Review

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Research Progress on the Mechanisms of Terrestrial Plant Uptake, Transport, and Growth Inhibition Responses to Micro (nano) Plastics

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Research Progress on the Mechanisms of Terrestrial Plant Uptake, Transport, and Growth Inhibition Responses to Micro (Nano) Plastics

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Abstract: Micro (nano) plastics are emerging pollutants and their gradual accumulation in soil due to factors such as improper wastewater processing, plastic film abuse and atmospheric deposition could pose a significant threat to the environment. However, there is limited research on the uptake and transposition of micro (nano) plastics by terrestrial plants and the effects of microplastics on terrestrial plant growth. Therefore, the sources of plastics in soil as well as the uptake and transposition pathways of micro (nano) plastics in terrestrial plants are systematically summarized in this study. The effects of micro (nano) plastics on plants and their mechanisms are thoroughly discussed, which mainly affect the growth and development of plants by blocking roots, triggering oxidative damage and altering the nature of the soil and the microbial community as well as the combined toxic effects with other pollutants. Future research should strengthen the in-situ experiments to study the mechanisms by which soil micro (nano) plastics affect the uptake and transposition of individual plants and plant growth. It should also focus on the factors affecting the uptake of micro-(nano) plastics, the behaviour of micro-(nano) plastics in soil and plant uptake, transposition processes and their mechanisms and combined effects of micro-(nano) plastics and pathogens on plants. Moreover, new detection technologies should be developed to monitor their impacts on ecosystems to better manage their potential risks to the environment.

Keywords: micro (nano) plastics; plant growth; absorption; transposition pathways

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1. Introduction

Plastic products are widely used in various aspects of daily life and industry because they are inexpensive, chemical-resistant, thin and lightweight, not easily deformed, easy to process and stable. The extensive use of plastic products also produces a large amount of plastic waste, which is approximately 400 million tons each year. However, half of them are just used once [1,2]. In 2020, the total amount of plastic in the world exceeded 8 billion tons and it is estimated that in 2050, 12 billion tons of plastic waste will be landfilled and released into the environment. Most of the plastic waste cannot be properly disposed of due to its stable physicochemical properties such as corrosion-resistant, chemical-resistant and difficult to degrade. According to the Shanghai Recycled Plastics Recycling Industry Association, China's plastic waste reached 62.7 million tons in 2019, while the recycling rate was only 30% [3]. Plastic waste breaks into microplastics (MPs) or nanoplastics (NPs), having <5 mm and <100 nm dimensions, respectively, which are collectively referred to as micro (nano) plastics. The presence of plastics in terrestrial (ex: agroecosystems), marine and atmospheric environments indicates their resistance to degradation potential [4]. Micro-(nano) plastics have been widely detected in agricultural fields, rangelands, forest soils, industrial areas and remote flood plains. Micro-(nano) plastics can accumulate up to 6.7% of soil's weight in certain heavily contaminated places [5], which presents a serious threat to terrestrial ecosystems.

Micro (nano) plastics are emerging pollutants, which could be classified into primary and secondary MPs according to their source. Primary MPs are directly produced in the form of small particles and released into the environment through various abiotic pathways, with relatively small impacts on the environment and organisms. The secondary MP particles are produced after the larger

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plastic materials enter the environment through routes such as weathering, photo-dissolution, mechanical abrasion and chemical degradation and undergo aging and cracking. Those produced through abiotic and biotic degradation, are generated from a wide range of sources. Moreover, their quantity, scope and impact are higher than those of primary MPs [6]. In addition, the interaction of MPs with other contaminants may also result in profound contamination and affect their rate of degradation as well as the impact on the environment [7]. Various chemical additives are commonly used to produce plastics with different properties, some of which may be hazardous to human health. Hahladakis et al. [8] identified numerous toxic compounds in MP that can act as carriers and accumulate hydrophobic or hydrophilic organic pollutants in the environment. This is mainly attributed to the large specific surface area and affinity of MP towards these pollutants. As a result, MP can act as a carrier to adsorb a wide range of organic pollutants including pesticides, PAHs, PCBs and pharmaceuticals [9]. This interaction between MP and organic pollutants leads to the potential environmental risks associated with MP and highlights the need for effective management and pollution mitigation strategies.

Micro (nano) plastics can cross certain biological barriers and thus have toxic effects on living organisms. Rillig et al. [10] discussed the potential effects of micro (nano) plastics on plants as well as food safety of crops. Several recent studies have confirmed that micro-(nano) plastics at nanoscale (< 100 nm) or sub-micron scale (< 1 μm) can be taken up by the plant root system and translocated to above-ground aerial tissues [11–15]. In addition, foliar uptake of micro (nano) plastics is another source of pollutant loads for terrestrial plants [13,16]. These findings imply that micro (nano) plastics can pose a health hazard to humans and livestock once they enter the food chain. However, there are currently insufficient comprehensive evaluations on uptake, translocation and the underlying mechanisms of toxicity in plants. In a recent review, micro (nano) plastics were shown to alter the physical, chemical and microbial properties of soil [17]. This implies that micro (nano) plastics can indirectly affect plant uptake, translocation and phytotoxicity. In this study, the pathways of micro (nano) plastics intake into the plants as well as their effects and hazards on plants have been discussed. Moreover, the basic mechanisms of their influence on plants as well as the current research priorities and future research directions are presented.

2. Plastic Sources in Soil

Soil is a vital repository of micro (nano) plastics, which could occur in different forms. Terrestrial plants may take up microplastics from the soil, especially those microplastic particles that are bound to soil particles. This uptake affects the growth and health of the plant as well as transfers microplastics to the various parts of the plant including leaves, stems and fruits. Micro (nano) plastics can have a significant impact on the surrounding soil as they accumulate in the environment and contribute to potentially toxic elements (PTEs). As a result, their toxicity and concentration increase in the surrounding soil [18,19], which may have an impact on the plants and the whole ecosystem. The main source pathways of micro (nano) plastics in soil are wastewater processing, plastic mulch use, composting and atmospheric deposition.

2.1. Wastewater Treatment

Particulate matter from washing chemical fiber clothing, personal care products, household cleaners and plastic waste are the main sources of MP and NP in wastewater processing [20]. According to Li X et al. [21], 90% of MP is collected in municipal wastewater at concentrations ranging from 1,500 to 56,400 particles kg^{-1}. Since both treated and untreated wastewater are used as agricultural soil amendments, soils have been found to contain more than 895 MP particles kg^{-1} [22]. Therefore, regular use of organic fertilizers and wastewater watering can contaminate the soil with MP [23] and increase the concentration of MP in agricultural soils to levels that may be harmful to the environment and humans. In order to fast-track the development of improved sewage sludge treatment technologies in agricultural systems, it is crucial to establish independent dewatering systems.

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2.2. Plastic Mulching

Plastics, especially low-density polyethylene (LDPE), are frequently used as agricultural mulches to increase fruit and vegetable yields. At the beginning of this century, 700,000 tons of mulch were used annually in agriculture worldwide, with China being the largest user (about 80%) [24]. Plastic mulch covers about 20 million hectares of farmland in China [25]. This is because it has several advantages such as it alters soil temperature, reduces water evaporation, provides better weed control, reduces pesticide damage to the soil and allows plants to mature earlier or later. Since plastic mulch films are used in each crop cycles as well as farmers generally do not choose to recycle and reuse them, plastic residues in the soil will become more and more abundant. Films remaining in the field could gradually decompose into MPs and NPs via photolysis as well as physical, chemical and biological effects, leading to contamination of the soil with micro- (nano) plastics [26,27].

2.3. Composting

Nizzetto et al. [28] estimated that about 63,000 to 430,000 tons of microplastics enter the agroecosystem annually through biocomposting alone in Europe. Considering only North America, it is estimated that 44,000 to 300,000 tons of microplastics enter the agroecosystem each year. The use of biofertilizers is also widespread in China, where animal manure, crop straw and industrial sludge are treated and used as fertilizers. Compost can improve the quality of the soil and permeability as they are rich in organic matter and nutrients. This practice turns human waste into treasure for agriculture. It is estimated that approximately 52-26,400 tons of microplastics enter the soil through biofertilizers annually in China, with an annual accumulation rate of 1.25±0.61 microplastics per kilogram of soil in fertilized soil, which is significantly higher than in unfertilized soil [29]. Therefore, the potential pollution of agricultural ecosystems by secondary microplastics and nano-plastics is envisioned to be extremely severe.

2.4. Atmospheric Deposition

Microplastics in soil may also come from suspended particles in the atmosphere. Electrostatic interaction and physical retention are the main mechanisms of interaction between microplastics and soil. The production and use of plastics, the processing of petrochemicals, human activity and plastic particles in water bodies are the main sources of suspended plastic particles in the atmosphere. Microplastics are brought into the atmosphere under the action of wind or light energy. It has been shown that plastics have formed their own global circulatory system, while migrating and transforming globally through a variety of pathways, out of which the atmospheric transportation is fast and wide-ranging. It is the main pathway of the plastic cycle, where plastics are deposited on land surfaces through atmospheric deposition, wind transport and electrostatic adsorption. They propel microplastics to enter the soil, which in turn further affects the soil environment [29].

3. Terrestrial Plant Uptake and Transport of Micro (Nano) Plastics

Early research focused primarily on the uptake and effects of microplastics on aquatic plants. However, investigation on the uptake and transport of microplastics by terrestrial plants has started in recent years. This area of research mainly focuses on understanding the impact of microplastics on plant growth and physiological characteristics as well as the behavior and transport mechanisms of microplastics in soil-plant systems (cited references). Although this field is still in its infancy, research in this area is crucial for understanding the impact of microplastics on ecosystems.

It is generally believed that plants cannot directly absorb microplastics due to the high molecular weight or large size of plastic particles, which prevents them from penetrating the cellulose-rich plant cell walls [30]. However, the existence of disconnected regions in the Casparian strip could allow microplastics to undergo apoplastic transport in plant roots [12]. Some studies have shown that certain nanoparticles (ex: metals, oxides and carbon isomers) can enter plant roots and disperse in different plant structures [31–33]. Microplastics can cause cell wall distortion and deformation, leading to the formation of larger pores, allowing larger plastic particles to enter the plant body [11].

For example, carrot root systems' intercellular space has been found to contain 1 μm polystyrene (PS) particles [11].

Unlike microplastics, nanoplastics have been proven to be absorbed by plant roots. Bandmann et al. [34] first reported that nanoplastics can directly enter plant cells. In their experiment, they observed that tobacco BY-2 cells absorbed fluorescent PS nanoparticles (20-40 nm) through endocytosis while excluding 100 nm PS particles from the plant body. Numerous studies have shown that various plants can absorb micro (nano) plastics of different sizes and types (Table 1).

Table 1. Microplastics Absorption by Plant.

plants	micro (nano) plastics			observation	citations
	types	size	concentration		
Wheat and lettuce	PS and PMMA	0.2–10 μm	0.5–50 mg/L or 150–500 mg/kg	Bead grains of 0.2 um and 2 um were found in roots, xylem sap, stems and leaves of the plant.	[12]
Swamp rice	PS	19 ± 0.16 nm	10–100 mg/L	PS particles are taken up by rice roots and accumulate in the cell interstitial space.	[35]
Carrot	PS	0.1–5 μm	10–20 mg/L	PS particles of ≤1 um can enter carrot cells and accumulate in the cell interstitium; Larger sized particles (≥1 um) are less likely to be found in root tissues; PS particles smaller than 0.2 um can migrate to leaves.	[11]
Tobacco BY-2 cells	PS	20–1000nm	1:1000 v/v dilution in cultures	Tobacco BY-2 cells could rapidly internalize 20-40 nm PS nanobeads by cytosis, but could not take up 100 nm PS nanobeads.	[34]
Cucumbers	PS	100– 700 nm	50 mg/L	PS granules are absorbed by plant roots and transported to plant stems and leaves ; PS particles were detected in the intercellular space of plant roots, stems, leaves, calyxes and the first fruit.	[36,37]
Onion	PS	20– 190 nm	0.01–1.0 g/L	25 nm PS particles were detected in the nucleus; PS particles entered root cells and accumulated in the vesicles and cytoplasm.	[38]
Corn	PE	3 μm	100 mg/L	PE exposure significantly increased root contrast carbon content.	[39]
Arabidopsis thaliana	PS-COOH and PS-NH2	70– 200 nm	10– 100 mg/L 10– 50 mg/L	Compared with PS-NH2, PS-COOH was more easily absorbed by plants; Different regions of PS-COOH\PS-NH2 accumulation.	[40]
Chinese sweetgum	SMA	12±4.5nm	55mg/L	SMA nanoparticles are present in plant stems and are continuously enriched over time.	[41]

3.1. Plant Root Absorption

Plant root absorption is one of the main pathways for microplastics to enter plants (Table 1), which is similar to the main pathway for plant absorption of MNPs [12,40]. Li J et al. [42] studied the absorption of micro (nano) plastics by wheat and lettuce roots while using 0.2 μm fluorescently labeled polystyrene (PS) microbeads to pretreat the roots. They observed that some PS microbeads were blocked outside the cells and retained in the cell wall, while the rest entered the cells, proving that plant roots can absorb microplastics. The negatively charged mucilage and exudates were found to be the main reason for interfering with plant absorption of positively charged PS [43].

PS microbeads could move through intercellular channels and apoplastic transport networks [42]. The active cell division in the root tip (meristematic zone) facilitates the invasion of microplastics. PS particles were found in the meristematic cells and lateral root tips of wheat and lettuce. The researchers inferred that this might be due to the high instability of the cell membrane during cell division and the enhanced recognition of the cell membrane by nanoparticles in the root tip mucilage, allowing nanoparticles to disperse into the meristematic zone. The intact epidermal layer of the root tip is the only site where PS microbeads can penetrate the meristematic zone. Due to the incomplete development of the Casparian strip, it only allows movement through intercellular channels and not through apoplastic transport.

A large amount of PS was found to disappear at the fracture site of the lateral root tip. The microbeads penetrated the epidermis and inner epidermis, indicating that the fracture site is also a vital entry point for micro-PS beads into the vascular tissue of lettuce and wheat [42]. PS microbeads were found in the epidermis and vascular system of wheat after 48 hours [37], confirming that PS particles can form aggregates at the new lateral root site and enter the vascular tissue through fractures [12]. This suggests that micro (nano) plastics can accumulate in roots through root system fractures induced by underground herbivores and mechanical damage and enter the incomplete Casparian strip during root development. They can eventually move to the above-ground parts through apoplastic transport along the vascular tissue cell walls.

Micro (nano) plastic particles have a short-term impact on root formation and germination rate. Wheat growth and production are inhibited under the influence of low-density polyethylene and biodegradable plastics, following the reduced root and above-ground biomass [44]. Bean sprouts have witnessed a significant decrease in cell division index under 100 nm PS conditions and only root length and plant biomass are reduced under 5 μm conditions, indicating that 100 nm PS has greater genotoxicity and oxidative damage than 5 μm PS [45]. Watercress seeds also have witnessed changes in germination rate, root length and seedling growth under PS exposure conditions, which are related to exposure time and particle size [46]. Guo et al. [47] found that the germination rate and germination trend of three leafy ornamental plants (clover, violet and Chinese chives) decreased significantly (2 μm and 80 nm) with the increase in polystyrene microplastics concentration (0, 10, 50, 100, and 500 mg/L).

3.2. Micro (Nano) Plastic Transfer in Plants

Micro (nano) plastics can be transferred from the roots to the above-ground parts of plants. Recently, researchers have observed 1 μm fluorescently labeled PS microspheres in the leaf veins of rice using confocal laser scanning microscopy [48], confirming that micro-sized plastics can be transferred from the roots to the above-ground parts. PS microbeads (100-700 nm) can be transported from the root system of cucumbers to leaves, flowers and fruits through the stem [37]. Zhang T R et al. [41] described the absorption and transportation dynamics of styrene-maleic anhydride (SMA) nanoparticles (12 ± 4.5 nm) in one-year-old Murraya exotica plants, indicating that the plants can transport SMA nanoparticles to the stem after exposure to 55 mg/L SMA nanoparticles for one hour. Furthermore, the accumulation of SMA nanoparticles in Murraya exotica plants is linearly related to the exposure concentration, suggesting that plant absorption of plastic particles may be a passive process [41]. The maximum size of micro (nano) plastics that plants can absorb needs to be clarified in the future.

The water potential gradient generated by plant transpiration is the driving force for the migration of micro (nano) plastics in the plant vascular system. Li J et al. [42] reported that micro-sized (2 μm) and sub-micro-sized (200 nm) plastic particles were detected in the xylem sap and leaves of wheat and lettuce, indicating that micro (nano) plastics are transferred from the roots to the shoots through the vascular system driven by transpiration flow. In a hydroponic study of wheat, PS nanoparticles (100 nm) were observed in the root and tender shoot xylem of wheat plants after 21

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days of exposure, further confirming that the vascular system is an important pathway for the upward transfer of micro (nano) plastics [13].

3.3. The Pathway of Micro (Nano) plastics Absorption through Leaf Surface

The diversity and persistence of micro (nano) plastics in the atmosphere make them ubiquitous [49,50]. Due to atmospheric deposition, micro (nano) plastics are likely to reach and attach to the above-ground parts of plants, especially leaves. Research has shown that microplastics account for 28% of the total substances attached to leaves. The stomatal pathway is considered the only possible route for nanoparticles to enter leaves. Using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analysis, Lian et al. [51] proved that PS nanoparticles (93.6 nm) can be absorbed by lettuce leaves through stomata and then transported downward to the roots. Sun H et al. [16] used fluorescently labeled PS nanoparticles (22-24 nm) with different surface charges. They observed not only the aggregation of NPs on the leaf surface but also confirmed that they entered the vascular system of corn leaves through the stomatal pathway and were transported to the roots through the phloem. Moreover, the absorption of these PS nanoparticles by leaves and their subsequent downward transport are closely related to their surface charge and aggregation ability. Compared to PS-COOH with negative charges, PS-NH2 with positive charges can form larger aggregates, which may be due to the electrostatic attraction of the negatively charged cell wall [16]. Stronger aggregation ability may hinder the absorption of micro (nano) plastics by leaves and their subsequent transport to the roots.

In summary, leaf absorption and leaf-root transport can represent another important pathway for micro (nano) plastics to enter plants. Given that this phenomenon occurs widely in nature, further research is needed to investigate the absorption of micro (nano) plastics by plant leaves, the transfer pathways after absorption and their impact on plants.

4. Microplastics' Impact on Terrestrial Plant Growth and Its Mechanism

4.1. Factors Affecting Plant Absorption and Transportation of Micro (Nano) Plastics

4.1.1. Particle Diameter

The size of nanoparticles (NPs) can influence the absorption and transportation of micro-(nano) plastics by terrestrial plants. Due to the porous structure of biological cell walls with diameters between 3.5 nm and 5.2 nm, particles larger than this value may be directly blocked by the cell membrane from entering plant tissues [52]. However, plants can absorb larger foreign particles through endocytosis. For example, tobacco BY-2 cells rapidly absorb PS particles as small as 40 nm [14]. Additionally, PS microspheres (25-130 nm) have been detected in the cytoplasm, vacuoles and nuclei of onion root cells [38]. The diameter of the plasmodesmata in the channels between plant cells is approximately 50-60 nm [53]. Therefore, NPs (e.g., 60 nm) can penetrate the root hair zone and enter the root xylem through the apoplastic pathway. For larger NPs (hundreds of nanometers to several micrometers), the symplastic pathway may be the main transportation route in plant roots [40]. Although the Casparian strip may limit root cell transportation, plastics could also enter the root system through the Casparian strip [37]. It gets harder for micro-(nano) plastics to penetrate the root system with the increase in the particle diameter. For example, wheat or lettuce roots have difficulty absorbing 5 μm-sized NPs [12].

4.1.2. Micro-Particle Electrostatic Properties

The absorption of micro (nano) plastics by plants is also influenced by surface electrostatic charges. Some positively charged nano-plastics could be easily absorbed by plant roots. This is because plant roots typically carry negative charges, which attract positively charged nano-plastics, promoting the absorption process. However, Sun H et al. [16] found that Arabidopsis thaliana preferentially absorbs negatively charged PS nanoparticles (PS-COOH) rather than positively charged analogues (PS-NH2). They attributed this to the growth medium (MS vitamin solution) and root biomass, which favor the aggregation of positively charged polymers, mainly oxalate salts. Additionally, the negatively charged mucilage and exudates at the plant root surface have been shown to interfere with the absorption of positively charged polyvinyl chloride (PVC) particles [43]. Early research has mainly focused on the type of PS polymers, morphologies and environmental conditions, which may also influence the entry and persistence of micro (nano) plastics in terrestrial plants. Therefore, further research is needed to understand the impact of surface electrostatic charges on plant absorption and transport of micro (nano) plastics.

4.1.3. Transpiration Rate

Evapotranspiration is considered a major driver of micro (nano) plastic absorption and transfer into terrestrial plants. Therefore, variables that influence evapotranspiration rates may also affect the transfer of micro (nano) plastics into terrestrial plants. Li L et al. [12] found that by altering the relative humidity and temperature in a controlled climate chamber, plants with higher transpiration rates absorbed more plastic micro-particles. Once micro-plastic fragments enter the root, they can be transported to the above-ground parts of the plant through the xylem along with the transpiration stream. Thus, higher transpiration rates may become a stronger driving force for plant absorption and transport of micro (nano) plastic fragments. For example, when rice roots were exposed to mercuric chloride as a water vapor inhibitor, the formation of PS particles in root cells was significantly reduced [35]. The reduced absorption of PS particles by the rice root system was due to the inhibition of water vapor in root cells, leading to decreased transpiration flux.

Endogenous factors such as plant genotype, developmental stage and hormone conditions as well as environmental factors such as light, CO2 and water supply could influence plant absorption and transport of micro (nano) plastics [47].

4.2. Microplastics Effect on Plant Growth

Micro (nano) plastics can affect plant growth, although in some cases, microplastics can promote the growth of plants. However, significant attention has been paid to the inhibitory effects of microplastics on plants. The main mechanisms of these effects can be summarized into the following four aspects.

1. Micro (nano) plastics are attached to the root surface or accumulated in the root vascular system, thereby affecting plant water and nutrient uptake [39,54,55]. In hydroponic maize, Urbina et al. [39] observed that PE-treated plants had a 71.8% reduction in transpiration and a 16.9% reduction in nitrogen content in tender shoots. They attributed this finding to the impaired root development caused by micro (nano) plastic exposure.
2. Micro (nano) plastics exposure can induce oxidative damage in plants and disrupt metabolic processes [40,56,57]. One of the most common effects of micro (nano) plastics on terrestrial plants is oxidative stress, characterized by increased reactive oxygen species (ROS) production and elevated antioxidant enzyme activity. Zhou et al. [35] reported that exposure to high concentrations (≥50 mg/L) of PS Micro (nano) plastics led to significant increases in the activities of catalase (CAT), peroxidase (POD) and superoxide dismutase (SOD) in rice roots. In PS suspension-cultured lettuce roots and leaves, the activities of CAT, SOD and glutathione peroxidase (GSH-POD) as well as the contents of superoxide anion (O2-), hydrogen peroxide (H2O2) and malondialdehyde (MDA) all increased dramatically [58]. Similar reports of Micro (nano) plastic-induced oxidative stress have been found in Arabidopsis [40], mung beans [45], onions [38,59], rice [57], and celery [56]. Plants under biotic or abiotic stress could undergo biochemical changes such as increased ROS production, which can damage cellular lipids, proteins and nucleic acids [60]. As a protective mechanism, plants can secrete more antioxidant enzymes to eliminate excessive ROS [60,61]. The observed increases in ROS content and/or antioxidant enzyme activity in plants exposed to micro (nano) plastics suggest that micro (nano) plastic particles are a new type of abiotic stress that can cause oxidative damage to terrestrial plants. Some studies have shown that terrestrial plants in contact with micro (nano) plastics can affect chlorophyll synthesis in young leaves or leaf blades, indicating that micro (nano) plastics

may inhibit photosynthesis [36,54,62]. Chloroplasts are significant ROS generators in cells under stress [61,64]. The decrease in chlorophyll production in plants, exposed to micro (nano) plastics may be due to excessive ROS accumulation in chloroplasts.

3. Micro (nano) plastics can alter soil properties and microbial communities, thereby affecting plant root uptake of soil water and nutrients [65,66]. The absorption and accumulation of mineral elements by cucumbers are also influenced by PS exposure, which may be due to changes in physiological or biochemical metabolic processes involving mineral elements as enzyme activators or electron carriers [36,37]. As the accumulation of plastics in soil increases, the water utilization efficiency of maize exhibits a dose-dependent decrease, which is also a reason for the diminished root growth [67].

4. The attached toxic additives/pollutants on micro (nano) plastics can have higher toxicity effects on plants [8,63,68–70]. Micro (nano) plastics have a large surface area, making them a carrier and concentrator of various harmful substances, including hydrophobic organic pollutants [71], heavy metals [72], antibiotic-resistant genes [65,73] and pathogenic microorganisms [74]. The chemical load on plastic microbeads may be due to the presence of toxic additives/pollutants during the manufacturing process such as phthalates, heavy metals and polybrominated diphenyl ethers [8]. The presence of micro (nano) plastics can alter the plant toxicity of co-existing pollutants. In a hydroponic study on wheat, Lian Wu Zeb et al. [13] found that the addition of PS particles alleviated the negative effects of cadmium (Cd) on plant dry biomass, photosynthetic rate and chlorophyll content. Similarly, Dong et al. [54] observed that the inhibitory effect of arsenic (As) on rice growth and photosynthesis was reduced in the presence of low concentrations (0.04-0.1 g/L) of micro (nano) plastics. The adsorption of metals by micro (nano) plastics and the attachment of micro (nano) plastics to the root surface are considered two possible reasons for the alleviation of plant heavy metal toxicity [54,75]. However, higher doses of micro (nano) plastics (>0.2 g/L) can produce synergistic plant toxicity with co-existing pollutants, which may be attributed to the mechanical damage or physical blockage of plant roots caused by micro (nano) plastics [54,58,62]. The enhancement of cadmium toxicity to corn plants by PS and biodegradable micro (nano) plastics was significantly higher than that of PE, indicating that the specific impact of micro (nano) plastics on plant toxicity of related pollutants depends on the polymer type [63].

5. Summary and Future Research Directions

Plastic pollution is a globally recognized issue, ranking second only to climate change as a major ecological and environmental threat. Recent research has highlighted the ubiquitous presence of these polymers in the environment and their impact on human health. This review has delved into the sources of micro (nano) plastics in soil, their entry pathways into plants and impact mechanisms as well as the potential risks they pose to plants. The aim is to provide a reference framework for future research directions while prioritizing the following areas:

1. The influence factors of plant uptake micro (nano) plastics are root characteristics (volume, density, surface area), wood characteristics (volume, surface area), transpiration, growth rate, water and lipid composition, membrane potential, and vacuolar pH. However, current research often focuses on a single indicator to study the impact of these conditions on micro (nano) plastics uptake and thus, lacks a comprehensive approach that considers multiple factors. Therefore, it is necessary to simultaneously consider these conditions to assess the comprehensive impact of plant uptake of micro (nano) plastics and develop more accurate and systematic evaluation methods.

2. The adsorption capacity of plastics can affect the adsorption of pollutants, influencing soil microbial communities and plant growth. Due to their small size, micro (nano) plastics can directly penetrate plant tissues. However, the process of their absorption from soil and subsequent accumulation in plant tissues is still not well understood. Future research should focus on exploring the behavior of micro (nano) plastics in soil and their migration mechanisms within plant tissues as well as their impact on plant growth. They should develop new detection technologies to monitor their impact on ecosystems, thereby assessing and managing their potential environmental risks.

3. Micro (nano) plastics can also serve as vectors for pathogens, potentially carrying them into host organisms and causing infection. Future research should investigate the comprehensive impact of micro (nano) plastics and plant pathogens on terrestrial plants, which is crucial for understanding the potential impact of plastic pollution on ecosystems and agriculture.

4. Most experiments on plant uptake of micro (nano) plastics are short-term indoor trials with micro (nano) plastic concentrations far exceeding environmental background values. These indoor experiments may not fully simulate the behavior and impact of micro (nano) plastics in real-world environments. Therefore, more field-based research is needed to validate indoor experimental results, providing more valuable scientific evidence for environmental protection policies.

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