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Review

Recent Advances on Multilevel Effects of Micro(Nano)Plastics and Coexisting Pollutants on Terrestrial Soil-Plants System

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Abstract: Microplastics and nanoplastics (MPs/NPs) are posing emerging potential threats to global ecosystems and human health. Recently, the individual effects of MPs/NPs and combined effects of MPs/NPs-coexisting pollutants on soil–terrestrial plant systems have attracted increasing attention. Based on the latest research progress, this review firstly summarized the sources of MPs/NPs and the interaction between MPs/NPs and coexisting pollutants in soil environment, and then systematically induced their multilevel impacts on soil properties and terrestrial plants. Soil and agroecosystem are major long-term sinks of primary and secondary MPs/NPs, with extensive sources. MPs/NPs exhibit universal adsorption capacities and can further serve as the vectors for varied heavy metal, organic and biological contaminants. Generally, MPs/NPs and the combination with coexisting contaminants may affect soil physical, chemical and microbiological properties, soil structure and functions, while the specific impacts and degree depend on MP/NP characteristics including polymer type, size, shape, concentration and degradability. Increasing evidence confirmed the uptake and translocation of MPs/NPs in terrestrial plants and proved their influence on growth performance, metabolism and physiological toxicity, as well as cytotoxicity and genotoxicity. The specific effects vary as a function of MP/NPs properties, plant species and environmental conditions. The joint effects of MPs/NPs and coexisting pollutants are complex, and synergistic, antagonism and neutralization effects have been reported at different circumstances. Further comprehensive and in-depth studies are urgently needed to fulfill the current knowledge gaps, especially the deficiency in the inherent mechanisms.

Keywords: micro(nano)plastics; coexisting pollutants; soil; terrestrial plants; multilevel effects

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1. Introduction

Microplastics (MPs) are emerging pollutants and are gaining worldwide concern due to their ubiquity detection and environmental risks [1]. Nanoplastics (NPs), plastic particles smaller than 100 nm or 1000 nm, tend to be separately distinguished from MPs with respect to their smaller size, unique characteristics, as well as their different environmental fate and behaviors [2,3]. Research studies on MPs/NPs and coexisting pollution have become the frontier hotspots in marine science, environmental science, pedology and botany [4–7].

Soil and agroecosystem are major long-term sink of MPs/NPs with extensive sources [8,9]. MPs/NPs can have adverse effects on agroecosystems via multiple pathways [10–12]. MPs/NPs and the combination with coexisting contaminants can not only influence soil properties, structure and function [13–15], but also can directly and indirectly affect the growth performance and physiological/biochemical process of soil biology, and even trigger physiological toxicity and genotoxicity [16–18].

Plants are basic living parts of terrestrial ecosystems, and a good understanding of the transport and accumulation of MPs/NPs in soil–plant systems is vital for the accurate prediction of their threats to the food chain and human health. Recently, impact and ecotoxicity of MPs/NPs on terrestrial plants are gaining increasing interest and become one of the most important research directions. A growing body of literature has reported that kinds of grain crops, vegetables, fruits, as well as a model plant (*Arabidopsis thaliana* L.) showed varying degrees of response to MP/NP exposure, depending on plant species, MPs/NPs properties and specific experimental conditions [12,16,19–22]. However overall, the relevant research is still in its infancy. It is hard to unify conclusions about their effects on soil-terrestrial plants, and the involved mechanisms are especially far from being understood. It is thus necessary and imperative to track the research direction, summarize and digest the latest research progress for promoting the understanding of MPs/NPs' threat, and create the foundation of future proposals. To date, several excellent reviews have been published, concentrating on the source, occurrence, fate and ecological risks of MPs/NPs pollution in soil and the terrestrial environment [23–25]. Nevertheless, comprehensive reviews aimed at the effects of MPs/NPs, especially the combined effects of MPs/NPs and coexisting contaminants on soil–terrestrial plants systems, are still insufficient [12,16,17,26–28].

This work aims to provide a critical review on the effects of MPs/NPs and coexisting pollutants on soil–plant systems based on the current knowledge. It firstly outlines the sources of MPs/NPs and the interaction between MPs/NPs and other coexisting contaminants in the soil environment. The influence of MPs/NPs on soil physical, chemical and microbiological properties is then summarized. Furthermore, the uptake and translocation of MPs/NPs in terrestrial plants and the effects of individual MPs/NPs and the combination of MPs/NPs and other contaminants on plants' growth performance, metabolism and physiological toxicity, cytotoxicity and genotoxicity are discussed in detail. Knowledge gaps and future perspective are proposed at the end.

2. MPs/NPs Pollution in Soil

2.1. Sources of MPs/NPs

MPs/NPs can be generally categorized into primary and secondary MPs/NPs. Primary MPs/NPs are produced by industrial manufacturing activities such as microbeads and the microsphere, while secondary MPs/NPs are derived from the breaking and decomposition of large plastic debris and fragments [1,29]. As shown in Figure 1, in soil and agroecosystems, primary MPs/NPs mainly come from sewage sludge, fertilizer application and wastewater irrigation, while secondary MPs/NPs mostly originate from plastic mulch films and greenhouse plastic material residues [30–33]. In addition, the improper disposal of municipal garbage and littering, atmospheric deposition and rainfall are other major origins [34,35]. Overall, detected MPs/NPs are composed of varied non-degradable and biodegradable plastic polymers, have a variety of shapes including regular spheres and beads, and irregular pellets, granules, films, fibers, foams and fragments with numerous colors, and the particle sizes range from a nanometer to a large schistose [23,36,37]. Notably, MPs/NPs are suffering a progressive aging process in natural environments, which will constantly change their physiochemical characteristics and thus alter their environmental behaviors [38–40].

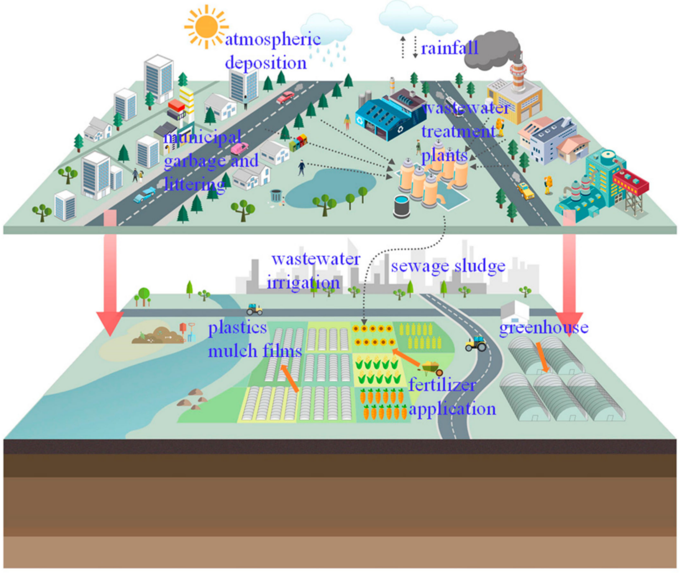

Figure 1. Sources of MPs/NPs in soil and agroecosystems.

2.2. Interaction between MPs/NPs and Coexisting Pollutants

Combined contamination of various pollutants in soil and agroecosystem is unavoidable. The combined soil pollution with heavy metals and organic contaminants has been widely reported [41–43], while coexisting emerging contaminants and traditional pollutants in soil and sediments are gaining increasing research attention [44,45]. Recently, the knowledge of the interaction between MPs/NPs and coexisting pollutants in soil systems has been regularly updated [46–48]. The large specific surface area and high hydrophobicity of MPs/NPs contribute to their adsorption and accumulation capability for coexisting heavy metal, organic and biological pollutants [49–52]. On the other hand, MPs/NPs may be regarded as a pollution source by releasing diversified additives to soil, especially during the disposal and aging process [38,53–55]. Furthermore, MPs/NPs can serve as the vectors for coexisting contaminants and subsequently alter their transport and fate behaviors [15,48,56]. MPs/NPs can influence the mobility of coexisting organic pollutants via multiple mechanisms [57–60]. For example, Li et al. [46] found that the presence of polyamide MPs promoted the transport of oxytetracycline in loamy soil, and attributed it to the inhibited adsorption into soil as well as the alteration in soil pore structure and dispersion coefficient. Meanwhile, MPs/NPs have been proved to be effective in influencing not only the mobility but also the speciation of heavy metals [61–63]. For example, polystyrene NPs improved the mobility of Pb and Cd in saturated porous media, and the aged NPs were more capable as heavy metal carriers compared to the pristine NPs [61]. Abbasi et al. [63] also indicated the vector role of plastic particles for heavy metals in the rhizosphere zone. Furthermore, MPs were proved to promote the transformation of Cu, Cr and Ni speciation and thus change their bioavailability [62]. Furthermore, increasing evidence has demonstrated that MPs/NPs could be as a carrier for antibiotic resistance genes (ARGs) and potential pathogens in natural soil, facility vegetable soil, and manured soil systems [64–67]. Ineluctably, the interactions between MPs/NPs and coexisting pollutants may cause potential combined effects on the aboveground plants.

3. Effect of MPs/NPs on Soil Properties

Soil properties are critical factors determining the fate and transport behaviors, bioavailability and toxicity of contaminants in the soil–plant system [68,69]. Currently, MPs/NPs are known to affect soil properties and structures via multiple pathways, and they can further affect the plants' performance indirectly [17,20]. The specific effect and degree depend on their physical and chemical characteristics including polymer types, size, shape, concentration and degradability [13,14,70,71] (Figure 2). Based on current research, this paper summarizes the effect of MPs/NPs on the physical, chemical and microbiological properties of a soil system.

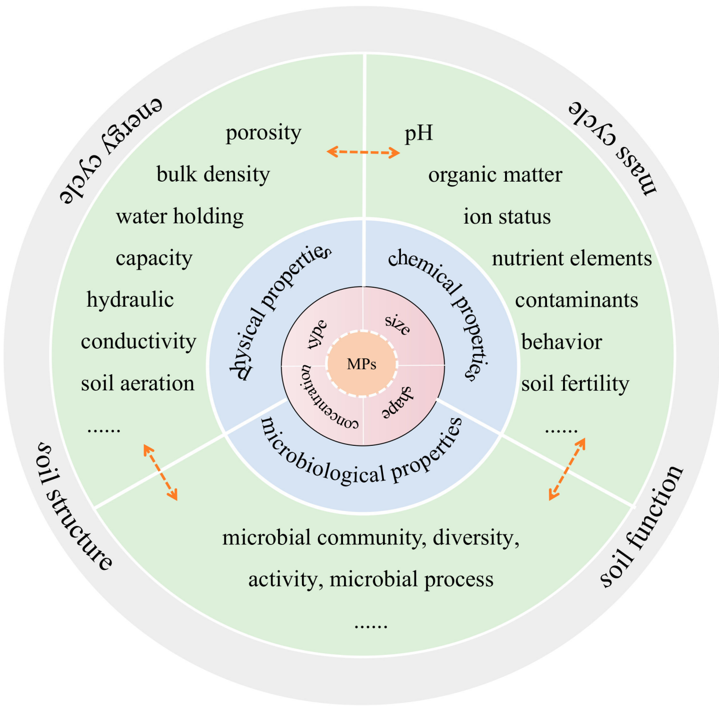

Figure 2. Effect of MPs/NPs on soil properties.

3.1. Physical Properties

MPs/NPs can be conceptually regarded as physical contaminants, the porosity and pore structure tend to be directly changed after their occupation [72,73]. For example, Zhang et al. [74] found that polyester microfibers reduced the volume of <30 μm pores whereas increased the volume of >30 μm pores in soil. Machado et al. [13] indicated that MPs' shape is an important factor influencing pore space, water stable aggregates and soil structure due to the distant manner incorporated into the soil matrix; polyester fibers exhibited more apparent impact. The alteration in soil structure would consequently affect hydraulic parameters such as soil aeration, permeability and water flow status. MPs/NPs would increase, decrease or have no clear trend on the water holding capacity and soil bulk density, and specifically depend on MPs/NPs' type, shape and concentration as well as soil texture [13,73–75]. MPs/NPs are proved to affect the saturated hydraulic conductivity and evaporation dynamics, while the changes related to their types and dosage [72,75]. Notably, the effects of MPs/NPs on soil physical properties were correlated with the experiment scale. For example, increased soil aggregation due to polyester microfibers treatment was observed in pot experiment but not in field experiment [74]. Overall, limited information on the effects of MPs/NPs on soil physical properties is available, especially in the field scale with different soil textures, and the governing mechanisms are still unclear.

3.2. Chemical Properties

Plants' performance is very sensitive to soil chemical properties such as pH, organic matter content and nutrient availability [76]. pH is a major factor determining the environmental behaviors and bioavailability of both nutrients and contaminants [77,78]. Few studies reported that MPs/NPs would increase, decrease or cause ignorable effects on soil pH, depending on MPs/NPs' properties and exposure time [10,79–81]. Furthermore, MPs/NPs would change the amount and transformation of dissolved organic matter [82–84], influence the form and availability of nutrient elements, and even affect their circulation process by changing the activity of microorganisms and enzymes [85–87]. Moreover, MPs/NPs are proved be able to affect the production of plant root exudates, which may drive soil-pant feedbacks [21,88,89]. Transformation, mobility, bioavailability and toxicity of varied pollutants are also of great concern for soil chemical properties. As introduced above, MPs/NPs can not only release additives but also adsorb coexisting pollutants, and may further change their migration, transformation and bioavailability. The interaction may thus produce a combined ecotoxicological effect on soil–plant systems [15,90,91].

3.3. Microbiological Properties

Soil microbiological properties are critical for the whole soil and agroecosystem [92]. MPs/NPs pollution can influence microbial community, activity and microbial process directly and indirectly [93–95]. Firstly, individual MPs/NPs and their combination with coexisting pollutants would pose a direct toxicity to microbial composition and activity. Addition of polyvinyl chloride (PVC) and polyethylene (PE) to acid soil and sediment decreased the richness and diversity of the bacterial communities, and the effects were related to MPs' type and concentration [93,96]. Meanwhile, Wang et al. [90] indicated that PE exposure induced a hormesis effect on soil bacterial and the fungal numbers. On the other hand, MPs/NPs would indirectly alter microbiological features by changing soil physiochemical properties such as pH, conductivity, ratio of C/N and soil aeration [97–99]. Apart from their type, dosage, shape and properties, MPs/NPs' degradability also plays an important role in their concrete effect [79,100]. In addition to the impact of MPs/NPs on bacteria communities, MPs/NPs also have potential influence on the activity and abundance of arbuscular mycorrhizal fungal [97,101,102]. For instance, Lehmann et al. [103] found polyester fiber exposure increased arbuscular mycorrhizal fungi colonization. Wang et al. [102] found biodegradable polylactic acid (PLA) produced a stronger impact on arbuscular mycorrhizal fungal diversity and community than PE. Overall, there are still huge research gaps in the effect of MPs/NPs on soil microbiological properties.

Above all, MPs/NPs play a critical role in soil physical, chemical and microbiological properties (Figure 2). Notably, there are close connection between varied physical, chemical and biological parameters. The comprehensive interaction and alteration will eventually change soil structure and function, as well as soil mass and energy cycle, which may drive significant feedback to the whole plant–soil system [104,105]. However, previous investigations are scarce and systematic exploration is urgently required in further studies.

4. Effect of MPs/NPs on Plants

Recently, increasing attention has been paid to the research on the impact of MPs/NPs on terrestrial plants. Most of the studies have been carried out through pot experiments while some are conducted by field experiment [74,106,107]. The research objects mainly include model plant *A. thaliana*, grain crops (e.g., wheat, soybean, rice and maize), vegetable crops (e.g., lettuce, cucumber, onion and cress) and fruits (e.g., strawberry) [19,21,27,108]. Diversified non-biodegradable and biodegradable MPs/NPs with particle sizes ranging from nanometers to micrometers and even larger debris residues were applied, and a wide range of MP/NP concentrations were considered [22,107,109] (Table 1). As shown in Figure 3, MPs/NPs could be accumulated and translocated in plants through down-top and top-down pathways. MPs/NPs and the combination with coexisting pollutants could influence plants' growth performance and various physiology process, including photosynthesis, oxidative stress, nutrient uptake and cycle, and even cause cytotoxicity and genotoxicity.

Table 1. Effects of MPs/NPs on terrestrial plants.

Plant Species	MPs/NPs			Main Effects	References
	Type	Size	Concentration		
Cress (*Lepidium sativum* L.)	green fluorescent plastic	50, 500, 4800 nm	10^3–10^7 particles mL^{-1}	MPs exposure resulted in short-term and transient effects on germination rate and root growth	[110]
Cucurbita pepo L.	PE, PVC, PP, PET	40–50 µm	0.02%, 0.10%, 0.20%	MPs impaired root and shoot growth and influenced leaf size, chlorophyll content, photosynthetic efficiency and micro- and macro elemental profile; PVC was the most toxic and PE was less toxic	[111]
Vicia faba L.	PS	100 nm, 5 µm	10, 50, 100 mg L^{-1}	5 µm PS decreased biomass and CAT enzyme activity, increased SOD and POD enzyme activity; 100 nm PS (100 mg L^{-1}) decreased growth; 100 nm PS induced higher genotoxic and oxidative damage than 5 µm PS; 100 nm PS accumulated in root	[112]
Allium cepa L.	PES fibers	1.70 µm	0.4% (w:w)	PES fibers increased aboveground biomass	[103]
Lettuce (*Lactuca sativa* L.)	PVC	a: 100 nm–18 µm b: 18–150 µm	0.5%, 1%, 2%	0.5% a and 1% a increased the total length, surface area, volume, and diameter of roots; 1% a increased the SOD activity; PVC-a was related to photosynthesis, PVC-b was correlated with root morphology	[109]
Soybean (*Glycine max* (L.) Merr.)	PE, (Bio) mulch film	2 × 2 cm,1 × 1 cm 0.5 × 0.5 cm debris	0%, 0.1%, 0.5%, 1%	PE reduced plant height, culm diameter, leaf area and root/shoot ratio while Bio debris showed adverse effects on germination viability and root biomass	[107]
Cucumber (*Cucumis sativus* L.)	PS	100, 300, 500, 700 nm	50 mg L^{-1}	300 nm PS significantly increased root activity MDA and root proline content; PS significantly increased soluble protein in cucumber fruits; decreased the levels of Mg, Ca and Fe, and the effect depends on PS particle sizes	[113]

Table 1. *Cont.*

Plant Species	MPs/NPs			Main Effects	References
	Type	Size	Concentration		
Wheat (*Triticum aestivum* L.)	PS	100 nm	0.01–10 mg L^{-1}	enhanced wheat seedling growth, growth parameters and chlorophyll content, reduced the shoot to root biomass ratio and micronutrients contents, altered metabolic profiles	[114]
Lettuces (*L. sativa* L.)	PS	93.6 nm	0, 0.1, 1 mg L^{-1}	decreased the dry weight, height and leaf area, plant pigment content and nutritional quality, produced oxidative stress	[115]
Spring onion (*Allium fistulosum* L.)	PA beads: 15–20 µm PES fibers: 5000 µm length, 8 µm diameter PEHD, PP: 2–3 mm spheres PS, PET: 2–3 mm cylinders		PES: 0.2% Others: 2.0%	have different effects on plant performance including plant biomass, tissue elemental composition, root traits, and soil microbial activities depending on particle types	[20]
Common bean (*Phaseolus vulgaris* L.)	LDPE, Bio	250–500 µm, 500–1000 µm	0.5%, 1.0%, 1.5%, 2.0%, 2.5% (*w*/*w*)	effect of LDPE-MP depends on its concentration: ≥1.0% showed significantly higher specific root nodules, 2.5% showed significantly higher specific root length,1.0% caused higher leaf area and 0.5% caused lower leaf relative chlorophyll content Bio-MP treatments showed significantly higher specific root length and specific root nodules, lower shoot, root and fruit biomass	[116]
Garden cress (*L. sativum* L.)	PP, PE, PVC, PE+PVC	<0.125 mm	184 mg kg^{-1}	caused negative effect on biometric traits, depending on MPs' types and exposure time	[22]
Wheat (*T. aestivum* L.)	MacroLDPE: 6.92 × 6.10 mm MacroBio: 6.98 mm × 6.01 mm Micro: 50 µm–1 mm		1% (*w*/*w*)	affected above-ground and below-ground parts, biodegradable plastic residues showed stronger negative effects than PE	[117]
Flowering Chinese cabbage (*Brassica rapa* L.)	PS	70 nm, 5 µm	10 mg kg^{-1}	PS influenced the plant photosynthesis and growth depending on MP size	[118]

Table 1. *Cont.*

Plant Species	MPs/NPs			Main Effects	References
	Type	Size	Concentration		
Tomato (*Lycopersicon esculentum* L.)	PS, PP, PE	52–368 μm	10, 100, 500, 1000 mg L^{-1}	MPs (≤500 mg L^{-1}) had inhibitory effects on seed germination, and then alleviated under 1000 mg L^{-1} conditions; PE was more toxic to seedling growth than PS and PP	[119]
Arabidopsis (*Arabidopsis thaliana* L.) Wheat (*T. aestivum* L.)	PS	40 nm, 1 μm	8.3 × 1011 n mL^{-1} 5.3 × 107 n mL^{-1}	PS accumulated at Arabidopsis and wheat root cap cells	[120]
Maize (*Zea mays* L. var. Jubilee)	PE microbeads	3 μm	0.0125 mg L^{-1} 100 mg L^{-1}	PE bioaccumulation in the rhizosphere decreased transpiration, nitrogen content, and growth; PE may accumulate in the rhizosphere, impairing water and nutrient uptake, and eventually reaching root eaters	[121]
Arabidopsis (*A. thaliana* L.)	PS-SO_3H: 55 nm PS-NH_2: 71 nm		0.3,1.0 g kg^{-1} 10, 50, 100 μg mL^{-1}	decreased above-ground biomass, seedling growth, root elongation Arabidopsis can take up and transport PS	[21]
Rice (*Oryza sativa* L.)	BM and PE mulch film	50 μm	1% (*w*/*w*)	reduced the height and dry weight of rice plant, induced oxidative stress; caused negative effects on the growth of rice plants via nitrogen metabolism and photosynthesis	[122]
Wheat (*T. aestivum* L.)	PVC, PE	125 μm	1%, 5%, 10%, 20%	MPs had a negative, dose-dependent impact on plant growth affecting both above- and below-ground productivity	[123]

PE: polyethylene; PVC: polyvinyl chloride; PP: polypropylene; PET: polyethylene terephthalate; PS: polystyrene; PES: polyester; (Bio) mulch film: biodegradable plastic mulch film; PA: polyamide; PEHD: polyethylene high density; LDPE: low-density polyethylene; Bio: biodegradable plastic; PS-SO_3H: sulfonic-acid-modified polystyrene nanoparticles; PS-NH_2: amino-modified polystyrene nanoparticles; BM: PBAT based biodegradable mulch film; PBAT: butyleneadipate-co-terephthalate; CAT: catalase; SOD: superoxide dismutase; POD: peroxidase; MDA: malondialdehyde.

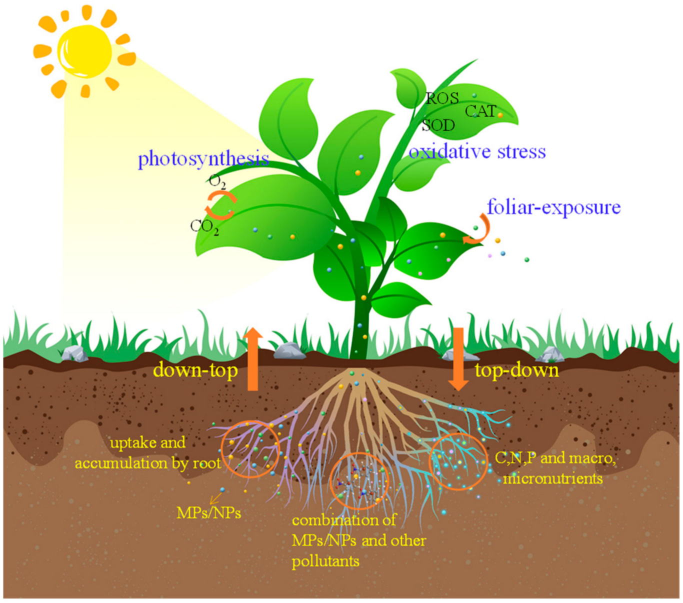

Figure 3. Physiological response of terrestrial plants to MPs/NPs.

4.1. Effect of MPs/NPs on Plant Growth Performance

The effect of MPs/NPs on seed germination and growth of terrestrial plants has been widely investigated. MPs/NPs species are certainly decisive, polyester (PES) and polystyrene (PS) caused significant increases in root biomass of spring onion than high density polyethylene (PEHD), polyethylene terephthalate (PET), and polypropylene (PP) [20]. MPs/NPs' size also plays important role in their interference: smaller size particles tend to induce greater toxicity than the larger ones [124]. MPs/NPs' dosage and type are also important: Yang et al. [97] studied polylactic acid (PLA) and high-density polyethylene (HDPE) on maize growth, found that maize growth was promoted by HDPE and low-dose PLA, while maize shoot and root biomass were decreased by high-dose PLA. In addition, seedling growth and root elongation response of *A. thaliana* depended on MPs' surface charge [21], which may affect the uptake and accumulation status.

Plant height, stem diameter, leaf area, plant fresh weight and dry weight are important biometric parameters indicating plants' growth performance. Previous studies showed that MPs/NPs exhibited positive, negative or negligible impact on terrestrial plants under certain environmental conditions, depending on their type, size, dosage and plant species [20,22,123]. For example, polyvinyl chloride (PVC) was more toxic than polypropylene (PP) and polyethylene (PE) for garden cress [22]. Onion bulbs' dry biomass was decreased by polyamide (PA) treatment but nearly doubled by polyester (PES) exposure; the water content increased 2-fold after PA exposure but decreased after PES, polyethylene terephthalate (PET) and PP treatment [20]. Degradability is also proved as an important factor, and the concrete effect is related to the released additives and the degradation byproducts of MPs/NPs [119]. Qi et al. [117] reported that biodegradable mulch film residues showed a stronger negative effect on wheat than non-degradable PE. Conversely, Li et al. [107] found PE induced a greater negative effect on soybean height, culm diameter and leaf area than biodegradable plastic mulch film debris. Apart from root treatment, foliar PS exposure significantly decreased the dry weight, height and leaf area of lettuce [115]. Of note, MPs/NPs' effect also depends on their exposure time. Nevertheless, the present studies were mainly conducted in the short-term; longer periods or life cycle reflections through field experiments should be addressed in further investigations.

4.2. Effect of MPs/NPs on Plants Physiology

4.2.1. Photosynthesis

There is a great progress in physiological response of terrestrial plants to MPs/NPs' exposure (Figure 3). Photosynthesis disturbance is regarded as one of the main mechanisms contributing to the effect of MPs/NPs on terrestrial plants [118,125]. Alterations in photosynthetic pigments (chlorophyll a and b, carotenoids) and chlorophyll fluorescence are important indicators of the response to MPs/NPs treatment. MPs/NPs exposure are proven to decrease [115,122,126] and increase [22,114] chlorophyll content of varied plants. Meanwhile, few studies did not observe the significant influence of MPs/NPs on plant chlorophyll content [117,127]. The discrepancy varied as a function of plant species, MPs/NPs characteristics as well as the experimental conditions. Reduction in light energy absorption capacity, dissipation, capture and electron transfer, the accumulation of ROS, as well as the proteases related to chlorophyll molecules synthesis are regarded as the possible mechanisms [27,109,115,128]. Furthermore, MPs also exhibited certain influences on other photosynthesis parameters such as the photosynthetic rate, stomatal conductance, intercellular carbon dioxide concentration and transpiration rate chlorophyll fluorescence and photosynthetic electron transport rate [114,128]. Overall, systematic research on the response of terrestrial plants to MPs/NPs is still urgently needed and the governing mechanisms still require further clarification.

4.2.2. Oxidative Stress

Oxidative stress is significant for plants' adaptability to the environment. It is also a critical biometric index to evaluate the phytotoxicity of MPs/NPs [129]. It has been confirmed that the contribution of MPs/NPs is mainly related to the polymer type, size, surface charge and dosage. For instance, Jiang et al. [112] found that 100 nm PS induced higher oxidative damage than 5 μm PS for *Vicia faba* L. Similarly, smaller PVC particles (100 nm~18 μm) at 1% more significantly increased superoxide dismutase activity of lettuce leaves than the larger particles (18–150 μm), whereas neither of them produced an obvious effect on malondialdehyde (MDA) content [109]. Gao et al. [128] found that the antioxidant levels of lettuce generally increased with the increasing PE content, and the damage was greater in the roots than in the leaves. Degradability of MPs/NPs was also considerable: the degree of oxidative stress on rice shoot and root caused by PE mulch film MPs was higher than poly(butyleneadipate-co-terephthalate)-based biodegradable mulch film MPs [122]. In addition to root treatment, foliar exposure of PS also triggered oxidative stress of lettuce, shown in the significantly increased electrolyte leakage rate and decreased total antioxidant capacity [115]. Moreover, the effect of MPs/NPs is related to their combination with other pollutants; for example, Zong et al. [127] found that the presence of PS remarkably reduced the heavy metal accumulation in wheat and reduced the accumulation of reactive oxygen species (ROS) of wheat, while single PS did not cause significant effect on the ROS.

4.2.3. Nutrient Uptake and Cycle

MPs/NPs can also influence the content and cycle of carbon (C), nitrogen (N), phosphorus (P), as well as various macro and micronutrients in soil–plant systems [83,130,131]. Zang et al. [123] found that MPs significantly affected key pools and fluxes within C cycle, specifically influenced assimilated ^{14}C allocation and CO_2 emission. PS MPs accumulation in *V. faba* root could probably influence the nutrients and water transport by blocking the cell connections or cell wall pores [112]. Urbina et al. [121] indicated that PE particles may accumulate in maize rhizosphere and then impair the nutrient uptake, and the bioaccumulation of PE obviously decreased N content of hydroponic maize. Furthermore, isotope analysis suggested that ~30% C in maize rhizosphere was originated from PE. PS exposure remarkably increased C and N content of wheat, while it reduced absorption and accumulation of micronutrients (Fe, Mn, Cu, Zn) [114]. Obvious micronutrient (Mn, Cu) and essential amino acid reduction in lettuce was induced by foliar-applied PS exposure, and leaf C:N ratio significantly decreased with increasing PS concentration [115]. The presence of MPs is also proved to stimulate phosphatase activity, influence P conversion, increase and decrease P content and availability in soil [83,85,96]. However, overall, there are still huge knowledge gaps on the effect of MPs/NPs on the nutrient uptake and cycling in soil–terrestrial plant systems; further investigations are in urgent demand for comprehensive understanding.

4.3. The Uptake and Translocation of MPs/NPs by Plants

Clarifying the mechanisms governing the uptake and translocation process of MPs/NPs in plants is necessary for the accurate evaluation of their potential risks to the food chain and human health [132]. Recently, great developments have been achieved successively (Table 2). MP particles would probably produce physical blockage of the pores in seed capsule and adsorb on root hair [110]. Taylor et al. [120] reported that nano and micro-PS would accumulate at root cap cells of Arabidopsis and wheat, but did not find the particles in internal root structure. Recently, evidence on the uptake, translocation and accumulation of MPs/NPs into plants' root and body has been identified through confocal laser scanning microscope and scanning electron microscope characterization. Li et al. [19] provided the visual evidence suggesting the uptake of submicrometre- (0.2 μm) and micrometre-sized (2 μm) PS and polymethylmethacrylate (PMMA) particles to wheat and lettuce via crack-entry mode, and transpirational pull was regarded as the main driving force for their movement. Notably, the absorption and translocation process of MPs/NPs by plants highly depend on their physiochemical properties, mainly including particle size and surface characterization [19,21,133,134]. For example, Sun et al. [21] provided direct evidence that both negatively charged (PS-SO_3H) and positively charged MPs (PS-NH_2) could accumulate in *A. thaliana*, while PS-NH_2 showed low levels due to the larger size increased aggregation. Zhu et al. [133] confirmed that smaller-size PS are easier to be taken up by wheat root tissues, and the -NH_2 group on PS surface are helpful for the translocation in wheat tissular/cellular compared to -COOH group.

Currently, down-top and top-down pathways were both reported. For example, Lian et al. [114] found PS (100 nm) were taken up by wheat roots and subsequently down-top transported to leaves via xylem pathways. Liu et al. [134] authenticated the uptake of nano (80 nm) and micro (1 μm) PS by rice root and the subsequent translocation to their aerial parts. Adversely, PS (93.6 nm) could probably be absorbed through lettuce leaves' stoma and then transported downwards to roots [115]. Sun et al. [135] also found that PS could accumulate in maize leaves and transfer to vasculature and then move down to the roots through the vascular bundle. Overall, compared to the research on plants performance under MPs/NPs stimulation, information on detailed uptake and transport processes of varied MPs/NPs in plants is still insufficient, and governing mechanisms need further exploration for the accurate assessment of their potential risks.

Table 2. The uptake and translocation of MPs/NPs by terrestrial plants.

Plant Species	MPs/NPs			Uptake and Translocation	Reference
	Type	Size	Concentration		
Cress (*Lepidium sativum* L.)	green fluorescent plastic	50, 500, 4800 nm	10^3–10^7 particles mL^{-1}	PS caused physical blockage of the pores in the seed capsule	[110]
Mung bean (*Vigna radiata* (L.) Wilczek)	carboxylate-modified polystyrene	28 nm	0, 10, 100 mg kg^{-1} dry soil	NPs were detected in leaves	[136]
Carrots (*Daucus carota* var. sativa Hoffm.)	PS	0.1–1 μm 5 μm	10 and 20 mg L^{-1}	1 μm PS can enter carrot roots and accumulate in the intercellular layer but are unable to enter the cells; 0.2 μm PS can migrate to the leaves.	[137]
Vicia faba L.	PS	50 nm	0.01, 0.1 1g L^{-1}	PS could internalize into different external compartments	[138]

Table 2. *Cont.*

Plant Species	MPs/NPs			Uptake and Translocation	Reference
	Type	Size	Concentration		
Italian lettuce (*Lactuca sativa* L.), radish (*Raphanus satives L.*), wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.)	PS	100 nm, 5 μm	1, 10 mg L^{-1}	fluorescent nano-PS in the roots or germs of the tested crops suggests that nanoplastics can be taken up by plants even at a very early growth stage	[139]
V. faba L.	PS	5 mm, 100 nm	10, 50, 100 mg L^{-1}	100 nm PS accumulated in root and most probably blocked cell connections or cell wall pores	[112]
Pea (*Pisum sativum* L.)	PS	20 nm	20, 40 mg kg^{-1}	MP translocation in cell wall of vascular bundle	[140]
Wheat (*T. aestivum* L.) Lettuce (*L. sativa* L.)	PS, PMMA	0.2 μm, 2 μm	50 mg L^{-1}	PS and PMMA penetrated the stele via the crack-entry mode, transpirational pull was the main driving force	[19]
Wheat (*T. aestivum* L.)	PS	0.2 μm	0.5 mg g^{-1}	uptake of PS into the root outer cortical exosome space and vascular tissue, transported to the aboveground stem vascular bundle and leaf vascular tissue	[141]
Cucumber (*Cucumis sativus* L.)	PS	100, 300, 500, 700 nm	50 mg L^{-1}	PS initially accumulated in root system, and then was transported to the aboveground parts. PS was distributed in the leaves, flowers, and fruits, through the stems	[113]
Wheat (*T. aestivum* L.)	PS	100 nm	0.01–10 mg L^{-1}	PS was taken up by wheat roots and subsequently down-top transported to leaves via xylem pathways	[114]
Lettuce (*L. sativa* L.)	PS	93.6 nm	0,0.1,1 mg L^{-1}	possible absorption of PSNPs through leaves stoma and the translocation downwards to plant roots.	[115]
Rice (*Oryza sativa* L.)	PS	80 nm, 1 μm	40 mg L^{-1}	both nano- and micro-sized PS could be absorbed by rice roots and translocated to aerial parts, apoplastic transport may be the main pathway	[134]
Wheat (*T. aestivum* L.) Lettuce (*L. sativa* L.)	PS, PS-Eu	200 nm	0–5000 μg L^{-1}	MPs accumulated mainly in the roots, while transport to the shoots was limited	[142]
Arabidopsis (*A. thaliana* L.)	PS-SO_3HPS-NH_2	55 nm 71 nm	0.3, 1.0 g kg^{-1} 10, 50, 100 μg mL^{-1}	PS can accumulate in *Arabidopsis thaliana*, depending on surface charge	[21]
Maize (*Z. mays* L.)	PS-COOH PS-NH_2	22.0 ± 1.5 nm 24.0 ± 2.2 nm	0, 10, 50, 100, 200, 400, 500 ng/spot	PS could accumulate on maize leaves PS in the leaves would transfer to the vasculature mainly through stomatal opening and move down to the roots through vascular bundle	[135]
Wheat (*T. aestivum* L.)	PS-NH_2PS-NH_2PS-COOHPS-COOH	38.3 nm 191.2 nm 34.4 nm 101.2 nm	20 mg L^{-1}	PS could be taken up by wheat root and cells, and the translocation is dependent on particle size and surface characterization	[133]

PS: polystyrene; PMMA: polymethylmethacrylate; PS-Eu: Polystyrene (PS) particles doped with the europium chelate Eu–β-diketonate; PS-SO_3H: sulfonic-acid-modified polystyrene nanoparticles; PS-NH_2: amino-modified polystyrene nanoparticles; PS-COOH: carboxy-modified polystyrene nanoparticles.

4.4. Cytotoxicity and Genotoxicity

Compared with the knowledge on plant growth performance response to MPs/NPs exposure, information on the inherent mechanisms, especially at the molecular level, is still scarce and vague, although it is necessary for the accurate prediction of the persistent risks of MPs/NPs for the whole ecosystems. MPs/NPs are proved to cause the cytotoxicity and genotoxicity on terrestrial plants [112,143,144]. Jiang et al. [112] studied the genotoxicity of PS in *V. faba* root tips using mitotic index and micronucleus test, PS treatment increased cytotoxicity while nano-sized (100 nm) particles induced higher genotoxic than micro-sized (5 μm) particles. Nano-sized PS (50 nm) exhibited cytotoxicity and genotoxicity to *Allium cepa* L. root meristems even at low dosage (0.01 g L^{-1}) [138]. Maity et al. [145] also studied the cytotoxic and genotoxicity of PS to *A. cepa*, apart from the decreased mitotic index indicating the cytotoxic, PS down regulated the expression of encoding gene cdc2. Recently, the metabolomic and transcriptomic analysis further advanced the understanding of the effect of MPs/NPs on crop plants [146–148]. Zhou et al. [149] indicated that PS would alter gene transcription of rice at elevated concentrations in hydroponically cultured conditions. Wu et al. [106] firstly investigated the molecular mechanisms of the response of rice to PS exposure via metabolomic and transcriptomic analyses through field study; different rice cultivars exhibited different performances in metabolite accumulation and gene regulation/interaction. These results confirmed the effects of MPs/NPs on terrestrial plants at the molecular level, and the insufficient studies and huge knowledge gaps urgently call for further exploration.

5. Combined Effect of MPs/NPs and Coexisting Pollutants

It is necessary to lay more stress on the combined effect of MPs/NPs and coexisting pollutions on terrestrial plants for the comprehensive assessment of their ecological risks [137,150,151]. The latest relative studies were listed in Table 3, and synergistic effect, antagonism effect and neutralization effect were all reported depending on varied species of plants, MPs/NPs and combined pollutants.

Table 3. Combined effects of MPs/NPs and coexisting pollutants on terrestrial plants.

Plant species	MPs/NPs			Coexisting Pollutants	Combined Effect	References
	Types	Size	Concentration			
Carrots (*Daucus carota* var. sativa Hoffm.)	PS	0.1–1 μm 5 μm	10, 20 mg L^{-1}	As: 1, 2, 4 mg L^{-1}	As increases the negatively charged area of PS and causes a greater amount of microplastics to enter the carrot; As exacerbates the effect of PS on carrots	[137]
Rice (*Oryza sativa* L.)	PS, PTFE	10 μm	0.04, 0.1, 0.2 g L^{-1}	As: 1.6, 3.2, 4.0 mg L^{-1}	PS and PTFE reduced As uptake, and absorbed As decreased with the increasing concentration of microparticles	[152]
Red lettuce (*Lactuca sativa* L. cv. *Red Sails*)	PS	100–1000 nm, >10,000 nm	0.25, 0.50, 1.00 g L^{-1}	DBP: 5 mg L^{-1}	PS reduced the DBP bioavailability, caused decrease in photosynthetic, and serious oxidative damage, and reduced the quality of DBP-treated-red lettuce	[153]
Rapeseed (*Brassia campestris* L.)	PMMA	<100 nm	0, 0.05, 0.5, 5 g L^{-1}	As: 0, 10, 20, 40, 60 mg L^{-1}	caused synergistic effect on rapeseed germination, promoted As uptake in rapeseed under high concentration	[124]
Lettuce (*L. sativa* L. var. *ramosa Hort*)	PE	~23 μm	0.25, 0.50, 1.00 mg mL^{-1}	DBP: 5 mg L^{-1}	MP can inhibit growth, hinder photosynthesis and interfere with the antioxidant defense system in lettuce; exposure to MP exacerbated the damage to lettuce by DBP	[128]
Lettuce (*L. sativa* L. var. *ramosa Hort)*	PS	100~1000 nm, >10,000 nm	0.25, 0.50, 1.00 mg mL^{-1}	DBP: 5 mg L^{-1}	PS reduced lettuce biomass and DBP enrichment in roots and leaves, exacerbated oxidative stress and subcellular damage	[151]
Rape (*B. napus* L.)	PE	293 μm	0.001%, 0.01%, 0.1%	Cu: 50, 100 mg kg^{-1} Pb: 25, 50 mg kg^{-1}	PE increased accumulation and toxicity of heavy metals to rape	[154]
Wheat (*Triticum aestivum* L.)	PS	87 nm	0, 10 mg L^{-1}	Cd: 0, 20 μM	PS partially alleviated Cd-induced toxicity in wheat	[155]

Table 3. *Cont.*

Plant species	MPs/NPs			Coexisting Pollutants	Combined Effect	References
	Types	Size	Concentration			
Strawberry (*Fragaria* × *ananassa* Duch.)	HDPE	20 µm thick, 2~5 mm	0.2 g kg^{-1}	Cd: 3 mg L^{-1}	HDPE increased Cd bioavailability and accumulation in roots, decreased the total number of fruits and total biomass per plant	[108]
Maize (*Zea mays* L. var. *Wannuoyihao*)	HDPE, PS	100–154 µm	0.1%, 1%, 10%	Cd: 5 mg kg^{-1}	high-dose of HDPE (10%) amplified Cd phytotoxicity PS negatively affected maize growth and phytoxicity further increased in the presence of Cd	[156]
Maize (*Z. mays* L. var. *Wannuoyihao*)	PE, PLA	100~154 µm	0.1%, 1%, 10%	Cd: 0, 5 mg kg^{-1}	PLA caused higher Cd bioavailability than PE, but no alterations in plant Cd content. MPs and Cd drove shifts in maize performance and root symbiosis	[102]
Lettuce (*L. sativa* L.)	PE	<0.5 mm	0.1%, 1%, 10%	Cd: 0.49, 1.75, 4.38 mg kg^{-1}	co-exposure of PE increased the toxicity, uptake, accumulation and bioavailability of Cd	[90]
Soybean (*Glycine max* (L.) *Merr.*)	PS	100 nm, 1, 10, 100 µm	10 mg kg^{-1}	phenanthrene, 1 mg kg^{-1}	PS decreased the uptake of Phe in soybean roots and leaves, but caused combined toxicity to soybean plants	[157]
Lettuce (*L.sativa* L.)	PS	100 µm, 100 nm	100, 1000 mg kg^{-1}	Cu: 82.00 mg kg^{-1} Zn: 174.84 mg kg^{-1} Pb: 42.08 mg kg^{-1} Cd: 0.20 mg kg^{-1}	MPs increased the uptake of heavy metals in lettuce	[150]
Maize (*Z. mays* L. var. *Wannuoyihao*)	HDPE, PLA	100–154 µm	0.1%, 1%, 10%	ZnO: 30 ± 10 nm 0, 50, 500 mg kg^{-1} soil	HDPE and PLA increased Zn accumulation in roots, decreased Zn translocation to aerial parts	[97]
Brassica chinensis L.	PS	75 µm	0.5%, 1.0%, 1.5%, 2.0%	Cd: 10 mg kg^{-1}	PS-Cd co-pollution produced higher phytotoxicity than PS alone, PS mitigated the phytotoxicity of Cd alone and reduce Cd uptake.	[158]
Wheat (*T. aestivum* L.)	PS	0.5 µm	100 mg L^{-1}	Cu: 2 mg L^{-1}, Cd: 1 mg L^{-1}	mitigated Cu and Cd bioavailability and toxicity	[127]

PS: polystyrene; PTFE: polytetrafluoroethylene; PMMA: polymethylmethacrylate; PE: polyethylene; HDPE: high–density polyethylene; PLA: polylactic acid; DBP: dibutyl phthal; Phe: phenanthrene.

5.1. Combined Effect of MPs/NPs and Heavy Metals

Heavy metal pollution in soil is one of the important environmental problems in the world. The availability and toxicity of heavy metals to plants is one of the hot spots in environmental science and botany [159,160]. Considering the interaction between MPs/NPs and heavy metals, there is an urgent need to evaluate the combined effect of MPs/NPs and heavy metals on terrestrial plants [71,161]. It has been proved that co-exposure of MPs/NPs would produce positive or negative effect on the uptake, accumulation and bioavailability of heavy metals by plants. The synergistic effect has been widely reported in recent studies. For example, Jia et al. [154] found that PE increased the uptake, accumulation and toxicity of Cu and Pb in rape, aggregated the oxidative damage and deteriorated rape quality. Treatment of polymethyl methacrylate (PMMA) and As (V) also caused synergistic interaction on rapeseed germination; the addition of PMMA enhanced As accumulation in rape sprouts under high As concentration conditions [124]. Meanwhile, the co-existence of As conversely enhanced the PS amount in carrots, and thus exacerbated the effect of PS on carrots [137]. Wang et al. [90] found that PE increased Cd bioavailability and accumulation in lettuce, and mainly attributed the synergistic effect to the alteration in soil microenvironment, including the decreased soil pH, cation exchange capacity (CEC) and increased soil dissolved organic carbon (DOC). Furthermore, MPs/NPs could also produce an antagonism effect when combined with heavy metals. Lian et al. [155] found PS alleviated Cd toxicity to wheat due to the reduction in Cd accumulation, acceleration in radicals' formation and enhancement of carbohydrate and amino acid metabolisms. Zong et al. [127] investigated the combined effect of PS and Cu/Cd on wheat seedlings by hydroponic experiment, and PS relieved Cu/Cd accumulation in wheat seedling, enhanced photosynthesis and reduced ROS accumulation occurred after PS-heavy metals co-treatment.

MPs aging would change their combined effect with heavy metals. Gu et al. [162] found aged polyvinyl chloride (PVC) promoted the bioaccumulation of Cd in wheat and thus produced greater synergistic effect with Cd on wheat root growth.

5.2. Combined Effect of MPs/NPs and Organic Pollutants

Apart from heavy metals, few studies have focused on the combined effect of MPs/NPs and various organic pollutants. Dibutyl phthalate (DBP) is one of the important additives in plastic polymer, and is easily released into the environment during the use and disposal process [163,164]. The combined effect of DBP, PE and PS of different sizes and concentrations on lettuce and red lettuce has been recently reported [128,151,153]. Gao et al. [128] found that PE exposure exacerbated the phytotoxicity and damage of DBP to lettuce; the growth parameters and photosynthesis were all inhibited under MP-DBP treatment conditions compared to the DBP-only treatment. Dong et al. [153] studied the co-exposure of PS and DBP on red lettuce in hydroponic systems: PS reduced DBP bioavailability, induced more negative effect on photosynthetic and oxidative stress, and finally reduced red lettuce quality. Traditional organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and total petroleum hydrocarbons (TPH) are of great significance for the ecosystem in soil environment. However, the consideration of their combined effect with MPs/NPs on terrestrial plant is serious limited. Xu et al. [157] studied the effect of combined effect of PS MPs and phenanthrene (Phe) on soybean seedlings: PS inhibited Phe uptake in soybean root and leaves but aroused combined toxicity, and the toxicity due to the coexistence of micron-size PS was higher than that of nano-size. Meanwhile, there are also great knowledge gaps regarding the interaction between MPs/NPs and engineering nanoparticles. Yang et al. [97] examined the combined effect of MPs and engineering nanoparticles (ZnO) on maize growth, and found that the presence of non-degradable high-density polyethylene and biodegradable polylactic acid increased Zn content in maize roots, and decreased Zn transport to aerial parts. Overall, the investigations on the combined effect of MPs/NPs and the coexisting pollutants for terrestrial plants are severely insufficient, and represent key knowledge gaps that need to move forward.

6. Conclusions and Future Perspectives

Valuable progress has been achieved based on current research. Individual NPs/MPs and their combination with coexisting pollutants have been proved to interfere with the seed germination and growth performance, cause varied physiology, as well as the cytotoxicity and genotoxicity in kinds of terrestrial plants, directly and indirectly. However, the relative studies are still in their infancy, and the involved mechanisms need further clarification. Further research should focus on the following points:

(1) Effect of MPs/NPs on terrestrial plants varies as a function of plant species and plastic properties. MPs/NPs used in previous studies are mostly primary commercial microsphere; more realistic pristine and aged secondary MPs/NPs deserve further attention. As for plants, the species firstly need to be expanded for a comprehensive understanding. Moreover, current research mainly focuses on individual plants; investigations about the effects of MPs/NPs on community-level plants should be moved forward.

(2) Present studies are mostly carried out by short-term laboratory pot experiments cultured with nutrient solution, sand or soil matrix. Considering the growth cycles of plants and the integrity of soil–plant systems, long-term and field-scale investigations in realistic circumstances are necessary for the accurate prediction of the ecological threat of MPs/NPs for terrestrial systems.

(3) Combined effects of MPs/NPs and coexisting pollutants are currently focused on limited heavy metals and organic pollutants. More efforts regarding the combined influence of various MPs/NPs and inorganic, organic and biological contaminants on terrestrial plants need to be carried out in the future.

(4) There are still knowledge gaps regarding the mechanisms governing the uptake, accumulation, physiological response, cytotoxicity and genotoxicity of plants to MPs/NPs' exposure; interdisciplinary advantages should be addressed for in-depth clarification from different levels and multiple pathways.

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References

1. Thompson, R.C.; Olsen, Y.; Mitche, R.P.; Davis, A.; Rowland, S.J.; John, A.W.G.; McGonigle, D.; Russell, A.E. Lost at Sea: Where is all the plastic? *Science* **2004**, *304*, 838. [CrossRef] [PubMed]
2. Alimi, O.S.; Budarz, J.F.; Hernandez, L.M.; Tufenkji, N. Microplastics and nanoplastics in aquatic environments: Aggregation, deposition, and enhanced contaminant transport. *Environ. Sci. Technol.* **2018**, *52*, 1704–1724. [CrossRef] [PubMed]
3. Gigault, J.; El Hadri, H.; Nguyen, B.; Grassl, B.; Rowenczyk, L.; Tufenkji, N.; Feng, S.; Wiesner, M. Nanoplastics are neither microplastics nor engineered nanoparticles. *Nat. Nanotechnol.* **2021**, *16*, 501–507. [CrossRef] [PubMed]
4. Law, K.L.; Thompson, R.C. Microplastics in the seas. *Science* **2014**, *345*, 144–145. [CrossRef] [PubMed]
5. Rillig, M.C.; Lehmann, A. Microplastic in terrestrial ecosystems. *Science* **2020**, *368*, 1430–1431. [CrossRef]
6. Stubbins, A.; Law, K.L.; Munoz, S.E.; Bianchi, T.S.; Zhu, L. Plastics in the Earth system. *Science* **2021**, *373*, 51–55. [CrossRef]

7. Nizzetto, L.; Langaas, S.; Futter, M. Do microplastics spill on to farm soils? *Nature* **2016**, *537*, 488. [CrossRef]
8. Nizzetto, L.; Futter, M.; Langaas, S. Are agricultural soils dumps for microplastics of urban origin? *Environ. Sci. Technol.* **2016**, *50*, 10777–10779. [CrossRef]
9. Rillig, M.C. Microplastic in terrestrial ecosystems and the soil? *Environ. Sci. Technol.* **2012**, *46*, 6453–6454. [CrossRef]
10. Boots, B.; Russell, C.W.; Green, D.S. Effects of microplastics in soil ecosystems: Above and below ground. *Environ. Sci. Technol.* **2019**, *53*, 11496–11506. [CrossRef]
11. Machado, A.A.D.; Kloas, W.; Zarfl, C.; Hempel, S.; Rillig, M.C. Microplastics as an emerging threat to terrestrial ecosystems. *Glob. Chang. Biol.* **2018**, *24*, 1405–1416. [CrossRef]
12. Huang, D.; Wang, X.; Yin, L.; Chen, S.; Tao, J.; Zhou, W.; Chen, H.; Zhang, G.; Xiao, R. Research progress of microplastics in soil-plant system: Ecological effects and potential risks. *Sci. Total Environ.* **2022**, *812*, 151487. [CrossRef]
13. Machado, A.A.D.; Lau, C.W.; Till, J.; Kloas, W.; Lehmann, A.; Becker, R.; Rillig, M.C. Impacts of microplastics on the soil biophysical environment. *Environ. Sci. Technol.* **2018**, *52*, 9656–9665. [CrossRef]
14. Wang, F.Y.; Wang, Q.L.; Adams, C.A.; Sun, Y.H.; Zhang, S.W. Effects of microplastics on soil properties: Current knowledge and future perspectives. *J. Hazard. Mater.* **2022**, *424*, 127531. [CrossRef]
15. Xiang, Y.; Jiang, L.; Zhou, Y.; Luo, Z.; Zhi, D.; Yang, J.; Lam, S.S. Microplastics and environmental pollutants: Key interaction and toxicology in aquatic and soil environments. *J. Hazard. Mater.* **2022**, *422*, 126843. [CrossRef]
16. Yu, Z.; Song, S.; Xu, X.; Ma, Q.; Lu, Y. Sources, migration, accumulation and influence of microplastics in terrestrial plant communities. *Environ. Exp. Bot.* **2021**, *192*, 104635. [CrossRef]
17. Chen, G.; Li, Y.; Liu, S.; Junaid, M.; Wang, J. Effects of micro(nano)plastics on higher plants and the rhizosphere environment. *Sci. Total Environ.* **2022**, *807*, 150841. [CrossRef]
18. Rillig, M.C.; Machado, A.A.D.; Lehmann, A.; Klumper, U. Evolutionary implications of microplastics for soil biota. *Environ. Chem.* **2019**, *16*, 3–7. [CrossRef]
19. Li, L.; Luo, Y.; Li, R.; Zhou, Q.; Peijnenburg, W.J.G.M.; Yin, N.; Yang, J.; Tu, C.; Zhang, Y. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. *Nat. Sustain.* **2020**, *3*, 929–937. [CrossRef]
20. Machado, A.A.D.; Lau, C.W.; Kloas, W.; Bergmann, J.; Bacheher, J.B.; Faltin, E.; Becker, R.; Gorlich, A.S.; Rillig, M.C. Microplastics can change soil properties and affect plant performance. *Environ. Sci. Technol.* **2019**, *53*, 6044–6052. [CrossRef]
21. Sun, X.D.; Yuan, X.Z.; Jia, Y.; Feng, L.J.; Zhu, F.P.; Dong, S.S.; Liu, J.; Kong, X.; Tian, H.; Duan, J.L.; et al. Differentially charged nanoplastics demonstrate distinct accumulation in *Arabidopsis thaliana*. *Nat. Nanotechnol.* **2020**, *15*, 755–760. [CrossRef] [PubMed]
22. Pignattelli, S.; Broccoli, A.; Renzi, M. Physiological responses of garden cress (*L. sativum*) to different types of microplastics. *Sci. Total Environ.* **2020**, *727*, 138609. [CrossRef] [PubMed]
23. Guo, J.; Huang, X.; Xiang, L.; Wang, Y.; Li, Y.; Li, H.; Cai, Q.; Mo, C.; Wong, M. Source, migration and toxicology of microplastics in soil. *Environ. Int.* **2020**, *137*, 105263. [CrossRef] [PubMed]
24. Wang, W.; Ge, J.; Yu, X.; Li, H. Environmental fate and impacts of microplastics in soil ecosystems: Progress and perspective. *Sci. Total Environ.* **2020**, *708*, 134841. [CrossRef] [PubMed]
25. Yang, L.; Zhang, Y.; Kang, S.; Wang, Z.; Wu, C. Microplastics in soil: A review on methods, occurrence, sources, and potential risk. *Sci. Total Environ.* **2021**, *780*, 146546. [CrossRef]
26. Ren, X.; Yin, S.; Wang, L.; Tang, J. Microplastics in plant-microbes-soil system: A review on recent studies. *Sci. Total Environ.* **2022**, *816*, 151523. [CrossRef]
27. Zhang, Z.; Cui, Q.; Li, C.; Zhu, X.; Zhao, S.; Duan, C.; Zhang, X.; Song, D.; Fang, L. A critical review of microplastics in the soil-plant system: Distribution, uptake, phytotoxicity and prevention. *J. Hazard. Mater.* **2022**, *424*, 127750. [CrossRef]
28. Wang, C.; Tang, J.; Yu, H.; Wang, Y.; Li, H.; Xu, S.; Li, G.; Zhou, Q. Microplastic pollution in the soil environment: Characteristics, influencing factors, and risks. *Sustainability* **2022**, *14*, 3405. [CrossRef]
29. Silva, A.B.; Bastos, A.S.; Justino, C.I.L.; da Costa, J.A.P.; Duarte, A.C.; Rocha-Santos, T.A.P. Microplastics in the environment: Challenges in analytical chemistry A review. *Anal. Chim. Acta.* **2018**, *1017*, 150–159. [CrossRef]
30. Gao, D.; Li, X.; Liu, H. Source, occurrence, migration and potential environmental risk of microplastics in sewage sludge and during sludge amendment to soil. *Sci. Total Environ.* **2020**, *742*, 140355. [CrossRef]
31. Kumar, M.; Xiong, X.; He, M.; Tsang, D.C.W.; Gupta, J.; Khan, E.; Harrad, S.; Hou, D.; Ok, Y.S.; Bolan, N.S. Microplastics as pollutants in agricultural soils. *Environ. Pollut.* **2020**, *265*, 114980. [CrossRef]
32. Qi, R.; Jones, D.L.; Li, Z.; Liu, Q.; Yan, C. Behavior of microplastics and plastic film residues in the soil environment: A critical review. *Sci. Total Environ.* **2020**, *703*, 134722. [CrossRef]
33. Serrano-Ruiz, H.; Martin-Closas, L.; Pelacho, A.M. Biodegradable plastic mulches: Impact on the agricultural biotic environment. *Sci. Total Environ.* **2021**, *750*, 141228. [CrossRef]
34. Roblin, B.; Ryan, M.; Vreugdenhil, A.; Aherne, J. Ambient Atmospheric deposition of anthropogenic microfibers and microplastics on the western periphery of Europe (Ireland). *Environ. Sci. Technol.* **2020**, *54*, 11100–11108. [CrossRef]
35. Wright, S.L.; Ulke, J.; Font, A.; Chan, K.L.A.; Kelly, F.J. Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environ. Int.* **2020**, *136*, 105411. [CrossRef]
36. Xu, B.; Liu, F.; Cryder, Z.; Huang, D.; Lu, Z.; He, Y.; Wang, H.; Lu, Z.; Brookes, P.C.; Tang, C.; et al. Microplastics in the soil environment: Occurrence, risks, interactions and fate—A review. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 2175–2222. [CrossRef]

37. Chia, R.W.; Lee, J.Y.; Kim, H.; Jang, J. Microplastic pollution in soil and groundwater: A review. *Environ. Chem. Lett.* **2021**, *19*, 4211–4224. [CrossRef]
38. Ren, J.; Wu, T.; Liu, C.; Cui, P.; Dang, F.; Yang, Q.; Wang, Y. UV-Irradiation facilitating pb release from recycled pvc microplastics. *Bull. Environ. Contam. Toxicol.* **2021**, *107*, 748–753. [CrossRef]
39. Liu, P.; Shi, Y.; Wu, X.; Wang, H.; Huang, H.; Guo, X.; Gao, S. Review of the artificially-accelerated aging technology and ecological risk of microplastics. *Sci. Total Environ.* **2021**, *768*, 144969. [CrossRef]
40. Zha, F.; Shang, M.; Ouyang, Z.; Guo, X. The aging behaviors and release of microplastics: A review. *Gondwana Res.* **2022**, *108*, 60–71. [CrossRef]
41. Wu, Y.; Song, Q.; Wu, J.; Zhou, J.; Zhou, L.; Wu, W. Field study on the soil bacterial associations to combined contamination with heavy metals and organic contaminants. *Sci. Total Environ.* **2021**, *778*, 146282. [CrossRef] [PubMed]
42. Liu, J.; He, X.X.; Lin, X.R.; Chen, W.C.; Zhou, Q.X.; Shu, W.S.; Huang, L.N. Ecological effects of combined pollution associated with e-waste recycling on the composition and diversity of soil microbial communities. *Environ. Sci. Technol.* **2015**, *49*, 6438–6447. [CrossRef] [PubMed]
43. Wang, X.; Teng, Y.; Wang, X.; Xu, Y.; Li, R.; Sun, Y.; Hu, W.; Zhao, L.; Ren, W.; Luo, Y. Effects of combined pollution of organic pollutants and heavy metals on biodiversity and soil multifunctionality in e-waste contaminated soil. *J. Hazard. Mater.* **2022**, *440*, 129727. [CrossRef] [PubMed]
44. Du, M.; Zheng, M.; Liu, A.; Wang, L.; Pan, X.; Liu, J.; Ran, X. Effects of emerging contaminants and heavy metals on variation in bacterial communities in estuarine sediments. *Sci. Total Environ.* **2022**, *832*, 155118. [CrossRef] [PubMed]
45. Zhou, L.; Li, S.; Li, F. Damage and elimination of soil and water antibiotic and heavy metal pollution caused by livestock husbandry. *Environ. Res.* **2022**, *215*, 114188. [CrossRef]
46. Li, J.; Guo, K.; Cao, Y.; Wang, S.; Song, Y.; Zhang, H. Enhance in mobility of oxytetracycline in a sandy loamy soil caused by the presence of microplastics. *Environ. Pollut.* **2021**, *269*, 116151. [CrossRef]
47. Sunta, U.; Prosenc, F.; Trebse, P.; Bulc, T.G.; Kralj, M.B. Adsorption of acetamiprid, chlorantraniliprole and flubendiamide on different type of microplastics present in alluvial soil. *Chemosphere* **2020**, *261*, 127762. [CrossRef]
48. Zhou, Y.; Liu, X.; Wang, J. Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. *Sci. Total Environ.* **2019**, *694*, 133798. [CrossRef]
49. Hu, B.; Li, Y.; Jiang, L.; Chen, X.; Wang, L.; An, S.; Zhang, F. Influence of microplastics occurrence on the adsorption of 17 beta-estradiol in soil. *J. Hazard. Mater.* **2020**, *400*, 123325. [CrossRef]
50. Khalid, N.; Aqeel, M.; Noman, A.; Khan, S.M.; Akhter, N. Interactions and effects of microplastics with heavy metals in aquatic and terrestrial environments. *Environ. Pollut.* **2021**, *290*, 118104. [CrossRef]
51. Wang, Y.; Wang, X.; Li, Y.; Li, J.; Liu, Y.; Xia, S.; Zhao, J. Effects of exposure of polyethylene microplastics to air, water and soil on their adsorption behaviors for copper and tetracycline. *Chem. Eng. J.* **2021**, *404*, 126412. [CrossRef]
52. Moresco, V.; Oliver, D.M.; Weidmann, M.; Matallana-Surget, S.; Quilliam, R.S. Survival of human enteric and respiratory viruses on plastics in soil, freshwater, and marine environments. *Environ. Res.* **2021**, *199*, 111367. [CrossRef]
53. Cheng, H.; Luo, H.; Hu, Y.; Tao, S. Release kinetics as a key linkage between the occurrence of flame retardants in microplastics and their risk to the environment and ecosystem: A critical review. *Water Res.* **2020**, *185*, 116253. [CrossRef]
54. Meng, J.; Xu, B.; Liu, F.; Li, W.; Sy, N.; Zhou, X.; Yan, B. Effects of chemical and natural ageing on the release of potentially toxic metal additives in commercial PVC microplastics. *Chemosphere* **2021**, *283*, 131274. [CrossRef]
55. Yan, Y.; Zhu, F.; Zhu, C.; Chen, Z.; Liu, S.; Wang, C.; Gu, C. Dibutyl phthalate release from polyvinyl chloride microplastics: Influence of plastic properties and environmental factors. *Water Res.* **2021**, *204*, 117597. [CrossRef]
56. Fajardo, C.; Martin, C.; Costa, G.; Sanchez-Fortun, S.; Rodriguez, C.; de Lucas Burneo, J.J.; Nande, M.; Mengs, G.; Martin, M. Assessing the role of polyethylene microplastics as a vector for organic pollutants in soil: Ecotoxicological and molecular approaches. *Chemosphere* **2022**, *288*, 132460. [CrossRef]
57. Abbasi, S.; Moore, F.; Keshavarzi, B. PET-microplastics as a vector for polycyclic aromatic hydrocarbons in a simulated plant rhizosphere zone. *Environ. Technol. Inno.* **2021**, *21*, 101370. [CrossRef]
58. Wang, T.; Wang, L.; Chen, Q.; Kalogerakis, N.; Ji, R.; Ma, Y. Interactions between microplastics and organic pollutants: Effects on toxicity, bioaccumulation, degradation, and transport. *Sci. Total Environ.* **2020**, *748*, 142427. [CrossRef]
59. Huffer, T.; Metzelder, F.; Sigmund, G.; Slawek, S.; Schmidt, T.C.; Hofmann, T. Polyethylene microplastics influence the transport of organic contaminants in soil. *Sci. Total Environ.* **2019**, *657*, 242–247. [CrossRef]
60. Ren, Z.; Gui, X.; Xu, X.; Zhao, L.; Qiu, H.; Cao, X. Microplastics in the soil-groundwater environment: Aging, migration, and co-transport of contaminants—A critical review. *J. Hazard. Mater.* **2021**, *419*, 126455. [CrossRef]
61. Xi, X.; Ding, D.; Zhou, H.; Baihetiyaer, B.; Sun, H.; Cai, Y.; Wang, N.; Yin, X. Interactions of pristine and aged nanoplastics with heavy metals: Enhanced adsorption and transport in saturated porous media. *J. Hazard. Mater.* **2022**, *437*, 129311. [CrossRef] [PubMed]
62. Yu, H.; Hou, J.; Dang, Q.; Cui, D.; Xi, B.; Tan, W. Decrease in bioavailability of soil heavy metals caused by the presence of microplastics varies across aggregate levels. *J. Hazard. Mater.* **2020**, *395*, 122690. [CrossRef] [PubMed]
63. Abbasi, S.; Moore, F.; Keshavarzi, B.; Hopke, P.K.; Naidu, R.; Rahman, M.M.; Oleszczuk, P.; Karimi, J. PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. *Sci. Total Environ.* **2020**, *744*, 140984. [CrossRef] [PubMed]

64. Ding, J.; Zhu, D.; Wang, Y.; Wang, H.; Liang, A.; Sun, H.; Chen, Q.; Lassen, S.B.; Lv, M.; Chen, L. Exposure to heavy metal and antibiotic enriches antibiotic resistant genes on the tire particles in soil. *Sci. Total Environ.* **2021**, *792*, 148417. [CrossRef] [PubMed]
65. Lu, X.; Lu, P.; Liu, X. Fate and abundance of antibiotic resistance genes on microplastics in facility vegetable soil. *Sci. Total Environ.* **2020**, *709*, 136276. [CrossRef]
66. Wang, Y.; Wang, X.; Li, Y.; Liu, Y.; Sun, Y.; Xia, S.; Zhao, J. Effects of coexistence of tetracycline, copper and microplastics on the fate of antibiotic resistance genes in manured soil. *Sci. Total Environ.* **2021**, *790*, 148087. [CrossRef]
67. Zhu, D.; Ma, J.; Li, G.; Rillig, M.C.; Zhu, Y. Soil plastispheres as hotpots of antibiotic resistance genes and potential pathogens. *ISME J.* **2021**, *16*, 521–532. [CrossRef]
68. Liu, Y.; Du, Q.; Wang, Q.; Yu, H.; Liu, J.; Tian, Y.; Chang, C.; Lei, J. Causal inference between bioavailability of heavy metals and environmental factors in a large-scale region. *Environ. Pollut.* **2017**, *226*, 370–378. [CrossRef]
69. Kumar, V.; Radziemska, M. Impact of physiochemical properties, microbes and biochar on bioavailability of toxic elements in the soil: A review. *Environ. Geochem. Health* **2021**, *44*, 3725–3742. [CrossRef]
70. Li, H.Z.; Zhu, D.; Lindhardt, J.H.; Lin, S.M.; Ke, X.; Cui, L. Long-term fertilization history alters effects of microplastics on soil properties, microbial communities, and functions in diverse farmland ecosystem. *Environ. Sci. Technol.* **2021**, *55*, 4658–4668. [CrossRef]
71. Feng, X.; Wang, Q.; Sun, Y.; Zhang, S.; Wang, F. Microplastics change soil properties, heavy metal availability and bacterial community in a Pb-Zn-contaminated soil. *J. Hazard. Mater.* **2022**, *424*, 127364. [CrossRef]
72. Jannesarahmadi, S.; Aminzadeh, M.; Raga, R.; Shokri, N. Effects of microplastics on evaporation dynamics in porous media. *Chemosphere* **2023**, *311*, 137023. [CrossRef]
73. Guo, Z.; Li, P.; Yang, X.; Wang, Z.; Lu, B.; Chen, W.; Wu, Y.; Li, G.; Zhao, Z.; Liu, G.; et al. Soil texture is an important factor determining how microplastics affect soil hydraulic characteristics. *Environ. Int.* **2022**, *165*, 107293. [CrossRef]
74. Zhang, G.S.; Zhang, F.X.; Li, X.T. Effects of polyester microfibers on soil physical properties: Perception from a field and a pot experiment. *Sci. Total Environ.* **2019**, *670*, 135931. [CrossRef]
75. Qi, Y.; Beriot, N.; Gort, G.; Lwanga, E.H.; Gooren, H.; Yang, X.; Geissen, V. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. *Environ. Pollut.* **2020**, *266*, 115097. [CrossRef]
76. Bezemer, T.M.; Lawson, C.S.; Hedlund, K.; Edwards, A.R.; Brook, A.J.; Igual, J.M.; Mortimer, S.R.; Van der Putten, W.H. Plant species and functional group effects on abiotic and microbial soil properties and plant-soil feedback responses in two grasslands. *J. Ecol.* **2006**, *94*, 893–904. [CrossRef]
77. Klaine, S.J.; Alvarez, P.J.; Batley, G.E.; Fernandes, T.F.; Handy, R.D.; Lyon, D.Y.; Mahendra, S.; McLaughlin, M.J.; Lead, J.R. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. *Environ. Toxicol. Chem.* **2008**, *27*, 1825–1851. [CrossRef]
78. Neina, D. The role of soil pH in plant nutrition and soil remediation. *Appl. Environ. Soil Sci.* **2019**, *2019*, 5794869. [CrossRef]
79. Qi, Y.; Ossowicki, A.; Yang, X.; Lwanga, E.H.; Dini-Andreote, F.; Geissen, V.; Garbeva, P. Effects of plastic mulch film residues on wheat rhizosphere and soil properties. *J. Hazard. Mater.* **2020**, *387*, 121711. [CrossRef]
80. Zhao, T.; Lozano, Y.M.; Rillig, M.C. Microplastics increase soil pH and decrease microbial activities as a function of microplastic shape, polymer type, and exposure time. *Front. Environ. Sci.* **2021**, *9*, 675803. [CrossRef]
81. Medynska-Juraszek, A.; Jadhav, B. Influence of different microplastic forms on pH and mobility of Cu^{2+} and Pb^{2+} in Soil. *Molecules* **2022**, *27*, 1744. [CrossRef] [PubMed]
82. Li, R.; Xi, B.; Tan, W.; Yuan, Y. Spatiotemporal heterogeneous effects of microplastics input on soil dissolved organic matter (DOM) under field conditions. *Sci. Total Environ.* **2022**, *847*, 157605. [CrossRef] [PubMed]
83. Liu, H.; Yang, X.; Liu, G.; Liang, C.; Xue, S.; Chen, H.; Ritsema, C.J.; Geissen, V. Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. *Chemosphere* **2017**, *185*, 907–917. [CrossRef] [PubMed]
84. Chen, M.; Zhao, X.; Wu, D.; Peng, L.; Fan, C.; Zhang, W.; Li, Q.; Ge, C. Addition of biodegradable microplastics alters the quantity and chemodiversity of dissolved organic matter in latosol. *Sci. Total Environ.* **2022**, *816*, 151960. [CrossRef] [PubMed]
85. Li, H.; Liu, L. Short-term effects of polyethene and polypropylene microplastics on soil phosphorus and nitrogen availability. *Chemosphere* **2022**, *291*, 132984. [CrossRef]
86. Meng, F.; Yang, X.; Riksen, M.; Geissen, V. Effect of different polymers of microplastics on soil organic carbon and nitrogen-A mesocosm experiment. *Environ. Res.* **2022**, *204*, 111938. [CrossRef]
87. Yan, Y.; Chen, Z.; Zhu, F.; Zhu, C.; Wang, C.; Gu, C. Effect of polyvinyl chloride microplastics on bacterial community and nutrient status in two agricultural soils. *Bull. Environ. Contam. Toxicol.* **2021**, *107*, 602–609. [CrossRef]
88. Shi, R.; Liu, W.; Lian, Y.; Zeb, A.; Wang, Q. Type-dependent effects of microplastics on tomato (*Lycopersicon esculentum* L.): Focus on root exudates and metabolic reprogramming. *Sci. Total Environ.* **2023**, *859*, 160025. [CrossRef]
89. Hu, L.; Robert, C.A.M.; Cadot, S.; Zhang, X.; Ye, M.; Li, B.; Manzo, D.; Chervet, N.; Steinger, T.; van der Heijden, M.G.A.; et al. Root exudate metabolites drive plant-soil feedbacks on growth and defense by shaping the rhizosphere microbiota. *Nat. Commun.* **2018**, *9*, 2738. [CrossRef]
90. Wang, F.; Wang, X.; Song, N. Polyethylene microplastics increase cadmium uptake in lettuce (*Lactuca sativa* L.) by altering the soil microenvironment. *Sci. Total Environ.* **2021**, *784*, 147133. [CrossRef]
91. Yu, H.; Zhang, Z.; Zhang, Y.; Fan, P.; Xi, B.; Tan, W. Metal type and aggregate microenvironment govern the response sequence of speciation transformation of different heavy metals to microplastics in soil. *Sci. Total Environ.* **2021**, *752*, 141956. [CrossRef]

92. Giacometti, C.; Demyan, M.S.; Cavani, L.; Marzadori, C.; Ciavatta, C.; Kandeler, E. Chemical and microbiological soil quality indicators and their potential to differentiate fertilization regimes in temperate agroecosystems. *Appl. Soil Ecol.* **2013**, *64*, 32–48. [CrossRef]
93. Li, W.; Wang, Z.; Li, W.; Li, Z. Impacts of microplastics addition on sediment environmental properties, enzymatic activities and bacterial diversity. *Chemosphere* **2022**, *307*, 135836. [CrossRef]
94. Zhang, H.; Quan, H.; Zhou, S.; Sun, L.; Lu, H. Enhanced performance and electron transfer of sulfur-mediated biological process under polyethylene terephthalate microplastics exposure. *Water Res.* **2022**, *223*, 119038. [CrossRef]
95. Sun, Y.; Duan, C.; Cao, N.; Li, X.; Li, X.; Chen, Y.; Huang, Y.; Wang, J. Effects of microplastics on soil microbiome: The impacts of polymer type, shape, and concentration. *Sci. Total Environ.* **2022**, *806*, 150516. [CrossRef]
96. Fei, Y.; Huang, S.; Zhang, H.; Tong, Y.; Wen, D.; Xia, X.; Wang, H.; Luo, Y.; Barcelo, D. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. *Sci. Total Environ.* **2020**, *707*, 135634. [CrossRef]
97. Yang, W.; Cheng, P.; Adams, C.A.; Zhang, S.; Sun, Y.; Yu, H.; Wang, F. Effects of microplastics on plant growth and arbuscular mycorrhizal fungal communities in a soil spiked with ZnO nanoparticles. *Soil Biol. Biochem.* **2021**, *155*, 108179. [CrossRef]
98. Han, L.; Chen, L.; Li, D.; Ji, Y.; Feng, Y.; Feng, Y.; Yang, Z. Influence of polyethylene terephthalate microplastic and biochar co-existence on paddy soil bacterial community structure and greenhouse gas emission. *Environ. Pollut.* **2022**, *292*, 118386. [CrossRef]
99. Seeley, M.E.; Song, B.; Passie, R.; Hale, R.C. Microplastics affect sedimentary microbial communities and nitrogen cycling. *Nat. Commun.* **2020**, *11*, 2372. [CrossRef]
100. Qin, M.; Chen, C.Y.; Song, B.; Shen, M.C.; Cao, W.C.; Yang, H.L.; Zeng, G.M.; Gong, J.L. A review of biodegradable plastics to biodegradable microplastics: Another ecological threat to soil environments? *J. Clean. Prod.* **2021**, *312*, 127816. [CrossRef]
101. Leifheit, E.F.; Lehmann, A.; Rillig, M.C. Potential effects of microplastic on arbuscular mycorrhizal fungi. *Front. Plant Sci.* **2021**, *12*, 626709. [CrossRef] [PubMed]
102. Wang, F.; Zhang, X.; Zhang, S.; Zhang, S.; Sun, Y. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. *Chemosphere* **2020**, *254*, 126791. [CrossRef] [PubMed]
103. Lehmann, A.; Leifheit, E.F.; Feng, L.; Bergmann, J.; Wulf, A.; Rillig, M.C. Microplastic fiber and drought effects on plants and soil are only slightly modified by arbuscular mycorrhizal fungi. *Soil Ecol. Lett.* **2020**, *4*, 32–44. [CrossRef]
104. Chen, L.; Han, L.; Feng, Y.; He, J.; Xing, B. Soil structures and immobilization of typical contaminants in soils in response to diverse microplastics. *J. Hazard. Mater.* **2022**, *438*, 129555. [CrossRef]
105. Machado, A.A.D.; Horton, A.A.; Davis, T.; Maaß, S. Microplastics and their effects on soil function as a life-supporting system. In *Microplastics in Terrestrial Environments*; Springer: Cham, Switzerland, 2020; pp. 199–222.
106. Wu, X.; Hou, H.; Liu, Y.; Yin, S.; Bian, S.; Liang, S.; Wan, C.; Yuan, S.; Xiao, K.; Liu, B.; et al. Microplastics affect rice (*Oryza sativa* L.) quality by interfering metabolite accumulation and energy expenditure pathways: A field study. *J. Hazard. Mater.* **2022**, *422*, 126834. [CrossRef]
107. Li, B.; Huang, S.; Wang, H.; Liu, M.; Xue, S.; Tang, D.; Cheng, W.; Fan, T.; Yang, X. Effects of plastic particles on germination and growth of soybean (*Glycine max*): A pot experiment under field condition. *Environ. Pollut.* **2021**, *272*, 116418. [CrossRef]
108. Pinto-Poblete, A.; Retamal-Salgado, J.; Lopez, M.D.; Zapata, N.; Sierra-Almeida, A.; Schoebitz, M. Combined effect of microplastics and Cd alters the enzymatic activity of soil and the productivity of strawberry plants. *Plants* **2022**, *11*, 536. [CrossRef]
109. Li, Z.X.; Li, Q.F.; Li, R.J.; Zhao, Y.F.; Geng, J.H.; Wang, G.Y. Physiological responses of lettuce (*Lactuca sativa* L.) to microplastic pollution. *Environ. Sci. Pollut. Res.* **2020**, *27*, 30306–30314. [CrossRef]
110. Bosker, T.; Bouwman, L.J.; Brun, N.R.; Behrens, P.; Vijver, M.G. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *Lepidium sativum*. *Chemosphere* **2019**, *226*, 774–781. [CrossRef]
111. Colzi, I.; Renna, L.; Bianchi, E.; Castellani, M.B.; Coppi, A.; Pignattelli, S.; Loppi, S.; Gonnelli, C. Impact of microplastics on growth, photosynthesis and essential elements in *Cucurbita pepo* L. *J. Hazard. Mater.* **2022**, *423*, 127238. [CrossRef]
112. Jiang, X.; Chen, H.; Liao, Y.; Ye, Z.; Li, M.; Klobucar, G. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. *Environ. Pollut.* **2019**, *250*, 831–838. [CrossRef]
113. Li, Z.; Li, Q.; Li, R.; Zhou, J.; Wang, G. The distribution and impact of polystyrene nanoplastics on cucumber plants. *Environ. Sci. Pollut. Res.* **2020**, *28*, 16042–16053. [CrossRef]
114. Lian, J.; Wu, J.; Xiong, H.; Zeb, A.; Yang, T.; Su, X.; Su, L.; Liu, W. Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (*Triticum aestivum* L.). *J. Hazard. Mater.* **2020**, *385*, 121620. [CrossRef]
115. Lian, J.; Liu, W.; Meng, L.; Wu, J.; Chao, L.; Zeb, A.; Sun, Y. Foliar-applied polystyrene nanoplastics (PSNPs) reduce the growth and nutritional quality of lettuce (*Lactuca sativa* L.). *Environ. Pollut.* **2021**, *280*, 116978. [CrossRef]
116. Meng, F.; Yang, X.; Riksen, M.; Xu, M.; Geissen, V. Response of common bean (*Phaseolus vulgaris* L.) growth to soil contaminated with microplastics. *Sci. Total Environ.* **2021**, *755*, 142516. [CrossRef]
117. Qi, Y.; Yang, X.; Pelaez, A.M.; Huerta Lwanga, E.; Beriot, N.; Gertsen, H.; Garbeva, P.; Geissen, V. Macro- and micro- plastics in soil-plant system: Effects of plastic mulch film residues on wheat (*Triticum aestivum*) growth. *Sci. Total Environ.* **2018**, *645*, 1048–1056. [CrossRef]
118. Ren, X.; Tang, J.; Wang, L.; Liu, Q. Microplastics in soil-plant system: Effects of nano/microplastics on plant photosynthesis, rhizosphere microbes and soil properties in soil with different residues. *Plant Soil* **2021**, *462*, 561–576. [CrossRef]

119. Shi, R.; Liu, W.; Lian, Y.; Wang, Q.; Zeb, A.; Tang, J. Phytotoxicity of polystyrene, polyethylene and polypropylene microplastics on tomato (*Lycopersicon esculentum* L.). *J. Environ. Manag.* **2022**, *317*, 115441. [CrossRef]
120. Taylor, S.E.; Pearce, C.I.; Sanguinet, K.A.; Hu, D.; Chrisler, W.B.; Kim, Y.M.; Wang, Z.; Flury, M. Polystyrene nano- and microplastic accumulation at Arabidopsis and wheat root cap cells, but no evidence for uptake into roots. *Environ. Sci.-Nano* **2020**, *7*, 1942–1953. [CrossRef]
121. Urbina, M.A.; Correa, F.; Aburto, F.; Ferrio, J.P. Adsorption of polyethylene microbeads and physiological effects on hydroponic maize. *Sci. Total Environ.* **2020**, *741*, 140216. [CrossRef]
122. Yang, C.; Gao, X. Impact of microplastics from polyethylene and biodegradable mulch films on rice (*Oryza sativa* L.). *Sci. Total Environ.* **2022**, *828*, 154579. [CrossRef] [PubMed]
123. Zang, H.; Zhou, J.; Marshall, M.R.; Chadwick, D.R.; Wen, Y.; Jones, D.L. Microplastics in the agroecosystem: Are they an emerging threat to the plant-soil system? *Soil Biol. Biochem.* **2020**, *148*, 107926. [CrossRef]
124. Dong, R.; Liu, R.; Xu, Y.; Liu, W.; Wang, L.; Liang, X.; Huang, Q.; Sun, Y. Single and joint toxicity of polymethyl methacrylate microplastics and As (V) on rapeseed (*Brassia campestris* L.). *Chemosphere* **2022**, *291*, 133066. [CrossRef] [PubMed]
125. Yin, L.; Wen, X.; Huang, D.; Du, C.; Deng, R.; Zhou, Z.; Tao, J.; Li, R.; Zhou, W.; Wang, Z.; et al. Interactions between microplastics/nanoplastics and vascular plants. *Environ. Pollut.* **2021**, *290*, 117999. [CrossRef] [PubMed]
126. Zhang, H.; Liang, J.; Luo, Y.; Tang, N.; Li, X.; Zhu, Z.; Guo, J. Comparative effects of polystyrene nanoplastics with different surface charge on seedling establishment of Chinese cabbage (*Brassica rapa* L.). *Chemosphere* **2022**, *292*, 133403. [CrossRef]
127. Zong, X.; Zhang, J.; Zhu, J.; Zhang, L.; Jiang, L.; Yin, Y.; Guo, H. Effects of polystyrene microplastic on uptake and toxicity of copper and cadmium in hydroponic wheat seedlings (*Triticum aestivum* L.). *Ecotox. Environ. Safe.* **2021**, *217*, 112217. [CrossRef]
128. Gao, M.; Liu, Y.; Song, Z. Effects of polyethylene microplastic on the phytotoxicity of di-n-butyl phthalate in lettuce (*Lactuca sativa* L. var. *ramosa* Hort). *Chemosphere* **2019**, *237*, 124482. [CrossRef]
129. Lee, T.Y.; Kim, L.; Kim, D.; An, S.; An, Y.J. Microplastics from shoe sole fragments cause oxidative stress in a plant (*Vigna radiata*) and impair soil environment. *J. Hazard. Mater.* **2022**, *429*, 128306. [CrossRef]
130. Rillig, M.C.; Leifheit, E.; Lehmann, J. Microplastic effects on carbon cycling processes in soils. *PLoS Biol.* **2021**, *19*, e3001130. [CrossRef]
131. Wang, X.; Xing, Y.; Lv, M.; Zhang, T.; Ya, H.; Jiang, B. Recent advances on the effects of microplastics on elements cycling in the environment. *Sci. Total Environ.* **2022**, *849*, 157884. [CrossRef]
132. Wang, F.; Feng, X.; Liu, Y.; Adams, C.A.; Sun, Y.; Zhang, S. Micro(nano)plastics and terrestrial plants: Up-to-date knowledge on uptake, translocation, and phytotoxicity. *Resour. Conserv. Recycl.* **2022**, *185*, 106503. [CrossRef]
133. Zhu, J.; Wang, J.; Chen, R.; Feng, Q.; Zhan, X. Cellular process of polystyrene nanoparticles entry into wheat roots. *Environ. Sci. Technol.* **2022**, *56*, 6436–6444. [CrossRef]
134. Liu, Y.; Guo, R.; Zhang, S.; Sun, Y.; Wang, F. Uptake and translocation of nano/microplastics by rice seedlings: Evidence from a hydroponic experiment. *J. Hazard. Mater.* **2022**, *421*, 126700. [CrossRef]
135. Sun, H.; Lei, C.; Xu, J.; Li, R. Foliar uptake and leaf-to-root translocation of nanoplastics with different coating charge in maize plants. *J. Hazard. Mater.* **2021**, *416*, 125854. [CrossRef]
136. Chae, Y.; An, Y.J. Nanoplastic ingestion induces behavioral disorders in terrestrial snails: Trophic transfer effectsviavascular plants. *Environ. Sci. Nano* **2020**, *7*, 975–983. [CrossRef]
137. Dong, Y.; Gao, M.; Qiu, W.; Song, Z. Uptake of microplastics by carrots in presence of As (III): Combined toxic effects. *J. Hazard. Mater.* **2021**, *411*, 125055. [CrossRef]
138. Giorgetti, L.; Spano, C.; Muccifora, S.; Bottega, S.; Barbieri, F.; Bellani, L.; Ruffini Castiglione, M. Exploring the interaction between polystyrene nanoplastics and *Allium cepa* during germination: Internalization in root cells, induction of toxicity and oxidative stress. *Plant. Physiol. Biochem.* **2020**, *149*, 170–177. [CrossRef]
139. Gong, W.; Zhang, W.; Jiang, M.; Li, S.; Liang, G.; Bu, Q.; Xu, L.; Zhu, H.; Lu, A. Species-dependent response of food crops to polystyrene nanoplastics and microplastics. *Sci. Total Environ.* **2021**, *796*, 148750. [CrossRef]
140. Kim, D.; An, S.; Kim, L.; Byeon, Y.M.; Lee, J.; Choi, M.J.; An, Y.J. Translocation and chronic effects of microplastics on pea plants (*Pisum sativum*) in copper-contaminated soil. *J. Hazard. Mater.* **2022**, *436*, 129194. [CrossRef]
141. Li, R.; Li, L.; Zhang, Y.; Yang, J.; Tu, C.; Zhou, Q.; Li, Y.; Luo, Y. Uptake and accumulation of microplastics in a cereal plant wheat. *Chin. Sci. Bull.* **2020**, *65*, 2120–2127. [CrossRef]
142. Luo, Y.; Li, L.; Feng, Y.; Li, R.; Yang, J.; Peijnenburg, W.; Tu, C. Quantitative tracing of uptake and transport of submicrometre plastics in crop plants using lanthanide chelates as a dual-functional tracer. *Nat. Nanotechnol.* **2022**, *17*, 424–431. [CrossRef] [PubMed]
143. Kaur, M.; Xu, M.; Wang, L. Cyto-genotoxic effect causing potential of polystyrene micro-plastics in terrestrial plants. *Nanomaterials* **2022**, *12*, 2024. [CrossRef] [PubMed]
144. Mondal, N.K.; Kundu, S.; Debnath, P.; Mondal, A.; Sen, K. Effects of polyethylene terephthalate microplastic on germination, biochemistry and phytotoxicity of *Cicer arietinum* L. and cytotoxicity study on *Allium cepa* L. *Environ. Toxicol. Pharmacol.* **2022**, *94*, 103908. [CrossRef] [PubMed]
145. Maity, S.; Chatterjee, A.; Guchhait, R.; De, S.; Pramanick, K. Cytogenotoxic potential of a hazardous material, polystyrene microparticles on *Allium cepa* L. *J. Hazard. Mater.* **2020**, *385*, 121560. [CrossRef] [PubMed]

146. Lian, J.; Liu, W.; Sun, Y.; Men, S.; Wu, J.; Zeb, A.; Yang, T.; Ma, L.Q.; Zhou, Q. Nanotoxicological effects and transcriptome mechanisms of wheat (*Triticum aestivum* L.) under stress of polystyrene nanoplastics. *J. Hazard. Mater.* **2022**, *423*, 127241. [CrossRef]
147. Qiu, G.; Han, Z.; Wang, Q.; Wang, T.; Sun, Z.; Yu, Y.; Han, X.; Yu, H. Toxicity effects of nanoplastics on soybean (*Glycine max* L.): Mechanisms and transcriptomic analysis. *Chemosphere* **2022**, *313*, 137571. [CrossRef]
148. Wang, Y.; Xiang, L.; Wang, F.; Wang, Z.; Bian, Y.; Gu, C.; Wen, X.; Kengara, F.O.; Schaffer, A.; Jiang, X.; et al. Positively charged microplastics induce strong lettuce stress responses from physiological, transcriptomic, and metabolomic perspectives. *Environ. Sci. Technol.* **2022**, *56*, 16907–16918. [CrossRef]
149. Zhou, C.Q.; Lu, C.H.; Mai, L.; Bao, L.J.; Liu, L.Y.; Zeng, E.Y. Response of rice (*Oryza sativa* L.) roots to nanoplastic treatment at seedling stage. *J. Hazard. Mater.* **2021**, *401*, 123412. [CrossRef]
150. Xu, G.; Lin, X.; Yu, Y. Different effects and mechanisms of polystyrene micro- and nano-plastics on the uptake of heavy metals (Cu, Zn, Pb and Cd) by lettuce (*Lactuca sativa* L.). *Environ. Pollut.* **2023**, *316*, 120656. [CrossRef]
151. Gao, M.; Xu, Y.; Liu, Y.; Wang, S.; Wang, C.; Dong, Y.; Song, Z. Effect of polystyrene on di-butyl phthalate (DBP) bioavailability and DBP-induced phytotoxicity in lettuce. *Environ. Pollut.* **2021**, *268*, 115870. [CrossRef]
152. Dong, Y.; Gao, M.; Song, Z.; Qiu, W. Microplastic particles increase arsenic toxicity to rice seedlings. *Environ. Pollut.* **2020**, *259*, 113892. [CrossRef]
153. Dong, Y.; Song, Z.; Liu, Y.; Gao, M. Polystyrene particles combined with di-butyl phthalate cause significant decrease in photosynthesis and red lettuce quality*. *Environ. Pollut.* **2021**, *278*, 116871. [CrossRef]
154. Jia, H.; Wu, D.; Yu, Y.; Han, S.; Sun, L.; Li, M. Impact of microplastics on bioaccumulation of heavy metals in rape (*Brassica napus* L.). *Chemosphere* **2022**, *288*, 132576. [CrossRef]
155. Lian, J.; Wu, J.; Zeb, A.; Zheng, S.; Ma, T.; Peng, F.; Tang, J.; Liu, W. Do polystyrene nanoplastics affect the toxicity of cadmium to wheat (*Triticum aestivum* L.). *Environ. Pollut.* **2020**, *263*, 114498. [CrossRef]
156. Wang, F.; Zhang, X.; Zhang, S.; Zhang, S.; Adams, C.A.; Sun, Y. Effects of co-contamination of microplastics and Cd on plant growth and Cd accumulation. *Toxics* **2020**, *8*, 36. [CrossRef]
157. Xu, G.; Liu, Y.; Yu, Y. Effects of polystyrene microplastics on uptake and toxicity of phenanthrene in soybean. *Sci. Total Environ.* **2021**, *783*, 147016. [CrossRef]
158. Zhang, Z.; Li, Y.; Qiu, T.; Duan, C.; Chen, L.; Zhao, S.; Zhang, X.; Fang, L. Microplastics addition reduced the toxicity and uptake of cadmium to *Brassica chinensis* L. *Sci. Total Environ.* **2022**, *852*, 158353. [CrossRef]
159. Dubey, S.; Shri, M.; Gupta, A.; Rani, V.; Chakrabarty, D. Toxicity and detoxification of heavy metals during plant growth and metabolism. *Environ. Chem. Lett.* **2018**, *16*, 1169–1192. [CrossRef]
160. Nagajyoti, P.C.; Lee, K.D.; Sreekanth, T.V.M. Heavy metals, occurrence and toxicity for plants: A review. *Environ. Chem. Lett.* **2010**, *8*, 199–216. [CrossRef]
161. Liu, G.; Dave, P.H.; Kwong, R.W.M.; Wu, M.; Zhong, H. Influence of microplastics on the mobility, bioavailability, and toxicity of heavy metals: A review. *Bull. Environ. Contam. Toxicol.* **2021**, *107*, 710–721. [CrossRef]
162. Gu, X.; Xu, X.; Xian, Z.; Zhang, Y.; Wang, C.; Gu, C. Joint toxicity of aged polyvinyl chloride microplastics and cadmium to the wheat plant. *Environ. Chem.* **2021**, *40*, 2633–2639.
163. Ye, X.; Wang, P.; Wu, Y.; Zhou, Y.; Sheng, Y.; Lao, K. Microplastic acts as a vector for contaminants: The release behavior of dibutyl phthalate from polyvinyl chloride pipe fragments in water phase. *Environ. Sci. Pollut. Res. Int.* **2020**, *27*, 42082–42091. [CrossRef] [PubMed]
164. Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* **2018**, *344*, 179–199. [CrossRef] [PubMed]