

*Review*

# Behavior of Microplastics and Nanoplastics in Farmland Soil Environment and Mechanisms of Interaction with Plants

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## Abstract

Plastics are extensively utilized across various industries due to their affordability, chemical stability, insulation properties, durability, and resistance to water. Nowadays, plastics have become an integral part of modern society, while microplastics (MPs) and nanoplastics (NPs) are rapidly accumulating in soil, which could have detrimental effects on both ecosystems and human health. This review first analyzes the latest literature on MPs, soil and plant, and analyzes the future research trends. The review encompasses the latest findings on the effects of MPs and NPs on higher plants, elucidating the mechanisms of MPs and NPs absorption by plants from the soil and their resulting phytotoxicity. Furthermore, the review underscores the imperative for further investigations aimed at comprehending the long-term repercussions of MPs and NPs on plant growth, physiology, reproduction, and their potential entry into the food chain. Notably, NPs exhibit a unique propensity to translocate via the xylem to various plant organs, including seeds, raising concerns for human health, given their heightened uptake by plant roots compared to MPs. In addition, the impacts of MPs and NPs in conjunction with other environmental contaminants might be amplified. Finally, important concerns and potential future research initiatives in the area are considered. The authors call for urgent action to address the problem of plastic pollution and suggest that a multi-disciplinary approach is needed to find solutions to this global problem.

**Keywords:** microplastic, nanoplastic, plant, soil

## Introduction

Plastics find widespread applications across various industries due to their affordability, chemical stability, insulating properties, durability, and resistance to water [1, 2]. The latest data indicate that the production of plastics worldwide has climbed to 368 million tons annually and is projected to reach 33 billion tons in mid-century [3, 4]. Current recycling rates are extremely low (only 9%), with approximately 79% of plastic waste being released to the environment [5]. When plastics enter the environment, they undergo various physical, chemical, and microbial processes, ultimately breaking down into minuscule plastic fragments or particles, some even reaching the nanometer scale [6]. Microplastics (MPs) are defined as plastic with a diameter of less than 5 mm, and nanoplastics (NPs) are primarily described as plastics with a size between 1 and 1,000 nm [6-8]. The “white pollution” caused by the vast buildup of plastics in the environment has caused widespread concern worldwide. In 2022, the General Office of the State Council of China issued the “Action Plan for the Control of New Pollutants”, which clearly pointed out that MPs, as an emerging pollutant, are in urgent need of environmental risk assessment and pollution control [9]. Additionally, at the Second United Nations Environment Assembly, MPs pollution was ranked as the second-most significant scientific concern in the field of environmental and ecological science research [10].

Until Rilling et al., (2012) proposed the need to quantify MPs in soil ecosystems, the majority of MPs/NPs research were primarily concerned on marine species and marine habitats [11]. A recent report suggested there may be 4 to 23 folds higher abundance of MPs in terrestrial systems as compared to the marine ecosystem, suggesting that soil ecosystems are also important sinks for MPs [12]. Furthermore, Non-degradable MPs are difficult to degrade and remove from the soil, which causes them to quickly accumulate in soil ecosystems [13]. However, there is currently limited information available regarding the impact of MPs/NPs on soil ecosystems, particularly concerning edible plants. Plants constitute a pivotal component of the human food supply chain, and the substantial buildup of MPs/NPs in soil raises concerns about their potential adverse effects on plants. This includes the potential for reduced yields, compromised nutritional quality, and even threats to human health [1, 14]. In August 2022, the World Health Organization (WHO) published a report on the potential effects of nanoplastics and microplastic particles (NMPs) on human health [15], and the health risks of microplastics have attracted widespread attention. Currently, micro- and nanoplastics are already in various organs and tissues of the human body, including blood [16], breast milk [17], heart [18], and even have the potential to cross the blood-brain barrier [19] and enter the placenta [20].

In addition, MPs/NPs tend to adsorb different types of environmental contaminants in the soil resulting in more complex biological effects, like cadmium, arsenic, copper, carbon tetrachloride, pesticides, antibiotics [21-23]. Notably, NPs exhibit more complex soil environmental behaviors because of their small particle size and unique nano-size effects [24-27]. There are studies indicating that small-scale NPs or engineered nanomaterials could be absorbed and delivered to the fruit or edible parts by plants [28-30], which may be hazardous to human health [8, 31, 32]. Studying the bioavailability and fate of MPs/NPs in soil is therefore urgently necessary, with a focus on their interactions with edible plants and risk assessment.

## Results and Discussion

### Status of Published Literature

Fig. 1 summarizes the relevant literature on nanoplastics or microplastics in the field of plants and soils. According to the Web of Science database, we counted the literature and citations of “Microplastics AND Soil OR Plant” (Fig. 1a) and “Nanoplastics AND Soil OR Plant” (Fig. 1b) respectively. As of October 7, 2023, there were 12038 publications on the topic of “Microplastics AND Soil OR Plant” and 1854 publications on the topic of “Nanoplastics AND Soil OR Plant”.

The exponential growth in both the number of publications and the total citations related to microplastics (MPs) is a direct reflection of the significant increase in MPs research intensity. While the total literature on microplastics in 2023 does not surpass that of 2022, the annual publication volume remains exceptionally high. Notably, the total literature on nanoplastics (NPs) continues to exhibit substantial growth, which underscores the presence of unexplored research gaps in the field of nanoplastics. The sheer volume of publications and the frequent citations underscore the paramount importance of the microplastics field. Given this deluge of emerging literature, it becomes evident that an up-to-date comprehensive literature review is essential to effectively synthesize and navigate the latest research findings while providing valuable insights into future research directions.

Research on the impacts of MPs/NPs on plant-soil systems remains in its infancy. This review offers a comprehensive overview of the current state-of-the-art in studies examining the interactions between MPs/NPs and higher plants within the soil environment. The primary objectives encompass (1) elucidating the primary pathways through which MPs/NPs enter the soil and their subsequent effects on soil health; (2) summarizing the consequences of MPs/NPs on plant phenotypic traits and physiological-biochemical systems; and (3) exploring the mechanisms of plant uptake of MPs/NPs and the factors influencing this

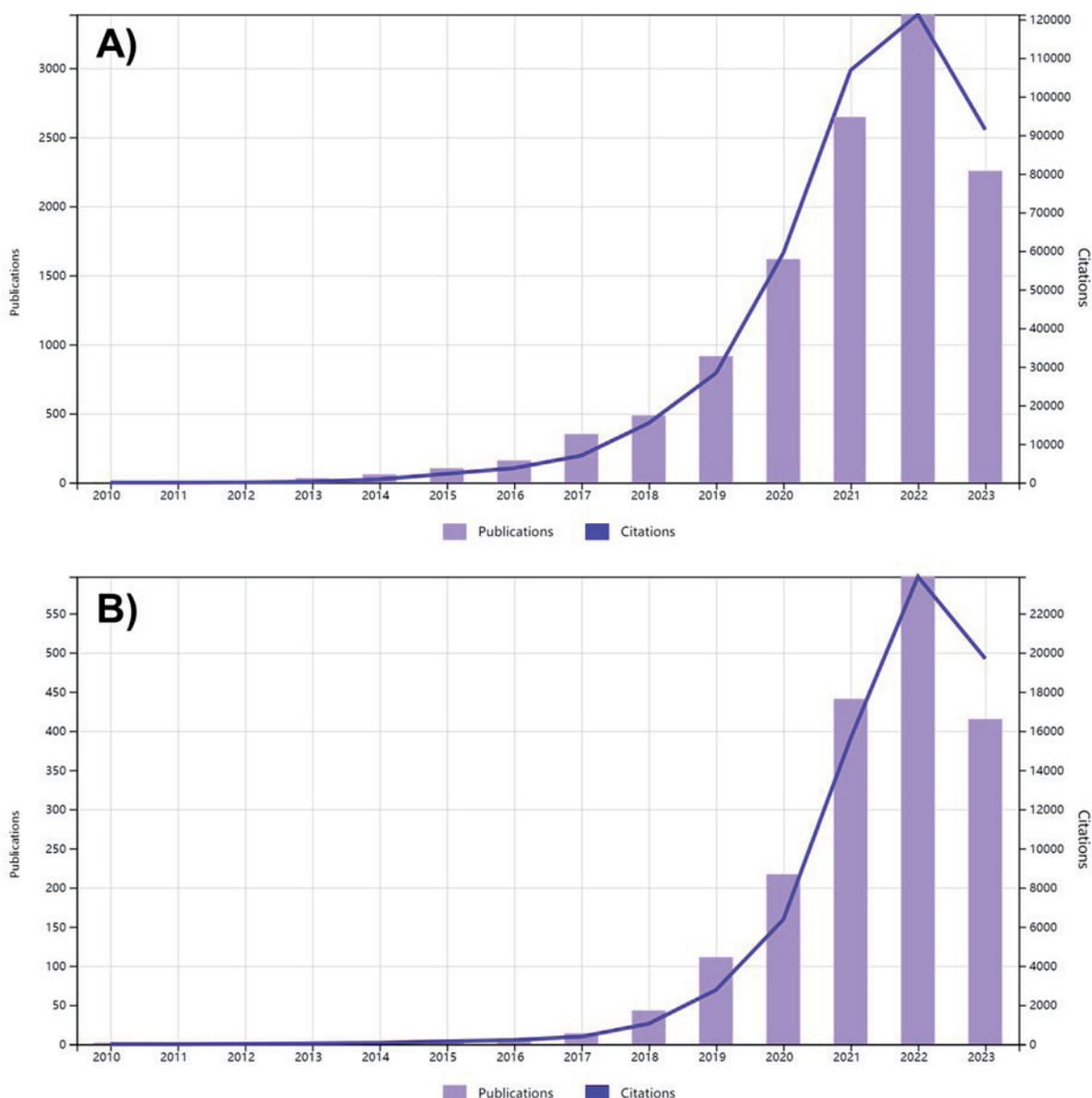


Fig. 1. Number of published literature and total citations based on Web of Science database since 2010. Number of relevant literature and citations for the topics “Microplastics AND Soil OR Plant” (Fig. 1a) and “Nanoplastics AND Soil OR Plant” (Fig. 1b).

process. This literature review serves as a foundation for guiding future investigations into the intricate interactions between plants and MPs/NPs. It delves into the hazards associated with the absorption of MPs/NPs from the soil by higher plants and the subsequent implications for the broader food chain.

### 3 Major Sources of MPs/NPs in Farmland Soil

In recent years, concerns about MPs/NPs in the ecosystem have gradually switched to the land system from the ocean, where approximately eighty percent of plastic waste comes from land-based sources [33]. Soil is now considered to be the largest temporary or permanent sink for MPs, receiving even more MPs than the ocean, retarding or impeding the MPs' migration to the marine [34]. The primary contributors

of MPs/NPs in farmland-soil consist of plastic packaging of farm products, agricultural plastic films, surface runoff, irrigation of agricultural wastewater, use of organic fertilizers and sludge, tire wear particles, and atmospheric deposition [34]. For food security, many fertilizers and pesticides are used in farmland soil, resulting in massive plastic packaging waste [35]. The vast majority of farmers use agricultural products and then discard them into the vicinity of farmland instead of collecting and disposing of them in a uniform manner. According to statistics, fertilizer packaging waste amounted to 150,000 t/year in 2018 and as many as 1010 t pesticide waste packaging in 2019 [36, 37]. Furthermore, PVC and PE are the two main components. Studies have found that agricultural films are left in Chinese agricultural soils every year to the tune of 18.6%, while Ren et al. (2021) claim that 10-30%



Fig. 2. Source and transport pathway estimates for plastics in the environment; data are in millions of tons (From Azeem et al., 2021) [1].

of the total agricultural soil MPs in China are contributed by agricultural mulch and greenhouse construction materials [38]. Moreover, other potential NPs sources include agricultural and municipal composts, sewage sludge applications, polymer-coated/slow-release fertilizers and insecticides, municipal landfills, organic and agricultural composts, and atmospheric deposition [39-41].

As an emerging area of research, there is little information on how plastics decompose to NPs in soil. Some opinions suggest that microplastics may be subjected to physical decomposition in soil primarily in the presence of microplastics, such as UV irradiation, mechanical abrasion, and temperature changes [42]. It may also be subjected to chemical decomposition in soil, especially in the presence of oxygen, plant root secretions, or other chemicals [43]. Some microorganisms also can degrade microplastics, converting microplastic particles into smaller particles, including nanoplastics [44]. And there are few quantitative data on the NPs produced when plastics are used. For example, lids of coffee cup released  $8 \times 10^{10}$  NPs/lid after 56 days of degradation [45], in addition, plastic tea bags released  $1.47 \times 10^{10}$  NPs after boiling water immersion [46]. Notably, a large number of NPs may be produced inadvertently, like simple wear and tear of plastics, boiling water immersion, etc. Overall, there is an urgent need for additional information on quantifying the generation of NPs in the farmland soil, particularly the potential pathways through which various human activities may generate NPs.

Plastic polymers are mixtures of polymer chains of different lengths. Micron- sized and even nanometer scale plastic particles may occur on the surface. Further, the interaction of multiple factors such as light, water,

temperature, and microorganisms can likewise break the hydrogen or van der Waals bonds that link polymers, resulting in the production of MPs and NPs. [47]. A NPs polluted farm soil in the middle of France was initially reported with 23.7 mg/kg [48]. This study discovers NPs in soils for the first time and suggests that NPs generation and plastic degradation may take place in the soil matrix. Although we are all aware of the presence of large amounts of NPs in soils, little information is available on NPs due to limited sampling and analytical tools. Table 1 summarizes more relevant information about NPs/MPs in soil. Table 1 clearly showed that there are notable variances in the abundance from various regions, particularly in agricultural soils with different uses. The reports clearly indicate the following MPs abundance order: greenhouse film-use soils>rice-growing soils>mulch-use soils.

The world's largest producer and user of plastics is China. In Chinese agricultural fields, MPs abundance varied from 0.1 to 411.2 kg/ha and 1.6 to 690,000 pieces/kg, with variances of up to 5 orders of magnitude. [49-51]. The abundance of plastics in the other countries in Table 1 was slightly lower than that in most agricultural soils in China. In addition, we found that different sampling depths significantly affected the abundance of MPs in soils, which usually showed a tendency to decrease with increasing sampling depth. The information presented above demonstrates, in conclusion, that the concentrations of MPs/NPs in soils are considerably influenced by geographic location, plastic type, soil use, and sampling depth. Although a large amount of information on MPs in soils has been reported, little information on NPs is available, so more research is urgently required to reveal more details about the presence of NPs in soils.

Table 1. Typical NPs/MPs concentrations in soil environment.

Location	Type of applied field	Type of plastics	Sampling depth	Mean Concentration (mg/kg)	Ref
Central France	Household waste Contaminated agricultural soils	NPs	0-10 cm	23.7±1.8 20-150 nm	[48]
Yong-In, Korea	Agricultural soils	MPs (pieces/kg, n = 60)	0-5 cm	1880±1563 (Inside greenhouse soil) 1302±2389 (Out greenhouse soil) 160±93 (Rice cultivation soil) 81±77 (Mulch-film use soil)	[52]
Lahore, Pakistan	Urban soils	MPs (pieces/kg, n = 40)	0-5 cm	4483±2315	[53]
Sydney, Australia	Industry area soils	MPs (mg/kg, n = 17)	\	7767±15442	[54]
Campeche, SE Mexico	Homegarden soils	MPs (pieces/g, n = 100)	0-10 cm	0.87±1.90	[55]
Shanghai, China	Farmland soils	MPs (pieces/kg, n = 60)	5-10 cm	62.50±12.97	[56]
			0-5 cm	78.00±12.91	
Shangsuan, Yunnan, China	Farmland soils	MPs (pieces/kg, n = 10)	0-10 cm	12905±3000 (0-5 cm) 10924±4018 (5-10 cm)	[57]
Anle, Yunnan, China	Farmland soils			25245±4358 (0-5 cm) 29886±6623 (5-10 cm)	
Dunshang, Yunnan, China	Farmland soils			15566±3962 (0-5 cm) 13075±4868 (5-10 cm)	
Dagoujian, Yunnan, China	Farmland soils			26094±5150 (0-5 cm) 26037±5886 (5-10 cm)	
Buffer zone, Yunnan, China	Buffer zone soils			15962±4075 (0-5 cm) 12905±5320 (5-10 cm)	

### Effect of MPs on Soil Physicochemical Properties

An increasing number of studies have shown that soils are major sinks for MPs/NPs, found in a variety of soil types. MPs/NPs in different soils exhibit a high degree of heterogeneity due to the large variation in the properties of different MPs/NPs [58]. A more widely accepted current explanation is that the potentially different sources of MPs/NPs contribute to the heterogeneity. For example, agricultural processes such as agricultural films, organic fertilizers, and sewage irrigation are the most important sources of MPs in agricultural soils [13]. With the continuous accumulation of MPs in soil, they have the potential to greatly affect the physicochemical and biochemical properties of soil, thus indirectly affecting the growth and development of crops, and may even cause the risk of consumption of agricultural products [59, 31]. More and more people have investigated the fugitive patterns of MPs/NPs in different areas and types of soils, and there is ample evidence that increasing concentrations have more drastic effects on soil physicochemical qualities. Fig. 2 summarizes the potential effects of MPs/NPs on physical properties (soil aggregates, soil porosity, soil bulk density, soil water holding capacity, etc.), chemical properties (pH, Eh, organic matter, nutrients, coexisting contaminants, etc.) and biological properties (arthropods

such as earthworms, bacteria, fungi, antibiotic resistance genes, etc.) of soils, as well as some current findings. Due to the potential for charges on the surface of MPs/NPs, heterogeneous aggregation with soil colloids or homogeneous aggregation between MPs may occur, thus affecting the agglomeration of the soil [60]. In addition, MPs may obstruct soil pore space, which would increase the soil's ability to hold water [61]. In general, most MPs have a low density compared to soil, so incorporation of MPs into soil will necessarily result in a decrease in soil bulk capacity [62].

Although many existing studies have shown that abundance is an important factor affecting soil properties, most of these experiments used initial MPs. It is worth noting that MPs in soils may undergo aging, thus changing their properties and correspondingly their ability to affect the soil to some extent [63]. Another key factor affecting soil properties is the size of the MPs. Smaller sized NPs are more easily absorbed by plants, animals, or microorganisms, inducing oxidative stress and thus potentially more serious environmental risks [64]. Also, due to the decrease in size, the specific surface area of MPs increases correspondingly, thus potentially adsorbing more coexisting contaminants [65]. It is worth noting that the adsorbed MPs/NPs will be desorbed again after entering the plants and animals, which may pose a greater risk [66]. The shape of

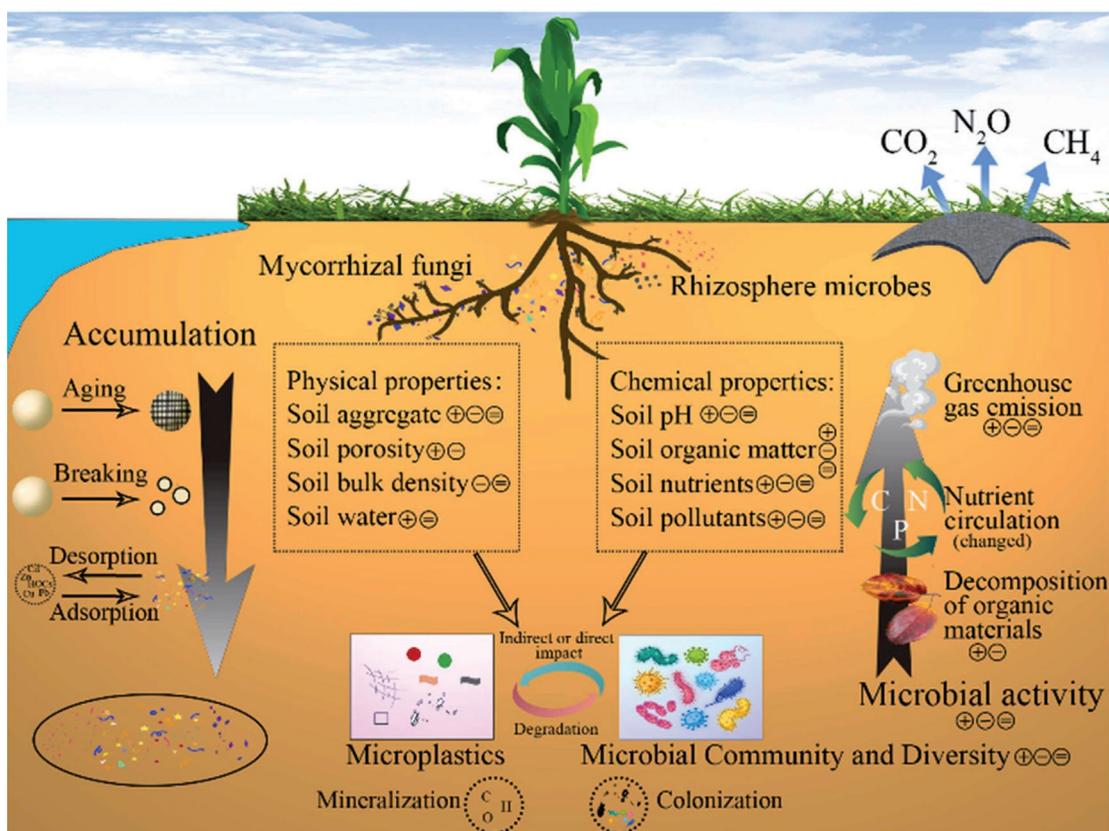


Fig. 3. Impacts of MPs/NPs on physical, chemical, and microbiological properties of soils. The symbols of +, - and = representing increasing, decreasing and non-significant effect by MPs, respectively [34] (Copyright 2022, Elsevier).

MPs/NPs is also worth studying, especially for NPs. Most of the current studies on NPs are mostly on spherical NPs due to various reasons such as limited synthesis and cost, which is quite different from the actual situation [67]. Moreover, the effects of different shapes of MPs on the physical and chemical properties of soils vary greatly. To address this phenomenon, Rillig et al. (2019) proposed the “shape difference hypothesis” [68]. They suggested that pollutants that are less like soil particles in shape may have a stronger impact. The main shapes currently reported in soils are fragments, fibers, films, foams, spheres, etc. Some of the meta-analyses suggest that MPs fibers and films may have a more significant effect on soil than spheres [14]. Some existing studies have summarized some patterns, such as fiber-shaped MPs may increase the water holding capacity of soil, thin film reduces the soil bulk, while foam and fragment MPs help how to make the soil more porous [34]. It should also be noted that the shape of MPs in soil is not constant, but will undergo some transformation over time, but this transformation rate is much lower compared to MPs in water bodies [69]. Recent evidence suggests that microplastics alter micro-scale oxygen availability, DOM properties and DOM electron transfer capacity in soil [70]. They found that changes in gas emissions caused by conventional microplastics (PE) were mainly due to induced DOM electron transfer, whereas changes in gas emissions

caused by biodegradable microplastics were mainly due to PLA degradation, a process that increases DOM concentration and electron transfer capacity [70].

Different types of MPs have distinct impacts on the soil because of the large differences in their chemical composition [71]. Currently, a wide variety of MPs have been found in soil, including PE, polypropylene, polyamide, polyvinyl chloride, polystyrene, and others [72]. MPs may release these additives during the degradation process, which may cause some pollution. The degradation rate of different types of MPs/NPs varies greatly, but there are still few studies on the long-term effects of MPs. Therefore, future research should emphasize the long-term nature of MPs in the environment by using MPs in the environment as the study's subject and highlighting the relevance of the environment.

#### Uptake of NP by Soil Plants

Since large amounts of MPs/NPs are found in the atmosphere, water bodies and soil, plants present within these three media will interact with MPs/NPs [73]. And due to the strong adsorption of MPs/NPs, they can easily attach to the leaves and roots of plants and may negatively affect the growth and development of plants [74]. Earlier studies on engineered nanomaterials have well demonstrated that nanoscale objects can be

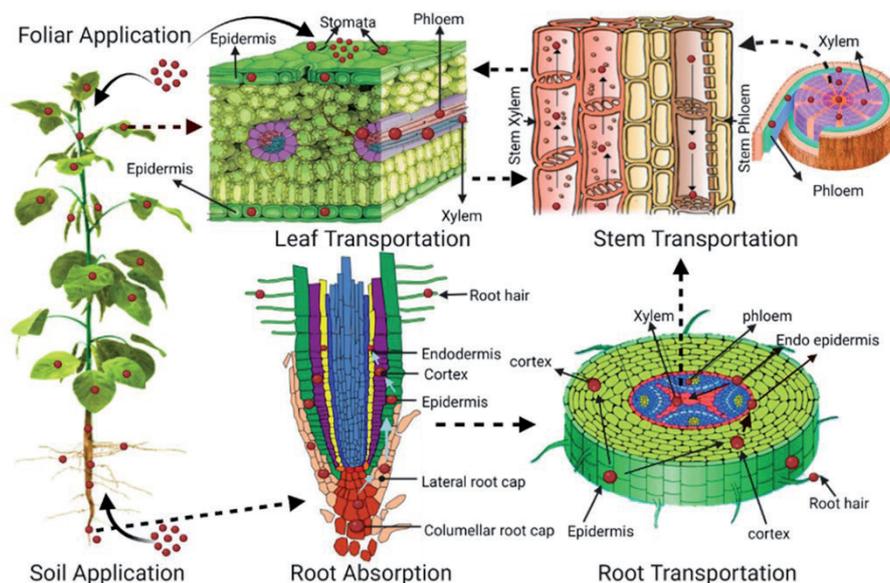


Fig. 4. Schematic diagram of the uptake and translocation mechanisms of MPs/NPs by plants (From Azeem et al., 2021) [1].

absorbed by plants, either from the leaf surface or from the roots [75]. Since there are some similarities in the properties of carbon-based nanomaterials and MPs/NPs, the study of plant translocation and effects of MPs/NPs can be referred to the previous studies on engineered nanomaterials [76, 77]. MPs exposed to the root system have the potential to be taken up by plants, and the amount of uptake depends greatly on the particle size of MPs, while for NPs the uptake capacity is much stronger [78]. MPs must first pass through several tissues before reaching the stems and leaves of a plant, including the cuticle, epidermis, cortex, endodermis, Casparian strips, and periplasm. MPs exposed to leaves are also likely to be absorbed by plants and transported downward by the bast to the plant root system after passing through a series of barriers.

When MPs are exposed to plant roots, MPs with larger particle size may not be absorbed by plants and adhere to the root surface, which may lead to blockage of transport channels [79]. Moreover, MPs adhering to root hairs may also affect the development of cell walls, thus affecting water and nutrient uptake by plants. A similar phenomenon was observed during seed germination, where high concentrations of MPs led to a significant reduction in seed germination [75]. However, a study on NPs reported the opposite conclusion, that NPs enhanced water uptake by seeds and promoted seedling growth rate by stimulating water channel proteins [80]. As the present conclusions are highly controversial, more microscopic mechanistic studies are undoubtedly needed to reveal the mechanism of their effects.

The extraplasmic pathway (primary) and the coplasmic pathway are two generally recognized hypothesized routes for the absorption and translocation of MPs/NPs [81]. The term "extraplasmic pathway" describes the crossing of the cell wall, intercellular

layer, or cell gap by MPs and NPs without involving the cytoplasm. The coplasmic pathway, on the other hand, involves the transfer of NPs from one cell's cytoplasm to the cytoplasm of an additional cell through intercellular filaments, creating a cytoplasmic continuum [81]. The first barrier that MPs need to cross may be the root cuticle, but it is mainly found in the root primordia and root crowns of lateral roots (this structure is not present on most root surfaces) [82]. MPs then need to cross the cell wall and Casparian zone for transport from the xylem up to the aboveground. Most of the plants reported so far have cell wall pore sizes between 5 and 20 nm, but even micron-sized MPs occur inside the root system, indicating the complexity of MPs/NPs uptake and transport [83]. Some current speculations include the entry of MPs/NPs into the root system through the pores at the lateral root junctions, the influence of MPs/NPs on cell wall formation, cell wall damage caused by MPs/NPs-induced oxidative stress, and mechanical damage caused by sharp surfaces of certain objects [84]. The Casparian zone is in the endothelium and can intercept most of the contaminants because it is a special band of cell wall material sealed by lipophilic hydrocarbons [85]. MPs/NPs can enter the vascular system through some lateral root junctions where the Casparian zone is disconnected or at the apical part of the root that is not yet fully formed, thus avoiding the blockage of the Casparian zone [86].

The coplasmic pathway is another hypothetical transport pathway that crosses the Casparian zone by sequentially passing through the cell membrane and intercellular filaments [87]. There are various hypotheses for the transmembrane transport of NPs in plant cells, including membrane damage, cellular endocytosis, ion channels, and water channel proteins [88]. However, endocytosis is the transmembrane mechanism that

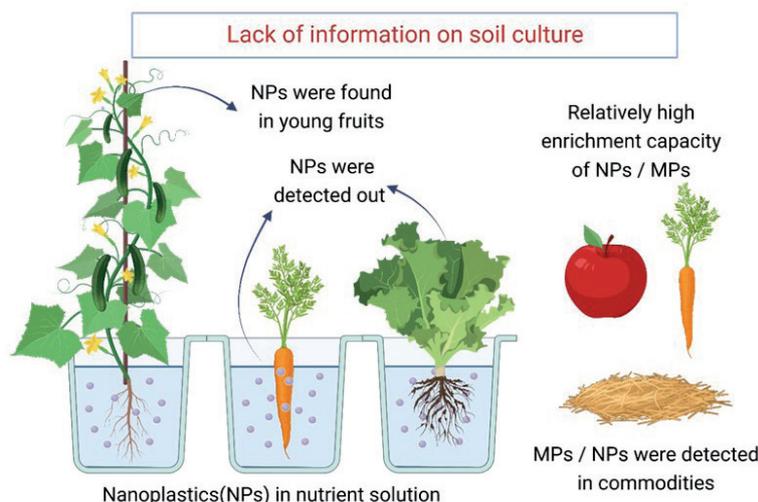


Fig. 5. Current information on NPs / MPs in fruits, vegetable and grains (Created with BioRender).

is currently acknowledged [89]. It is possible that NPs after transmembrane translocation enter neighboring cells via intercellular filaments and thus cross the Casparian band [90, 91]. Plant root intercellular filaments have been found to contain gold and silver nanoparticles [88]. And a recent study also revealed that graphene is present in intercellular filament transport, indirectly providing evidence for intercellular linkage transport of NPs [91]. Since graphene is a nanomaterial made of carbon, its characteristics are more comparable to those of NPs. As of now, it has not been clearly demonstrated that MPs/NPs can undergo intercellular transport via intercellular linkages, and therefore more attention should be paid to in situ characterization of cells with nanoscale in the future.

Through fluorescent dye studies, Li et al. (2022) showed that PS microbeads smaller than 2  $\mu\text{m}$  can access the circulatory system at a very low level but those of 5 and 7  $\mu\text{m}$  cannot [84]. Because xylem is the upward water and nutrient transport channel for plants, MPs/NPs can be transported upward by the driving force of the water potential gradient produced by plant transpiration [24]. And MPs have been found in xylem sap of various plants such as wheat and lettuce, which fully demonstrates the transport function of xylem. However, due to weight and size, most of the micron-sized MPs are only present in the roots, and only a small fraction of them is transported upward to various plant parts.

There may be a chance for MPs/NPs to contaminate edible sections of plants because they can be carried upward through the xylem to the above-ground parts of plants [92]. MPs/NPs and their adsorbed contaminants may alter the nutritional quality of crops because they affect the physiological and biochemical systems of crops, like traditional heavy metals and nanomaterials [93, 22, 94, 95]. Moreover, the impact of MPs/NPs and their adsorbed contaminants on food health is a topical issue and one that needs to be addressed urgently [96,

23]. Fig. 5 summarizes some of the findings regarding MPs in vegetables, crops and fruits. There have been numerous studies on the existence of MPs/NPs in vegetable leaves, but there is still much debate over whether MPs/NPs may go from vegetable leaves to grains or fruits. In comparison to vegetable leaves, MPs/NPs encounter more physiological hurdles as they attempt to reach seeds or fruits [60, 97]. Due to the distance of transport, MPs/NPs may likewise be distributed in different locations in the plant like heavy metals [93]. A recent study found for the first time that 500 nm and 700 nm PS NPs were present in young cucumber fruits, and they also found that smaller particle size NPs were not present in the fruits [31]. It is generally believed that smaller particle size NPs are easier to transport through various barriers, and the findings of this study contradict this, but they also do not give a good explanation. It is important to note that because tuberous vegetables, like carrots and potatoes, are directly exposed to soil, additional research is needed to determine the potential risks associated with their ingestion. MPs/NPs have also been detected in various vegetable, fruit and cereal commodities, but their main source is likely to be packaging contamination. Dessi et al. (2021) measured the plastic content of rice in various packages using pyrolysis-GC/MS [98]. They found non-significant differences in rice's plastic content across various packages and a significant 20-40% reduction in the abundance of MPs after water washing [98]. These results unequivocally demonstrate that agricultural production, processing, shipping, and marketing involve plastic contamination. To calculate the plastic content and potential harm in vegetables, cereals, and fruits, more lifetime experiments are required.

#### Effect of MPs/NPs on Plant Growth

Plants are capable of absorbing MPs and NPs, which means that both MPs and NPs have the capacity to

Table 2. Summarization of research on the effects of MPs/NPs on plant physiological and biochemical systems.

Plant species	NPs Types	Size (nm)	Conc	Exposure duration	Culture medium	Effects	Ref
<i>Triticum aestivum</i>	PS	200	20-50000 µg/L; 1-10 mg/kg	6 days, 14 days	Hydroponic and sandy soil	<ul style="list-style-type: none"> <li>No significant changes in fresh biomass</li> <li>There was no significant effect on photosynthesis.</li> </ul>	[103]
<i>Brassia campestris</i>	PMMA	<100	0.01-10 g/L	4 days	Ultrapure water	<ul style="list-style-type: none"> <li>The germination index was reduced</li> <li>PMMA increased biomass and length at the concentration of 5 g/L.</li> </ul>	[108]
<i>Oryza sativa</i>	PS	50	0.1-1 g/L	4 days	Water	<ul style="list-style-type: none"> <li>Cell development was abnormal and mitosis was inhibited by PS</li> <li>No obvious influence of PS on rice seeds germination, but reduced viability index and root length.</li> </ul>	[109]
<i>Lactuca sativa var. ramosa Hort., Raphanus sativus and Zea mays</i>	PS	100	1 and 10 mg/L	7 days	Distilled water	<ul style="list-style-type: none"> <li>The content of Cu in both roots and stems decreased.</li> <li>PS NPs increased the content of Zn in the roots.</li> </ul>	[104]
<i>Rape</i>	PS	70	10 mg/kg	21 days	Clay soil	<ul style="list-style-type: none"> <li>PS promotes photosynthesis by increasing the content of chlorophyll a, which in turn promotes photosynthesis and promotes plant biomass.</li> </ul>	[110]
<i>Zea mays</i>	PS-NH <sub>2</sub> PSCOOH	22-24	10-500 ng/spot (foliar)	7 days	Sterile soil	<ul style="list-style-type: none"> <li>Positively charged PS-NH<sub>2</sub> adhered to the leaf surface better than negatively charged PS-COOH.</li> <li>Reduced multiple chlorophylls, photosynthesis.</li> <li>PS-NH<sub>2</sub> increased the MDA content, while PS-COOH did not.</li> </ul>	[111]
<i>Cucumis sativus</i>	PS	100-700	50 mg/L	65 days	Hoagland solution	<ul style="list-style-type: none"> <li>NPs caused oxidative damage (increased content of MDA and decreased content of proline)</li> <li>NPs reduced magnesium, calcium, and iron in edible part.</li> </ul>	[112]
<i>Vigna radiata</i>	PS	28	10-100 mg/kg	10 days	LUFA 2.2 standard soil	<ul style="list-style-type: none"> <li>There was a tendency for the root length to increase with increasing concentration of NPs, whereas diameter did not.</li> </ul>	[113]
<i>Allium cepa</i>	PS	50	0.01-1 g/L	3 days	Distilled water	<ul style="list-style-type: none"> <li>Seed germination was not affected by NPs</li> <li>NPs at medium to high doses (0.1 and 1 g/L) suppressed root growth</li> <li>H<sub>2</sub>O<sub>2</sub> and thiobarbituric acid reactive substances increased</li> </ul>	[114]
<i>Lepidium sativum</i>	Green fluorescent plastic particles	50, 500 and 4800	10 <sup>3</sup> -10 <sup>7</sup> particle/mL	8, 24, 48 and 72 h	Distilled water	<ul style="list-style-type: none"> <li>Lower germination rate of seeds</li> <li>Film and surface pores on seed capsules that accumulate plastic particles</li> </ul>	[75]
<i>Ceratopteris pteridoides</i>	PS	100	0.16-100 µg/mL	28 days	Artificial freshwater	<ul style="list-style-type: none"> <li>Suppressed spore infiltration and germination</li> <li>The growth of gametophytes is severely hindered at the highest concentration</li> </ul>	[115]

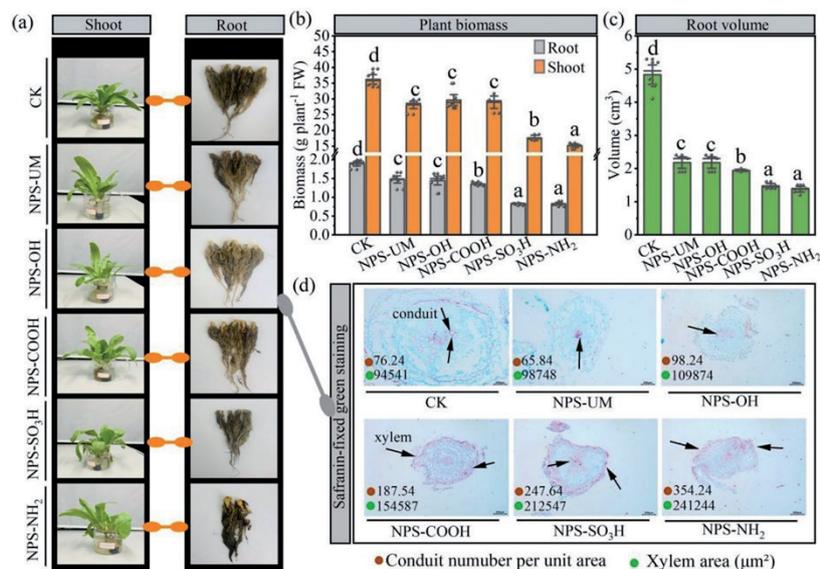


Fig. 6. Effects of exposure to MPs of different charges on plant growth and root xylem (Copyright 2022, Elsevier) [108].

influence physiological markers including plant seed germination, biomass, and yield [99]. Beyond a certain toxicity threshold, the toxic effects of the same high concentration of NPs are much higher than those of MPs. because of the smaller size of NPs, they easily cause oxidative stress in cells and generate excessive ROS leading to cell membrane damage [100]. It is noteworthy that most of the information accessible currently on the effects of NPs on the physiology of higher plants is negative, which may be due to the high concentrations of NPs set in most studies [79]. It is clear from a meta-analysis that there is a strong association between NPs concentrations and biological effects of NPs and low concentrations of NPs may have a facilitative effect on some physiological indicators [14]. Table 2 summarized the studies on the effects of MPs and NPs on plants, such as MPs/NPs in soil begin to have an impact during the seed germination stage, and both positive and negative effects are mostly influenced by concentration. For instance, wheat greatly improved its root length, germination rate, and net photosynthetic rate when exposed to NPs at 0.1 mg/L due to the up-regulation of water channel protein genes [101]. While another study reported that NPs encased the seed surface and prevented it from absorbing water, substantially impairing seed germination [75].

During the extension of the root system in the soil, there is a possibility of direct friction with the sharp surface of MPs/NPs thus causing mechanical damage and thus inhibiting root growth and development. Moreover, due to the electrostatic effect and the strong adsorption of MPs/NPs, MPs may also adhere to the root surface in large quantities, impeding the uptake of water and nutrients. MPs/NPs that have entered the root system may also accumulate in the cell space, and some of them may even enter the cell wall and cell membrane, which may also block the cell pores [102]. As a result,

because MPs/NPs obstruct water and nutrient transport channels, they may have an impact on how well plants absorb nutrients and water [103]. In addition, a significant decrease in photosynthetic pigments and photosynthetic rate when leaves are exposed to MPs/NPs has been clearly indicated in some studies, and this phenomenon has also been found in some experiments with root exposure [104]. They suggest that exposure of leaves to MPs/NPs hinders light uptake and produces oxidative stress that leads to photosynthetic cell damage, thereby reducing plant biomass. Because of the large number of pollutants present in the environment [23, 105], it is possible to influence the effects of MPs/NPs on plants. Some recent metabolomics studies showed that MPs induced the regulation of purine metabolism, glycerophospholipid metabolism, phenylpropanoid biosynthesis, cysteine and methionine metabolism [106]. PS MPs inhibited 29.63% of the metabolic pathways related to substance accumulation and 43.25% of the metabolic pathways related to energy expenditure in rice grains [107]. In addition, MPs/NPs can influence the C/N cycle, hormone production, antioxidant enzyme activity, protein synthesis, and gene expression, all of which can have an indirect impact on plant growth and development [74].

## Conclusions

Most of the current research is based on hydroponic conditions. Although hydroponics has become an increasingly popular method of plant growth, especially in urban agriculture. However, soil growing conditions are still the predominant method of plant culture, thus more research on actual exposure is needed. Although relevant studies are still in the initial stage, there is clear evidence that aging MPs/NPs in soil may differ

significantly from their initial forms, which needs to be considered in the risk assessment of NPs in soil. Future research on the interactions between MPs/NPs and plants is suggested from the following four viewpoints.

#### Standardization Methods for MPs/NPs in Agricultural Soil

There is a lack of uniform standards for the separation, extraction and detection methods of MPs/NPs in soil. It is difficult to compare the levels of MPs/NPs in different studied scientifically and objectively. Therefore, methodological research on the separation, extraction and detection of MPs/NPs should be strengthened and standardized technical specifications should be established, especially for NPs.

#### Traceability and Behavior of MPs/NPs in Agricultural Soils

It is important to understand the origins and contributions of the microplastics and nanoplastics found in agricultural soils. Revealing the migration and transformation patterns of micro- and nanoplastics in soil and the generation of nanoplastics. To establish the migration and transformation model of micro and nano plastics in soil and predict the characteristics of micro and nano plastics pollution behavior in soil.

#### Pollution Remediation Technology and Safety Threshold of MPs/NPs

MPs/NPs in agricultural soils are difficult to be completely removed in a short period of time due to their characteristics, so there is an urgent need for efficient MPs/NPs pollution remediation technologies. Moreover, the safety thresholds of MPs/NPs that do not affect agricultural production and guarantee ecological safety and human health should be explored.

#### New Technologies to Investigate the Toxicity Mechanisms and Risks of MPs/NPs

With the help of new technologies like metabolomics, transcriptomics, and proteomics, the mechanisms of MPs/NPs phytotoxicity can be shown in greater detail. Combined with Artificial Intelligence/Machine Learning to quickly estimate the biological and environmental dangers of MPs/NPs with an emphasis on elucidating the processes of phytotoxicity from nuclear power sources.

#### Human Health Risks of MPs/NPs in Edible Portions

The risk of MPs or NPs in edible parts of plants was explored through animal experiments. Compare the difference between direct exposure and indirect exposure from food through bio efficacy and

bioavailability exploration experiments. And still need to further explore the genetic risk of MPs and NPs.

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#### Conflict of Interest

The authors declare having no conflict of interest.

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