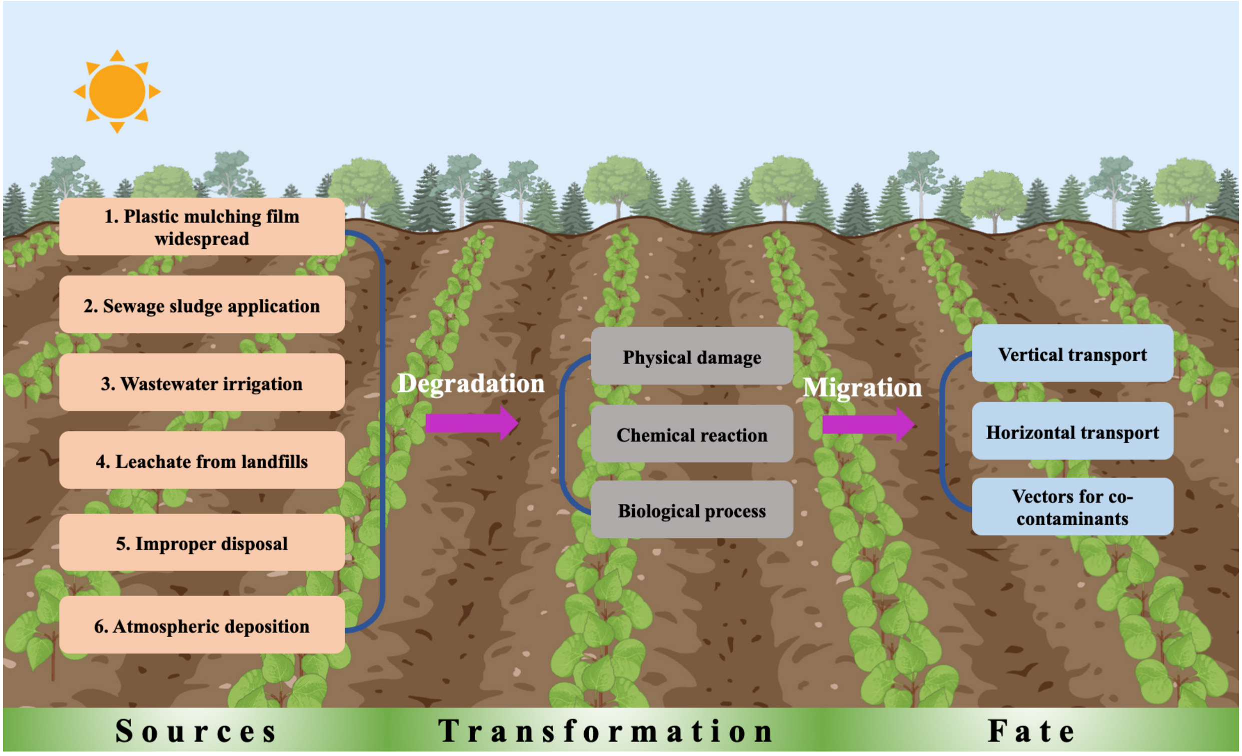

Figure 1. Conceptual diagram summarising the sources, degradation mechanisms, and migration pathways of microplastics in agricultural soils. This figure was created by the authors using BioRender.com (https://www.biorender.com/, accessed on 18 June 2025). The content and structure of this figure were developed with reference to [23–31,34–62].

2.2. Degradation of Microplastics in Agricultural Soils

(1) Physical degradation: agricultural practices (e.g., tillage, ploughing, and trampling) impose mechanical stress on MPs, leading to progressive size reduction and the development of surface defects [34]. Additionally, daily temperature fluctuations can induce cycles of thermal expansion and contraction, while changing wet–dry soil conditions and contributing to structural fatigue and fragmentation of MPs [35,36]. These processes increase the surface area of MPs, thereby enhancing their mobility within soil pores and promoting interactions with soil particles and organic matter [37,38].

(2) Chemical degradation: MPs in soil are exposed to UV radiation, moisture, and oxygen, which collectively initiate photo-oxidation and thermo-oxidation reactions [39]. During photo-oxidation, UV light breaks the C–C and C–H bonds in the polymer backbone, introducing polar functional groups such as carboxyl (–COOH) and hydroxyl (–OH). These chemical changes alter the surface hydrophilicity and reactivity of MPs [40]. In high-temperature environments, thermal degradation further accelerates the scission of polymer chains [41]. Additionally, shifts in soil pH, for example, due to fertilisation, may influence the chemical stability and degradation pathways of MPs [42]. These reactions collectively enhance the sorption capacity of MPs for heavy metals, organic pollutants, and soil enzymes, potentially affecting their environmental behaviour and interactions within the soil matrix [43].

(3) Biological degradation: recent studies suggest that certain microorganisms, including in vitro environmental microorganisms and in vivo gut microorganisms of insects, are capable of initiating MP degradation within hours [44]. When microbial communities accumulate densely on plastic surfaces, they may evolve enzymatic systems and convert polymers into bioavailable carbon sources [45]. While the overall biodegradation efficiency remains relatively low under natural conditions, it holds growing promise, particularly in the context of developing biodegradable agricultural films and environmentally friendly plastic alternatives.

2.3. Migration of Microplastics in Agricultural Soils

Vertical migration of MPs in soil is strongly influenced by particle size, polymer type, and density. For instance, Gao et al. [46] observed that low-density polyethylene (LDPE) particles penetrated deeper into the soil profile compared to denser polyethylene terephthalate (PET) particles. Similarly, Wahl et al. [47] reported that the composition of MP polymers varied with soil depth, with an increasing proportion of PVC and PE, while polystyrene (PS) decreased. However, Weber et al. [48] found that the average particle size of MPs decreased progressively within the 0–90 cm soil layer, suggesting fragmentation or selective transport of smaller particles. Agricultural practices also contribute to the vertical redistribution of MPs in soil [42]. Moreover, elevated soil pH has been shown to alter surface functional groups and aggregation behaviour of MPs, thereby enhancing their mobility through soil pore spaces and promoting deeper transport [49,50]. Biological factors further complicate this process. Soil organisms (e.g., plants, animals, and microorganisms) can influence MP migration through root exudation, bioturbation, and microbe-mediated surface modification [51,52].

Horizontal migration of MPs in soils is primarily influenced by surface hydrodynamic processes, topographical features, and anthropogenic disturbances. Laermanns et al. [53] found that MP horizontal transport was impeded by interactions with microrelief structures but enhanced along preferential flow paths formed by macrorelief on rough soil surfaces. Rainfall-induced surface runoff significantly contributes to the lateral movement of MPs, particularly favouring particles with lower density and smaller sizes (<1 mm), which exhibit higher mobility [54]. However, Han et al. [55] reported that the presence of vegetation can effectively increase MP retention in the soil by approximately 20%. Wind erosion is another critical mechanism driving lateral dispersion, especially in bare or degraded agricultural land. Entrainment by wind and subsequent atmospheric transport can further facilitate the lateral spread of MPs from soil surfaces [56]. In addition, agricultural operations can disturb the soil matrix and redistribute plastic particles horizontally [57,58]

2.4. Microplastics as Vectors for Co-Contaminants in Agricultural Soils

Due to their high surface roughness, large specific surface area, and the presence of various polar and hydrophobic functional groups, MPs have strong adsorption capacities for persistent organic pollutants (POPs), heavy metals, pesticides, and pharmaceutical residues [59,60]. Furthermore, MPs can serve as particulate substrates for microbial colonization, and their sorption behaviour is influenced by environmental factors, such as pH, ionic strength, and ageing processes [61].

Additionally, MPs often contain plastic additives (e.g., plasticisers, antioxidants, and flame retardants), which may gradually leach into surrounding soil and water through weathering or degradation [62]. These features collectively position MPs as complex contaminant carriers in agroecosystems, capable of influencing the environmental distribution and mobility of associated pollutants.

3. Effects of Microplastics on Soil–Plant Systems: Consequences for Soil Function, Plant Development, and Food Safety

3.1. Effects of Microplastics on Soil Properties

3.1.1. Soil Physical Properties

Due to their lower density compared to natural soil particles, MPs can alter soil bulk density, thereby affecting soil structure [63,64]. These effects are highly dependent on soil texture. For instance, Ingraffia et al. [65] reported that PES microfibers reduced the bulk density of Vertisol by 9%, while no significant changes were observed in Entisol and Alfisol soils. MPs also affect soil water-holding capacity (WHC), with outcomes varying based on particle size, concentration, and soil texture. For example, low concentrations (0.5% *w*/*w*) of PE-MPs had no significant effect on soil WHC. In contrast, at higher concentrations (2% *w*/*w*), PE-MPs significantly influenced WHC: smaller particles (150 µm) increased WHC in loamy soil, while larger particles (950 µm) reduced WHC in sandy soil [66]. These findings highlight the complex interactions between MP characteristics and soil properties.

MPs additionally affect soil water-stable aggregates (WSAs), with outcomes dependent on their polymer type and shape. For instance, PES microfibers have been shown to increase the proportion of soil macroaggregates [67]. In contrast, PET microfragments and PS microspheres tend to decrease macroaggregate formation while promoting microaggregates [21].

3.1.2. Soil Chemical Properties

The effects of MPs on soil pH vary depending on polymer type and concentration. For instance, PET foams and PS fragments (0.4% *w*/*w*) have been reported to increase soil pH, whereas high-density polyethylene (HDPE) at a lower concentration (0.1% *w*/*w*) can decrease it [68,69]. MPs also affect soil carbon dynamics. Wang et al. [70] synthesised existing research and found that MPs, regardless of type, size, dose, or soil characteristics, consistently increase dissolved organic carbon (DOC), total organic carbon (TOC), methane (CH_4), and carbon dioxide (CO_2) emissions. These changes may result from MPs serving as sources of organic carbon and interacting with soil biota and plants, potentially influencing global carbon cycling [71].

Furthermore, MPs can alter nutrient availability and biogeochemical processes. For example, Jiang et al. [72] found that MPs influence phosphorus dynamics in rice fields with high phosphorus levels. Wang et al. [73] reviewed studies showing that MPs can stimulate soil enzyme activities, thereby impacting carbon turnover. Similarly, Shen et al. [74] reported that MPs affect nitrogen cycling by modifying processes like nitrification and denitrification.

3.2. Effects of Microplastics on Soil Microbial Communities

The impact of MPs on soil microbial communities has been widely studied. For instance, exposure to LDPE microfragments (200 particles/g, 2 mm × 2 mm × 0.1 mm) altered the temporal dynamics of soil microbial communities [75]. Similarly, 2% *w*/*w* of 200 µm MPs has been shown to affect microbial richness, evenness, and diversity in rhizosphere soils [76]. Biodegradable plastics like polyhydroxyalkanoates (PHAs) can further enhance microbial activity, promoting microbial biomass and growth due to their degradability and unique composition [77].

Emerging evidence indicates that MPs not only alter microbial community composition but also facilitate the spread of antibiotic resistance genes (ARGs) by disrupting microbial diversity and structure [78]. MPs promote biofilm formation by providing surfaces for colonisation, which may enhance the persistence and transfer of antibiotic-resistant bacteria. These conditions are conducive to horizontal gene transfer (HGT), thereby accelerating the dissemination of ARGs [79]. Furthermore, MPs may selectively enrich resistant strains while suppressing susceptible ones, ultimately reshaping resistance profiles and exacerbating public health risks [80]. Table 1 shows a summary of studies on the effects of MPs on soil properties and microbial communities.

Table 1. Summary of studies on the effects of microplastics on soil properties and microbial communities.

Soil Type	MP Type	MP Size	MP Concentration	Key Results	Reference
Loam, clay and sand soil	PP-MPs	0, 200, and 500 μm	6% (w/w)	The effects of MPs on soil hydraulic properties were strongly modulated by soil texture.	[64]
Vertisol, *Entisol*, and *Alfisol* soils	PES-MPs	n/a	0.1%, 0.4% (w/w)	PES microfibers exhibited soil type-dependent impacts on soil physical parameters.	[65]
Loam and sand soil	PES-MPs	150, 550, and 950 μm	0.5%, 1%, and 2% (w/w)	Soil texture had a stronger influence on the soil water retention curve than MP concentration and size.	[66]
Clay soil	PES-MPs	<0.25 mm	0.1%, 0.3% (w/w)	PES microfibers enhanced soil aggregation in pot experiments, but not under field conditions.	[67]
Loam soil	PES, PET, and PS-MPs	5 μm, 48 μm, and 1 mm	100 mg/kg	PET and PS-MPs reduced the formation of macroaggregates while promoting microaggregate formation.	[21]
Loamy sandy soil	PA, PC, PE, PES, PET, PP, and PS-MPs	1.26–2.26 mm	0.4% (w/w)	The impact of MPs on soil pH was dependent on particle shape, polymer composition, and exposure duration.	[68]
Sandy clay loam soil	HDPE-MPs	102.6 μm	0.1% (w/w)	HDPE-MPs significantly decreased soil pH even at a low concentration (0.1% w/w).	[69]
Dry soil	PE-MPs	2 mm × 2 mm × 0.01 mm	200 pieces	MPs accelerated the turnover rate of soil bacterial communities.	[75]
Pot soil	PE, PVC, and PS-MPs	200 μm	2% (w/w)	PE-MPs caused greater reductions in rhizosphere bacterial richness and diversity than PS and PVC-MPs.	[76]
Field soil	PHAs-MPs	n/a	1–20% (w/w)	Biodegradable MPs promoted microbial turnover and improved nutrient use efficiency.	[77]

Note: The abbreviations for microplastic polymer types used in this table are as follows: **PP:** polypropylene; **PES:** polyester; **PET:** polyethylene terephthalate; **PS:** polystyrene; **PA:** polyamide; **PC:** polycarbonate; **PE:** polyethylene; **HDPE:** high-density polyethylene; **PVC:** polyvinyl chloride; **PHAs:** polyhydroxyalkanoates.

3.3. Microplastic–Plant Interactions

3.3.1. Entry and Uptake Pathways

The uptake of MPs by plants is influenced by multiple factors, including particle size, concentration, plant species, and environmental conditions. Since Li et al. [17] first visualized the internalization of fluorescent PS microspheres in edible crops, research on MP uptake into plant systems has expanded rapidly. Table 2 summarises and compares MP uptake and distribution across different studies.

Size-dependent uptake mechanisms have been increasingly elucidated. Larger MPs (≥5 μm) typically adhere to the surface of roots, where they may impede water and nutrient absorption but are generally unable to penetrate root tissues [20,81]. In contrast, smaller MPs in the submicron and nanoscale ranges can more readily breach the root epidermis and accumulate in internal tissues. Submicron particles may enter through crack-entry sites or via apoplastic pathways, while nanoplastics (NPs) can be internalised through symplastic transport mechanisms, such as endocytosis or plasmodesmata-mediated movement [18,82].

Table 2. Summary of studies on microplastic uptake and distribution in terrestrial higher plants.

Plant Species	MP Type	MP Size	Cultivation Environment	MP Concentration	Exposure Time	Key Results	Reference
Wheat (*Triticum aestivum* L.) and Lettuce (*Lactuca sativa*)	PS-MPs	0.2 µm, 2.0 µm	Soil and Aqueous	150, 500 mg/kg (Soil) 50 mg/L (Aqueous)	20 days (Soil) 10 days (Aqueous)	Microspheres of 2 µm mainly accumulated in roots, with limited translocation to aerial tissues; in contrast, 0.2 µm particles were transported to shoots and leaves via the transpiration stream.	[17]
Fava bean (*Vicia faba*)	PS-MPs	5 µm, 100 nm	Aqueous	10, 50, 100 mg/L	48 h	Micron-sized MPs were mainly adsorbed on root surfaces, whereas nanoscale MPs were able to penetrate root tissues.	[20]
Garden cress (*Lepidium sativum*)	PS-MPs	50, 500, 4800 nm	Aqueous	10^3 to 10^7 particles/mL	72 h	MP exposure significantly affected seed germination and root development, primarily due to physical blockage effects.	[81]
Oilseed rape (*Brassica napus*)	PS-MPs	80 nm, 1 µm	Aqueous	40 mg/L	14 days	MPs were translocated within plant tissues through the symplastic transport system.	[18]
Rice (*Oryza sativa* L.)	PS-MPs	80 nm, 1 µm	Aqueous	7×10^{13}, 7×10^{11} particles/L	14 days, 40 days	MPs were absorbed by roots and translocated to aerial tissues via apoplastic pathways.	[82]
Cucumber (*Cucumis sativus.*)	PS-MPs	100, 300, 500, and 700 nm	Aqueous	50 mg/L	65 days	Nanoscale MPs accumulated in root tissues and were subsequently transported to aboveground organs, including leaves, flowers, and fruits.	[83]
Mung beans (*Vigna radiata*)	PS-MPs	28 nm	Soil	10, 100 mg/kg	14 days	Strong fluorescence signals in leaves at 100 mg/kg exposure indicated effective translocation of MPs to aerial tissues.	[84]
Barley (*Hordeum vulgare*)	PS-MPs	5 µm	Aqueous	2 g/mL	14 days	Most MPs were localised on the root surface, with fluorescence intensity significantly higher in roots than in stems or leaves.	[16]

Note: The abbreviation for microplastic type used in this table is as follows: **PS-MPs:** polystyrene microspheres.

Despite the growing number of studies, most are based on hydroponic systems or aqueous suspensions and often employ short term, high-concentration exposure conditions. These artificial settings may not reflect MP behaviour under field conditions, where soil complexity can significantly affect uptake. Moreover, research has largely relied on PS microspheres with defined size and fluorescence, limiting our understanding of the uptake of MPs with more environmentally relevant forms—such as fibres, fragments, or films—across different polymer types commonly found in agricultural soils.

3.3.2. Accumulation and Translocation Patterns

Once MPs are absorbed by plant roots, they may be translocated to aerial organs through several pathways. Transpiration-driven vascular transport, apoplastic diffusion, and endocytosis are considered the primary mechanisms facilitating the systemic movement of MPs within plant tissues [17,18,82]. In particular, when MPs penetrate the endodermis and enter the xylem, they can be transported upward via the transpiration stream, ultimately accumulating in stems, leaves, and other aboveground tissues (Figure 2). Empirical studies have confirmed that NPs can be internalised and subsequently transported to aerial parts in various edible crops, such as oilseed rape (*Brassica napus*), cucumber (*Cucumis sativus*), and mung bean (*Vigna radiata*), demonstrating their capacity to bypass root barriers and undergo long-distance translocation [18,83,84].

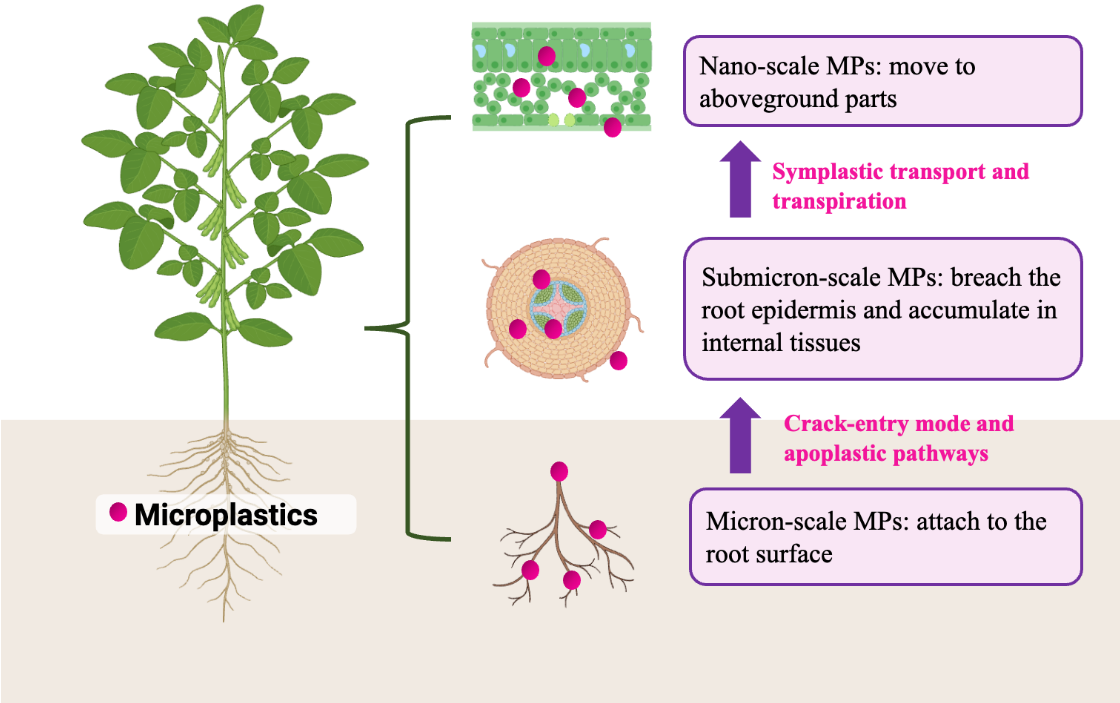

Figure 2. Overview of microplastic entry, uptake, and translocation within the plant body. This figure was created by the authors using BioRender.com (https://www.biorender.com/, accessed on 18 June 2025). The content and structure of this figure were developed with reference to [14,16–18,20,81–85].

Furthermore, MP accumulation patterns vary considerably both among plant species and within different tissues of the same plant. Inter-species differences are particularly notable. For instance, Liu et al. [85] reported that leafy vegetables tend to accumulate higher concentrations of MPs in aerial tissues compared to cereals and legumes, likely due to variations in transpiration rates and water-use strategies. The intra-plant distribution also exhibits distinct localisation trends. Li et al. [16] observed that in barley (*Hordeum vulgare*), MP-associated fluorescence signals were most intense in root tissues and significantly lower in stems and leaves.

In summary, the spatial distribution of MPs within plants is influenced by multiple factors, including particle size, plant species, and physiological traits. A deeper understanding of these accumulations and translocation patterns is essential for evaluating the potential for MP transfer through the food chain and for assessing associated food safety risks.

3.4. *Ecotoxicological Effects of Microplastics on Plants*

3.4.1. Physical Toxicity

One of the most immediate toxicological effects of microplastics MPs on plants is physical toxicity. Larger particles (micrometre range) tend to adhere to or entangle around plant root surfaces in soil, leading to localised mechanical obstruction. This physical blockage can hinder water and nutrient uptake in the root hair zone, reduce gas exchange efficiency in the rhizosphere, and ultimately impair plant growth and development [17]. For instance, Jiang et al. [20] reported that 5 μm PS-MPs remained attached to the root surface of the fava bean (*Vicia faba*), significantly reducing both plant height and biomass.

In contrast, NPs are small enough to be internalised by plant root cells via endocytosis. These particles can accumulate in the epidermis, cortex, and vascular tissues, potentially disrupting cellular integrity and tissue organisation [86]. For example, Li et al. [87] observed that exposure to 75 nm PS microspheres led to significant reductions in photosynthetic pigments and chlorophyll content in lettuce (*Lactuca sativa*), indicating functional impairment of key physiological processes.

Overall, tissue blockage and cellular damage caused by MPs represent critical early-stage toxic effects. These effects often initiate a cascade of secondary stress responses, including osmotic imbalance and metabolic disruption.

3.4.2. Oxidative Stress and Antioxidant Responses

Following the accumulation of MPs on root surfaces and the resulting physical obstruction, plants commonly initiate oxidative stress responses as part of their defence strategies. A central feature of this response is the dynamic balance between the excessive generation and scavenging of reactive oxygen species (ROS), including hydroxyl radicals (·OH), superoxide anions (O_{2^-}), and hydrogen peroxide (H_2O_2). MPs can promote ROS accumulation by compromising cell membrane integrity, disrupting mitochondrial function, and activating inflammation-like signalling pathways, ultimately leading to sustained oxidative stress in plant cells [88].

To mitigate oxidative damage, plants activate a suite of antioxidant defence systems, comprising both enzymatic antioxidants, such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and non-enzymatic antioxidants like glutathione (GSH) and ascorbic acid. For instance, He et al. [89] reported significant increases in malondialdehyde (MDA) and GSH levels in sweet pepper (*Capsicum annuum*) treated with 2 μm PS-MPs at 50 g/L, indicating intensified membrane lipid peroxidation and activated antioxidant responses. Conversely, Dong et al. [90] observed no significant change in MDA levels in oilseed rape (*Brassica campestris* L.) exposed to 63 nm PMMA-NPs at 0.5 g/L, suggesting concentration dependence and species-specific responses.

The type and physicochemical properties of MPs also influence antioxidant activity. Sun et al. [91] found that exposure to 1% (*w*/*w*) PE-MPs significantly increased SOD activity in maize (*Zea mays* L.), whereas the same concentration of biodegradable Bio-MPs led to decreased SOD activity. Similarly, Pignattelli et al. [92] observed a reduction in GSH content in garden cress (*Lepidium sativum*) after six days of exposure to 0.02% (*w*/*w*) PP-MPs. Interestingly, Gao et al. [93] reported contrasting trends in DPPH radical scavenging activity between wheat (*Triticum aestivum* L.) and maize treated with 13 μm PE-MPs at 1% (*w*/*w*): wheat exhibited enhanced antioxidant capacity, while maize showed a decline.

These findings collectively highlight that oxidative stress induced by MP exposure is highly dependent on particle size, polymer type, exposure concentration, and plant species. A better understanding of these parameters is essential for evaluating the redox-based phytotoxic effects of MPs and their broader ecological implications.

3.4.3. Genotoxicity and Cellular Effects

In addition to physical obstruction and oxidative stress, increasing attention has been directed toward the potential cytotoxic and genotoxic effects of MPs (particularly NPs) on plants [94]. Due to their small size and high surface area, NPs exhibit strong penetrative capabilities, allowing them to cross the plant cell wall and plasma membrane and even enter the nucleus and other subcellular organelles [95,96]. Once inside the cell, NPs can cause DNA damage, chromosomal aberrations, and cell cycle disruption, threatening genomic stability and long-term plant viability [97].

Current assessments of MP-induced genotoxicity in plants primarily rely on classical cytogenetic methods, such as the comet assay, micronucleus test, and mitotic index analysis [20,98]. For example, Kaur et al. [99] observed significant size- and concentration-dependent reductions in the mitotic index of *Allium cepa* root tip cells, with the lowest values recorded at 100 mg/L of 100 nm PS-MPs. Additionally, both chromosomal aberration index (CAI) and nuclear abnormality index (NAI) were significantly reduced under these conditions. In contrast, Biba et al. [100] found no significant DNA damage in *Allium cepa* root tip cells exposed to 0.01, 0.1, and 1 g/L of PS or PMMA-MPs, as measured by the comet assay.

Although these studies offer preliminary insights into the genotoxic potential of MPs in terrestrial plants, the field remains in its early stages. Importantly, many of the reported effects have been observed at concentrations exceeding environmentally relevant levels, potentially overstating real-world risks. Future research should therefore prioritise studies under realistic exposure scenarios to more accurately assess the threat MPs pose to plant genomic stability and cellular function.

3.4.4. Carrier Effects

As previously discussed, due to their unique physicochemical properties, MPs can act as vectors for various environmental contaminants, including heavy metals, pesticides, antibiotics, and other organic pollutants. These co-contaminants may enter plant systems alongside MPs, leading to additive or even synergistic toxic effects. For instance, Xu et al. [101] reported that the co-occurrence of MPs and phenanthrene (Phe) significantly enhanced toxicological stress in soybeans. In addition, MPs offer favourable surfaces for the colonisation of microbial biofilms, which can facilitate the propagation of ARGs and promote HGT among microbial communities. This process has been shown to indirectly impact the growth and health of terrestrial higher plants [102].

Moreover, plastic additives (e.g., plasticisers, antioxidants, and flame retardants) are widely incorporated into plastic products to improve their performance, durability, and cost-efficiency. Over time, these additives can leach from the polymer matrix into surrounding environmental media, including soil, water, and food, or migrate from the interior to the plastic surface [103]. While the toxicological impacts of such leached additives on animal and human health have been relatively well-documented, their specific effects on soil–plant systems remain largely understudied and warrant further investigation [104].

3.4.5. Omics-Based Molecular Evidence

With the advancement of high-throughput analytical technologies, omics approaches have emerged as powerful tools for elucidating the molecular mechanisms underlying plant responses to MP stress. Compared to traditional physiological indicators, these techniques offer system-level insights into the dynamic regulation of metabolic pathways and gene expression in plants [42,105].

Huang et al. [106] conducted a non-targeted metabolomics study that systematically revealed substantial metabolic reprogramming in spinach (*Spinacia oleracea*) exposed to both pristine and photoaged polystyrene nanoplastics (PSNPs). Their findings showed that both types of PSNPs could be absorbed by the roots and subsequently translocated to aerial tissues; however, photoaged particles induced more severe stress responses, particularly in root tissues. Pathway enrichment analysis indicated that photoaged PSNPs significantly disrupted aminoacyl-tRNA biosynthesis and phenylpropanoid metabolism, while pristine PSNPs mainly affected sulphur metabolism and the biosynthesis of unsaturated fatty acids. These results suggest that spinach may employ carbon and nitrogen metabolic reprogramming, as well as tissue-specific metabolic adaptations, to mitigate oxidative stress and toxic effects caused by NPs. This study provides valuable molecular-level evidence for the phytotoxic mechanisms of MPs.

Furthermore, transcriptomic studies have demonstrated that abiotic stress can activate the mitogen-activated protein kinase (MAPK) signalling pathway and significantly upregulate the expression of defence-related genes, such as glutathione S-transferase (GST) and catalase (CAT) in plants [88,107]. However, the specific gene regulatory mechanisms triggered by MP exposure remain insufficiently understood and warrant further investigation. Collectively, omics-based research offers critical insights into the molecular targets and toxicological pathways influenced by MPs in plants.

3.5. Impacts on Plant Growth

3.5.1. Plant Morphology

Exposure to MPs has been shown to alter plant morphological traits in diverse and sometimes contradictory ways. For instance, Qi et al. [108] found that wheat (*Triticum aestivum*) exposed to 1% *w*/*w* biodegradable plastic films (Bio-MPs) exhibited reduced plant height. In contrast, Xu et al. [109] reported decreased root length in Asian shortstem sedge (*Carex breviculmis*) under 1% *w*/*w* PP-MPs. Similarly, Meng et al. [110] observed increased root length in common bean (*Phaseolus vulgaris* L.) when exposed to 1% *w*/*w* Bio-MPs, underscoring species-specific responses to MP exposure with the same concentration.

Li et al. [111] reported that 0.5% *w*/*w* 18 μm PVC-MPs increased average root diameter in lettuce (*Lactuca sativa* L.), while 2% *w*/*w* 150 μm PVC-MPs caused a reduction. Bosker et al. [81] similarly showed a significant reduction in the root length of garden cress (*Lepidium sativum*) after 24 h exposure to 10^7 particles/mL of microbeads. These findings collectively highlight that plant morphological responses are modulated by MP characteristics, including size, shape, concentration, and exposure duration.

3.5.2. Plant Physiology

MPs are widely recognised for their potential to inhibit seed germination, primarily by physically obstructing root growth [112]. However, contrasting findings have been reported, with some studies observing no significant effects of MPs on the germination of certain crops, such as rice (*Oryza sativa* L.) and cherry tomato (*Solanum lycopersicum* L.) [113,114].

Physiological responses beyond the germination stage also display notable variability. For example, 0.2% *w*/*w* PES microfibers reduced the biomass of perennial ryegrass (*Lolium perenne*) but increased that of spring onion (*Allium fistulosum*) [115,116]. MPs also influence photosynthetic pigments in contrasting ways. Tunali et al. [117] observed a decrease in chlorophyll *a* (Chl *a*) in green alga (*Chlorella vulgaris*) exposed to 100–1000 mg/L PS-MPs, whereas Zhang et al. [118] reported an increase in Chl *a* in tobacco (*Nicotiana tabacum* L.) treated with LDPE-MPs at the same concentration range.

These contrasting findings indicate that not all high concentrations of MPs result in negative effects on plants, highlighting the necessity and importance of considering factors like MP characteristics, exposure conditions, and plant species when evaluating the impacts of MPs on soil–plant systems.

3.6. Contradictory Results in Soil–Plant–Microplastic Interactions and Possible Explanations

Despite growing interest in the effects of MPs on agroecosystems, current research reveals substantial inconsistencies in understanding their behaviour and impacts within soil–plant systems. These discrepancies arise from the complex interactions between MP characteristics, plant-specific responses, and experimental conditions.

One key reason is the heterogeneity of MP properties used across studies. Variations in particle size, shape, polymer type, concentration, and surface chemistry significantly influence observed outcomes. For instance, submicron MPs may penetrate plant root systems and translocate to aerial tissues, whereas larger particles often remain on root surfaces. Similarly, the same polymer type may have opposite effects on different soil properties or plant species, depending on its physical form and environmental context.

Another source of inconsistency stems from differences in plant sensitivity. Plant responses to MP exposure are highly species specific and may also vary across developmental stages and environmental conditions (Table 3). For example, certain crops exhibit inhibited biomass accumulation under MP stress, while others show compensatory or even stimulatory growth [21]. This variability complicates the extrapolation of findings across plant types and agricultural settings.

Table 3. Summary of studies on the effects of microplastics on plant growth.

Plant Species	MP Type	MP Size	MP Concentration	Key Results	Reference
Wheat (*Triticum aestivum* L.)	LDPE, Bio-MPs	50 μm–1 mm	1% (*w*/*w*)	Bio-based MPs exhibited more pronounced negative effects on plant growth compared to conventional MPs.	[108]
Asian shortstem sedge (*Carex breviculmis*)	PP-MPs	<500 μm	0.5%, 1%, and 2% (*w*/*w*)	High MP concentrations promoted fine root proliferation, increasing total root biomass.	[109]
Common bean (*Phaseolus vulgaris* L.)	LDPE, Bio-MPs	250–500 μm, 500–1000 μm	0.5%, 1.0%, 1.5%, 2.0%, and 2.5% *w*/*w* (*w*/*w*)	Bio-MPs significantly reduced shoot and root biomass and fruit yield, while increasing specific root length.	[110]
Lettuce (*Lactuca sativa* L.)	PVC-MPs	100 nm–18 μm, 18–150 μm	0.5%, 1%, and 2% (*w*/*w*)	MP size and concentration were important factors influencing plant physiological and biochemical responses.	[111]
Garden cress (*Lepidium sativum*)	PS-MPs	50, 500, and 4800 nm	10^3 to 10^7 particles/mL	Exposure time significantly affected plant responses to MP contamination.	[81]
Lentil (*Lens culinaris*)	PE-MPs	740–4990 nm	10, 50, and 100 mg/L	Adverse effects on seed germination intensified with increasing MP concentrations.	[112]
Rice (*Oryza sativa* L.),	PS-MPs	200 nm	10, 1000 mg/L	No significant impact on rice seed germination; however, PS-MPs promoted root elongation and decreased antioxidant enzyme activity.	[113]
Tomato (*Solanum lycopersicum* L.)	PP-MPs	<500 μm	0.1 g/L	Tomato germination remained largely unaffected, though MPs inhibited later vegetative growth.	[114]
Perennial ryegrass (*Lolium perenne*)	PLA, HDPE-MPs	65.5 μm, 102.6 μm	1 g/kg, 10 mg/kg	The impact of MPs on plant growth varied considerably depending on polymer type.	[115]
Spring onion (*Allium fistulosum*)	PES, PE, PET-MPs	15–20 μm	0.2%, 2% (*w*/*w*)	MP type had distinct effects on overall plant biomass.	[116]
Green alga (*Chlorella vulgaris*)	PS-MPs	0.5 μm	1, 5, 50, 100, and 1000 mg/L	Chlorophyll *a* content decreased under 50, 100, and 1000 mg/L MP treatments, but remained unchanged at 1 mg/L.	[117]
Tobacco (*Nicotiana tabacum* L.)	LDPE-MPs	13 μm	10, 100, and 1000 mg/L	High MP concentrations significantly inhibited root system architecture and overall growth performance.	[118]

Note: The abbreviations for microplastic polymer types used in this table are as follows: **LDPE:** low-density polyethylene; **HDPE:** high-density polyethylene; **PP:** polypropylene; **PE:** polyethylene; **PVC:** polyvinyl chloride; **PS:** polystyrene; **PET:** polyethylene terephthalate; **PES:** polyester; **PLA:** polylactic acid; **PBAT:** polybutylene adipate terephthalate; **Bio-MPs:** biodegradable microplastics.

Experimental conditions also contribute to the variability in reported results. For instance, studies often utilise different soil types, which can lead to divergent findings, as soil texture plays a crucial role in determining the impact of MPs (Table 1). Moreover, many studies employ hydroponic systems or artificial exposure scenarios with concentrations orders of magnitude higher than environmentally relevant levels. These conditions, while useful for mechanistic insights, may not accurately reflect MP behaviour in field soils [98]. Moreover, the lack of standardised protocols for MP characterisation, exposure assessment, and endpoint measurement can further impede cross-study comparisons.

4. Microplastic Detection and Quantification in Soil–Plant Systems

4.1. Detection and Quantification of Microplastics in Soil Samples

MP analysis in soil typically involves sequential processes of physical separation, organic matter removal, and chemical identification. Density separation remains the most widely used method, employing high-density salt solutions, such as zinc chloride ($ZnCl_2$), sodium iodide (NaI), or calcium chloride ($CaCl_2$), to isolate MPs from mineral particles [119,120]. This is often followed by oxidative or enzymatic digestion—commonly using hydrogen peroxide, strong acids, or alkalis—to degrade soil organic matter [121,122].

Recovery efficiency is influenced by both soil type and MP characteristics. In sandy soils, recovery rates of 80–95% have been reported, whereas in clay-rich soils, stronger MP–mineral adhesion reduces recovery to 50–70% [123]. The density of the polymer is another determining factor: low-density polymers such as PE and PP are readily separated, while denser polymers such as PET and PVC may be underestimated due to sinking behaviour [124].

For chemical identification and quantification, Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy are commonly employed, with detection limits of approximately $\geq$10 μm and $\geq$1 μm, respectively [125,126]. In addition, thermal degradation-based techniques, including thermogravimetric analysis (TGA) and pyrolysis–gas chromatography–mass spectrometry (Pyr-GC/MS), allow estimation of total MP mass and polymer composition based on thermal decomposition patterns [127]. However, organic-rich soils often introduce spectral interference, affecting the precision and reproducibility of these approaches [128].

4.2. Detection and Quantification of Microplastics in Plant Tissues

The detection of MPs in plant tissues presents specific analytical challenges due to the biological complexity and variability of plant matrices. Fluorescence microscopy, using dyes such as Nile Red, is frequently used to visualise MPs within roots and vascular tissues [129]. However, autofluorescence from plant cells can obscure MP signals, necessitating complementary approaches such as metal labelling, isotope tracing, or chemical embedding to enhance detection clarity [130,131]. These methods now have been applied mainly in aquatic systems, with limited adaptation to terrestrial plant environments [132].

Electron microscopy, including scanning (SEM) and transmission (TEM) techniques, enables high-resolution imaging of MP location and morphology at the tissue and cellular level [133]. However, these methods require the preparation of cross-sectional samples, which is both time-consuming and labour-intensive. Nuclear magnetic resonance (NMR) spectroscopy offers additional insights into polymer structure but is less commonly used due to its high technical demands [134].

For quantification, thermal degradation methods, such as TGA and Pyr-GC/MS, provide total MP mass but lack spatial resolution and cannot determine particle morphology. Gravimetric filtration coupled with optical or electron microscopy allows particle counting, although its accuracy is influenced by operator bias and the difficulty of distinguishing MPs from natural debris [135]. Spectroscopic methods (e.g., μ-FTIR, μ-Raman) offer polymer identification and semi-quantification but are constrained by their respective size detection thresholds (~10 μm and ~1 μm) [132]. Uneven MP distribution across plant tissues further complicates quantification, often requiring customised extraction protocols [85].

4.3. Cross-Matrix Approaches for Detection and Quantification of Microplastics

The detection and quantification of MPs across both soil and plant matrices are limited by their distinct physical and chemical properties. No single analytical method is currently suited to both environments, and techniques must be adjusted to account for matrix-specific factors, such as organic matter content, sample structure, and background interference (Figure 3).

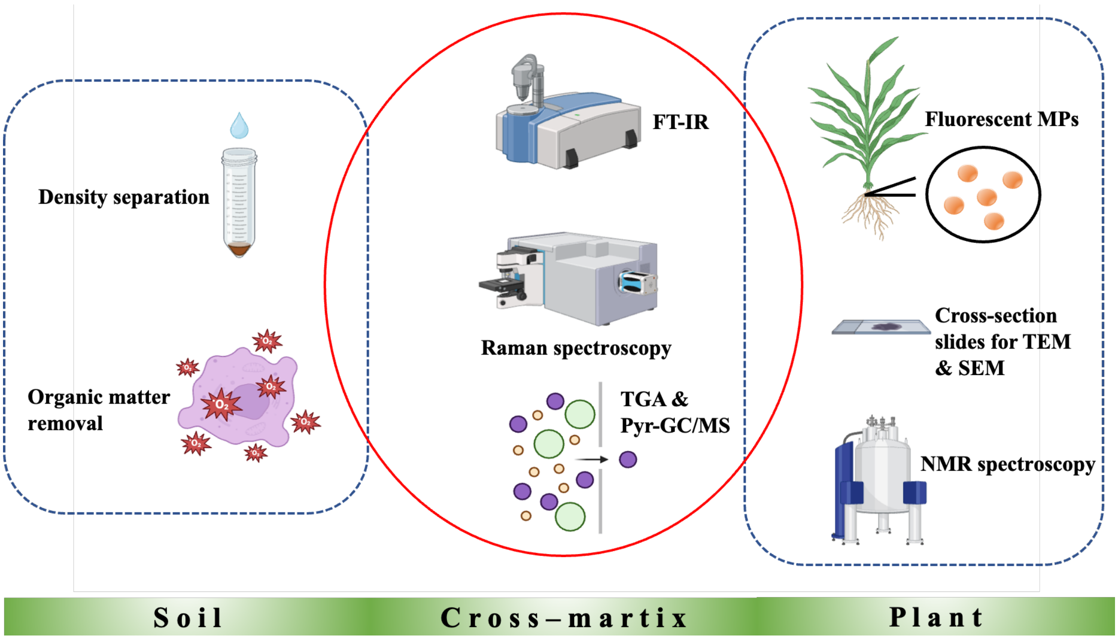

Figure 3. Analytical approaches for detecting and quantifying microplastics in soil and plant matrices. This figure was created by the authors using BioRender.com (https://www.biorender.com/, accessed on 18 June 2025). The content and structure of this figure were developed with reference to [119–135].

Thermal degradation-based methods are commonly applied in both contexts but may be affected by the presence of humic substances in soils or lignin-rich tissues in plants. Microscopy and fluorescence imaging can yield valuable spatial information but are often limited by throughput, signal interference, and preparation complexity [136].

Additionally, many experimental studies rely on PS microspheres as model particles due to their availability and uniformity. However, this approach does not adequately reflect the irregular shapes commonly found in agroecosystems, such as fibres, fragments, and films. Expanding detection capabilities to include a broader spectrum of environmentally relevant MP forms remains an important technical challenge.

5. Knowledge Gaps in Current Research

5.1. Limited Scope of Research Subjects

Current studies predominantly focus on a single plant species and a single type of MP, often under highly controlled conditions. However, both MP characteristics and plant species have been shown to significantly influence the outcomes, contributing to the variability observed across studies. In real agricultural settings, various types of MPs from multiple sources coexist, while a wide range of crop species are grown simultaneously. This complexity is rarely reflected in laboratory experiments, reducing the ecological validity and applicability of existing findings.

In addition, many studies assess the effects of MPs on either soil properties or plant growth in isolation, without considering the dynamic feedback between the two components (Tables 1 and 3). In reality, soil and plants function as a coupled system. For example, plant root traits may influence the mobility, aggregation, or retention of MPs in soil, while MP-induced changes in soil structure and chemistry can alter plant physiological responses. Investigating MP impacts from an integrated soil–plant system perspective is essential to unravel the bidirectional mechanisms driving MP behaviour and biological effects.

5.2. Lack of Environmental Relevance in Experimental Conditions

Many studies use MP concentrations that are substantially higher than those found in agricultural soils, which limits the ecological relevance of the results. Moreover, a large proportion of plant exposure experiments are conducted in hydroponic systems, where MPs exhibit greater mobility and volatility compared to soil environments [137]. While useful for mechanistic insights, these systems do not accurately reflect the complex interactions that occur in soil matrices.

Experimental durations also tend to be short term, typically ranging from several hours to days, which does not correspond to the full life cycle of most terrestrial crops [16,18,84]. As a result, the effects of long-term, low-dose exposure, which better reflects real agricultural scenarios, remain poorly understood. Furthermore, spatial variability in MP concentrations across different regions highlights the importance of incorporating realistic concentration gradients into experimental design to improve the generalizability of findings across diverse agroecosystems.

5.3. Technical Barriers to Detection and Quantification

A major limitation in current MP research lies in the narrow range of targeted particles used in studies. Most investigations focus on PS-MPs, while fibrous MPs, which are the predominant form in agricultural soils, have received relatively little attention. Detecting microfibers in both soil and plant tissues presents unique technical challenges, including their irregular shape, low contrast in imaging, and high tendency to entangle with organic matter. This restricts our understanding of their distribution, mobility, and potential impacts within real-world soil–plant systems.

In addition, there is currently no standardised protocol for detecting and quantifying MPs in soil and plant samples, and available techniques vary widely in accuracy, reproducibility, and resolution. Discrepancies among studies are common, often stemming from differences in sample preparation, staining protocols, or instrument sensitivity. There is an urgent need for high-throughput, matrix-specific methods to ensure reliable detection and quantification. Integrating complementary techniques, such as spectroscopy, thermal analysis, and microscopy, may enhance both analytical specificity and measurement robustness.

Another critical challenge involves detecting and quantifying MPs across complex soil–plant matrices, where strong background signals from organic matter and mineral particles often interfere with fluorescence or spectral imaging. Preparation of cross-sectional samples for electron microscopy is labour intensive and not scalable, limiting its use in large-sample studies. Although high-resolution tools such as confocal microscopy can provide spatial insights, they require destructive sampling and are impractical for in situ monitoring at the field scale.

5.4. Underexplored Co-Contaminant Interactions and Ecological Risks

In addition to their physical presence, MPs can act as vectors for a variety of chemical additives, including plasticisers, flame retardants, and stabilisers. The release dynamics of these additives in soil, their bioavailability to plants, and their potential ecotoxicological effects remain poorly understood. These substances may interact with soil microbes and plant metabolic pathways, potentially disrupting microbial functions and plant health.

Moreover, MPs often coexist with other pollutants, such as heavy metals, pesticides, and antibiotics, in agricultural soils. These co-contaminants may adsorb to MP surfaces, altering their environmental fate, mobility, and toxicity [101]. However, the mechanisms underlying these interactions remain largely unexplored. Research is needed to determine whether MPs enhance or suppress the persistence and bioavailability of such pollutants, and how these interactions influence cumulative ecological risks.

5.5. Insufficient Evidence on Long-Term Impacts of MPs on Soil Functionality

While most studies focus on short-term exposure, the long-term accumulation of MPs may have far-reaching impacts on soil ecosystems. Potential consequences include alterations to soil structure, changes in porosity and aggregation, disruption of nutrient cycling processes, and shifts in microbial diversity and function [138]. Additionally, MPs may interfere with organic matter decomposition and affect greenhouse gas (GHG) emissions, yet current evidence is limited. Long-term, field-based studies are urgently needed to assess the persistence and functional impacts of MPs on soil health and fertility under realistic agricultural conditions.

5.6. Overlooked Cross-System Transport and Environmental Spread of Microplastics

The long-term accumulation of MPs in agricultural environments presents multifaceted risks that extend beyond local soil systems. Within the soil ecosystem, MPs pose direct threats to keystone organisms, such as earthworms and nematodes, which are essential for organic matter decomposition, nutrient cycling, and soil structure maintenance [139]. Ingestion of MPs by these organisms has been shown to impair growth, reproduction, and survival, thereby reducing biodiversity and weakening ecosystem resilience [140,141].

Beyond soil organisms, MPs can migrate through hydrological pathways, affecting aquatic ecosystems and interconnected terrestrial systems, such as wetlands and forests [142]. Their persistence and mobility raise concerns about broader ecological disturbances, including disruptions to food webs, reductions in ecosystem services like water purification, and feedbacks to climate regulation [143]. Moreover, MPs often co-occur with pesticides, fertilisers, heavy metals, and antibiotics in agroecosystems, creating complex pollutant mixtures. These interactions may result in synergistic or antagonistic toxicity, amplifying the environmental risks [144]. Furthermore, MPs can indirectly affect atmospheric processes by altering soil microbial activity and carbon cycling, potentially influencing GHG emissions [145]. Given their persistence, mobility, and interactions with other stressors, understanding the cross-media transport and ecological implications of MPs is critical for evaluating their long-term impacts on agroecosystem stability and sustainability.

6. Future Directions for Microplastic Pollution in Agroecosystems

6.1. Bridging the Gap Between Laboratory Studies and Real-World Agroecosystems

In real agricultural environments, MPs are influenced by complex interactions among heterogeneous soils, dynamic microbial communities, and varying environmental factors, such as temperature, rainfall, irrigation, and tillage [146,147]. These factors affect MPs' mobility, bioavailability, and biological interactions, often causing discrepancies between laboratory results and field observations, especially in terms of physiological responses and plant uptake [42].

To bridge this gap, future research should move beyond short-term, single-site studies and prioritise long-term, multi-location field trials across different seasons. Such efforts are important to understand MP behaviour under diverse agricultural conditions, for example, how rainfall accelerates vertical migration or how soil texture influences retention and movement [46,64]. Field validation is essential to improve ecological risk assessments and to inform practical policies and farm management decisions.

6.2. Enhancing Microplastic Detection and Quantification in Soil–Plant Systems

Fluorescence-based imaging is widely used for detecting MPs in soil–plant systems but faces challenges, such as autofluorescence from soils and plants, particle overlap, and reliance on high dye concentrations (strong signals) that may pose ecological risks. Manual image interpretation also introduces inconsistencies [135].

Future research should focus on the following: (1) developing alternative labelling methods like metal tagging or isotope tracing to reduce autofluorescence and improve specificity; (2) combining complementary techniques such as spectroscopy, thermal analysis, and microscopy for better qualitative and quantitative analysis; and (3) applying artificial intelligence (AI)-driven image analysis to enhance detection accuracy, minimise bias, and enable high-throughput screening.

6.3. Addressing Multi-Pollutant Interactions in Agroecosystems

Given the frequent use of fertilisers and pesticides, MPs in agricultural soils often interact with co-occurring pollutants. These interactions can be synergistic—enhancing toxicity—or antagonistic—reducing pollutant efficacy [148]. Such context-dependent effects highlight the need to assess MPs not as isolated contaminants, but within a broader multi-pollutant framework.

To improve ecological realism and better assess cumulative stress effects, future research should pursue the following directions: (1) clarify physicochemical interactions between MPs and co-contaminants, including sorption–desorption dynamics and microbial mediation within the rhizosphere; (2) apply systems-level modelling (e.g., structural equation modelling) to disentangle direct and interactive effects of multiple stressors; (3) Integrate plant physiological and microbial responses to assess the cumulative impacts of MP–pollutant mixtures.

6.4. Safeguarding Soil Health and Biogeochemical Cycling

MPs pose emerging risks to soil health, with potential long-term impacts on soil structure, nutrient cycling, and soil–plant–microbe interactions [149]. MPs can alter key physical properties, such as porosity, water retention, and aggregate stability, which in turn affect microbial communities and biogeochemical processes, especially carbon and nitrogen cycling [73].

Future research should develop integrative models linking MP behaviour with microbial dynamics and soil biogeochemical processes, focusing on soil organic carbon turnover, nutrient mobility, and GHG emissions under field conditions. This is essential for assessing the long-term impacts of MPs on soil sustainability and guiding evidence-based management practices.

6.5. Securing Food Safety and Crop Resilience

The accumulation of MPs in agricultural soils raises growing concerns for food safety and crop performance. Leafy vegetables are especially vulnerable, as MPs can accumulate in both roots and shoots, forming an "invisible agrochemical residue" that is difficult to remove through conventional washing [150]. Beyond direct contamination, MPs can impair crop health by disrupting chlorophyll synthesis, antioxidant activity, and nutrient uptake, leading to reduced yields and quality, especially under climate stress or in degraded soils [21,116].

Current assessments often rely on single phenotypic indicators, limiting ecological relevance. Future research should adopt functional trait-based frameworks by focusing on traits such as root architecture, membrane integrity, and oxidative stress tolerance to better predict crop adaptability under MP exposure. These should be integrated into multi-parameter models for informed variety selection. Large-scale varietal screening is also needed to identify MP-tolerant genotypes across key crop species. Establishing threshold levels for MP accumulation in edible tissues and benchmarks for dietary exposure will be essential to guide food safety policies and support sustainable agriculture.

6.6. Advancing Systems-Level Understanding Under Global Change

MPs are increasingly viewed as persistent stressors contributing to global environmental change. Their widespread distribution, environmental persistence, and resistance to degradation pose long-term risks to ecosystem stability and may disrupt key planetary boundaries [143]. Due to their high mobility, MPs can move across terrestrial, aquatic, and atmospheric systems via wind, runoff, and irrigation, forming a diffuse pollution network that transcends agroecosystem boundaries [151]. This raises concerns about cascading ecological effects, such as altered plant–microbe–soil interactions, reduced functionality of pollinators and decomposers, and heightened crop vulnerability to climate extremes [152–154].

Future research should adopt a systems-based approach by (1) tracking MP transport across soil–water–air interfaces; (2) evaluating interactions with co-occurring stressors; and (3) integrating MP dynamics into ecosystem and biogeochemical models. Such cross-scale studies are vital to assess the cumulative impacts of MPs under global change scenarios.

6.7. Strengthening Policy Frameworks for Agricultural Microplastic Governance

Efforts to mitigate MP risks in agriculture should align with the United Nations Sustainable Development Goals (SDGs), particularly, **SDG 12: Responsible Consumption and Production**, by promoting sustainable plastic use and circular input systems in agriculture, and **SDG 15: Life on Land**, by maintaining soil functionality and safeguarding terrestrial ecosystem health.

Global Initiatives: The United Nations Environment Programme (UNEP) is leading negotiations on a legally binding Global Plastics Treaty. While agriculture-specific provisions are not yet included, the treaty highlights plastic risks in terrestrial systems, signalling future policy space for addressing agricultural MPs [155].

European Union (EU): The EU Green Deal and Farm to Fork Strategy call for reduced chemical inputs in agriculture [156]. The European Food Safety Authority (EFSA) has conducted several assessments on MP exposure in food [157], and in 2023, the European Parliament Research Service (EPRS) proposed regulating plastic pellet leakage to address primary MP emissions, as part of a broader strategy to mitigate plastic pollution [158].

United Kingdom (UK): The UK banned primary MPs in selected consumer products in 2018, though agricultural sources remain unregulated [159]. The Agricultural Transition Plan (2021–2024) promotes sustainable farmland management and soil health protection, offering indirect policy entry points for MP pollution [160]. Additionally, the Department for Environment, Food and Rural Affairs (DEFRAs) has proposed reducing sewage sludge use on farmland by up to 95% by 2030 and identified agricultural soils as a major source of MPs, providing critical data to support future regulatory action [161].

Despite progress, no unified global standards exist for managing MP emissions from key agricultural sources (e.g., mulch films) or for defining acceptable soil residue levels. Future policies should prioritise (1) life cycle regulation of agri-plastics, (2) soil MP monitoring systems, and (3) integration of MPs into food safety risk frameworks. Embedding MP science into global sustainability agendas will help bridge knowledge and policy, supporting resilient and sustainable agriculture.

7. Conclusions

MPs represent dynamic contaminants within soil–plant systems, exhibiting complex migration, transformation, and bioavailability patterns that challenge traditional risk assessment frameworks. Their interactions with soil structure, microbial communities, and plant tissues indicate that MPs are not passive particles but active agents capable of reshaping agroecosystem processes. Plant responses to MP exposure are multi-layered, encompassing physiological damage, oxidative stress, genotoxicity, and nutrient imbalances—effects that vary widely across species, MP types, and environmental contexts. Recent advances in omics technologies have revealed that MP-induced stress triggers metabolic reprogramming in plants, suggesting a deeper biochemical interplay than previously recognised. Understanding and mitigating these impacts requires integrated, cross-disciplinary efforts that link soil science, plant physiology, molecular biology, and environmental management to secure food safety and agricultural sustainability in a plastic-altered world.

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