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Nano/microplastics in agricultural soils and their impacts on physiology, morphology, and plant health

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ABSTRACT

Nowaday, plastic contamination is one of the most pressing environmental challenges. With annual production exceeding 360 million tons, plastics have infiltrated into various parts of ecosystem and are alarmingly prevalent in gardens, agricultural fields, and soils of industrial zones worldwide. Over time, these larger plastic particles degrade into smaller fragments, including microplastics (MPs) and nanoplastics (NPs). Among these, NPs pose the most significant threat due to their diminutive size, allowing them to be absorbed by living organisms and subsequently move into the food chain and leading to potential bioaccumulation. This review article aims to synthesize current knowledge on the impact of micro and nanoplastics (MNPs) on soil health, plant physiology, and human health by identifying key themes and knowledge gaps in the literature. Recent studies have highlighted the detrimental effects of MNPs on soil health, revealing that agricultural practices, such as utilizing plastic mulch and synthetic fertilizers, have contributed to the elevated MNP concentrations in soils worldwide. The uptake of MNPs by plants can alter their physiological and morphological characteristics, as well as their gene expression profiles, leading to unpredictable consequences for plant health, growth, and productivity. These contaminants can be absorbed directly into plant tissues or adhere to root surfaces, raising concerns about the potential transfer of MNPs into the food supply. The implications for human health are profound, as the consumption of contaminated crops may lead to adverse health effects, including endocrine disruption and inflammatory responses. While the impact of traditional soil pollutants, such as heavy metals, has been extensively studied**,** the emerging risks posed by plastic contaminants require urgent attention. This review contributes to existing literature by broadening our understanding of MNPs and their effects, ultimately aiming to safeguard both plant and human health despite escalating environmental plastic contamination.

Keywords: Soil health, Human health, Nanoparticles, Plant, Plastic, Polyethylene.

1. Introduction

Plastics have a significant impact on all facets of our daily life, by discarding most used plastics after only one time use. This practice has led to a serious environmental problem, as discarded plastics accumulate in landfills, oceans, rivers, and soils. Concerns have been raised when the potential toxicity of these materials to both humans and environment degrade from micro to nano sizes (Yee et al., 2021; Bakhshaee et al., 2025).

Globally, plastic production has reached staggering levels, with estimates of 50% manufacturing in Asia, followed by Europe (19%), North America (18%), the Middle East and Africa (7%), and Latin America (4%) (Ali et al., 2021). In 2021, almost 390 million metric tons of plastics were produced, reflecting a 4% increase from the previous year. China alone accounted for 32% of global plastic production, manufacturing between six and twelve million metric tons of plastic items per month. North America, with an 18% share, produced 125.5 billion pounds of plastic in 2022, marking another increase over the previous year.

The demand for plastic converters in the European Union (EU-27 + 3) reached 50.3 million metric tons in 2021, illustrating the significant role that plastic plays in various industries. Notably, plastic pollution (PP) accounted for 10 million metric tons of this demand, highlighting the environmental challenges associated with plastic production. This pollution is prevalent in a wide range of products, from banknotes to food packaging. Among the polymers, low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) emerged as the most sought-after materials in 2021. Additionally, the global demand for polystyrene (PS) has notably increased, rising from 13 million tons in 2000 to approximately 15 million tons in 2010. This surge in demand reflects the broader trends in plastic production globally, where regions like Asia, Europe, and North America continue to drive significant manufacturing outputs, contributing both to economic growth and environmental concerns (Song et al., 2020).

Another side of the problem is long degradation time of these materials, which can persist in the environment for decades to millennia due to their chemical inertness (Alabi et al., 2019). Small particles of plastic are produced as large plastic items break down through chemical, physical, and biological processes such as water flow, wind, animal digestion, and UV radiation. It is estimated that up to 94% of the plastic wastes end up in landfills or the environment, with only about 6-26% being properly managed or recycled (Nizzetto et al., 2016).

Microplastics (MPs) and nanoplastics (NPs) are the two most critical forms of plastic pollution. The MPs with diameters ranging from 5 mm to 100 nm, while NPs are particles measuring between 1 and 1000 nm (Cole et al., 2011; Gigault et al., 2018). These particles are originated from the primary or secondary sources by fragmentation of larger plastic items. Common polymers used to create MPs and NPs include PP, low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS), and polyamide (PA) (Barceló and Picó, 2019).

Research on micro and nanoplastics has significantly evolved over the past two decades. Initial studies focused primarily on the presence of these particles in marine areas, with significant contributions from authors such as Thompson et al. (2009), who first coined the term "microplastics" and highlighted their ecological impacts. Since then, the scope of research has expanded to include terrestrial ecosystems, with a growing recognition of the effects of MPs and NPs on soil health and agricultural productivity (Wong et al., 2020). Recent developments have emphasized the need for standardized methodologies in sampling and analyzing microplastics across different environments, as well as the importance of understanding the mechanisms of toxicity and bioaccumulation in food webs (Kochanek et al., 2025). Future research directions should focus on long-term ecological impacts, potential remediation strategies, and the development of biodegradable alternatives to conventional plastics, which could mitigate the ongoing pollution crisis.

The increasing presence of MPs and NPs in agricultural soils raises significant concerns regarding their impacts on ecosystems and human health (Wolff Leal et al., 2025). Studies indicate that MPs and NPs can penetrate deeper soil layers through tillage and soil biota activities, potentially impairing plant growth and entering the human food chain. These particles may remain in the soil, be taken up by plants, and accumulate in edible parts, posing risks to both plant and human health (Gao et al., 2025).

This review aims to address the following guiding question: How do micro and nanoplastics (MNPs) impact agricultural productivity and human health? The following sections will be structured as: (1) summarize the primary sources and pathways of MNPs contamination in agricultural soils, (2) critically evaluate the documented effects of MNPs on plant physiology and growth, and (3) synthesize the evidence for MNPs transfer through the food chain and the potential implications for human health.

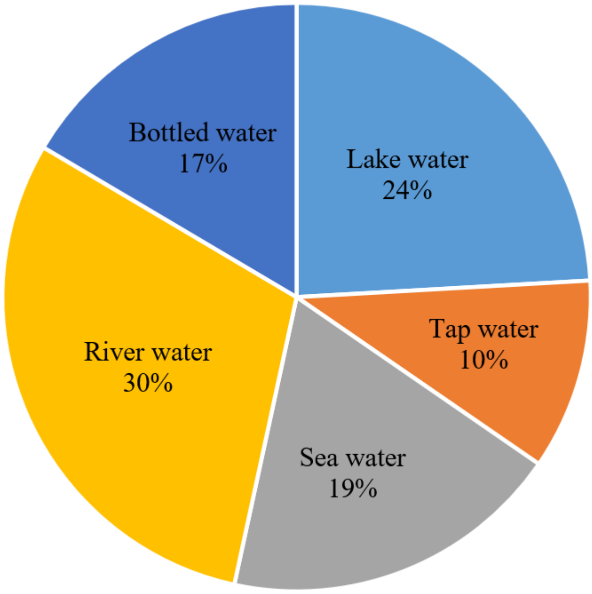

Figure 1. Microplastics in different aquatic ecosystems.

2. Methodology

To ensure a rigorous and systematic review, we employed a comprehensive literature search strategy using Scopus and Google Scholar databases. Our search primarily focused on articles published from 2018 to 2025, with exceptions made for seminal studies published prior to this timeframe when relevant literature was scarce. A combination of specific keywords, including microplastics, nanoplastics, soil, agriculture, plant uptake, and toxicity, was used to capture a broad spectrum of relevant research. Initially, we identified 150 articles through this search process. After applying our inclusion and exclusion criteria focusing on peer-reviewed experimental and field studies relevant to our objectives, we narrowed our selection down to 121 articles that provided the most pertinent insights into the effects of MPs and NPs on agricultural soils and plant physiology.

3. Results

3.1. The impacts of MNPs on aquatic environments

The increasing volume of plastic waste dumped into coastal regions has raised significant concerns about the prevalence of these debris with various sizes in marine environments and its potential effects on aquatic life (Brandts et al., 2018). Once in the water, larger plastic debris can be fragmented into smaller polymers, such as MPs and NPs, through processes of chemical and biological , and UV photodegradation (Koelmans et al., 2015; Lambert and Wagner, 2016). Due to their diminutive size, MPs and NPs evade removal by standard wastewater treatment processes, resulting in their inevitable entry into rivers, seas, and freshwater systems (Vance et al., 2015). Figure 1 shows the amount of MPs in different aquatic ecosystems (Bhowmik and Saha 2025).

It is estimated that plastic constitutes up to 85% of all marine debris, with approximately 80% of this waste originating from terrestrial sources (Auta et al., 2017). More than 800 million tons of plastics in the ocean are believed to have originated from land-based activities. Additionally, MPs and NPs are present in soil and can eventually migrate to aquatic systems through natural erosion processes (Horton et al., 2017). Of the 275 million tons of plastic waste generated in 2010, between 4.8 and 12.7 million tons ended up in aquatic systems (Mattsson et al., 2018). This highlights a critical gap in waste management practices and the urgent need for improved strategies to prevent plastic leakage into the environment.

Forecasts suggest that between 100 and 250 million tons of plastic litter could enter marine ecosystems by 2025, worsening the existing problem. Current research estimates that at least 5.25 trillion plastic particles, weighing up to 270,000 tons, are floating in the oceans of the world. Tiny plastic particles, defined as those smaller than 200 μm, are estimated to number between 15 and 51 trillion, accounting for approximately 93,000 to 236,000 tons, or around 1% of the global plastic waste (Rakesh et al., 2020). The annual production of plastic, encompassing over 5,800 distinct polymers, is approximately 400 million tons, illustrating the issue's enormity. According to Barceló and Picó (2019), approximately 4 trillion plastic bags and 1 million plastic bottles are used each year, contributing to an estimated 4–12 million tons of plastic in aquatic environments and around 270,000 floating plastic objects in marine and coastal habitats**.** If the current trend of plastic waste accumulation continues, MPs could outnumber the fisheris activities by 2050 (Prata et al., 2019), which poses serious ecological and economic implications.

MPs can be ingested and accumulated by various freshwater and marine species, including humans (Barría et al., 2020). The small size of NPs allows them to potentially disrupt the food chain, as they can concentrate in secondary consumers and be absorbed by organisms such as phytoplankton and zooplankton (Cedervall et al., 2012). This raises critical questions about the long-term ecological impacts of MNPs and their bioaccumulation in aquatic food webs. Despite the growing body of research, significant knowledge gaps remain regarding the specific mechanisms by which MNPs affect marine organisms and ecosystems. Understanding these interactions is crucial for assessing the broader implications of plastic pollution on marine biodiversity and food security. Further investigation is needed to explore the pathways of MNPs accumulation in marine species and the potential for these particles to enter human food systems, thereby posing health risks to consumers.

Fish are aquatic animals found all over the world and may be found in both freshwater and marine habitats. As a food product, they are essential in meeting the increasing global need for protein, which is increasing (Barría et al., 2020). A potential pathway for human exposure to NPs is

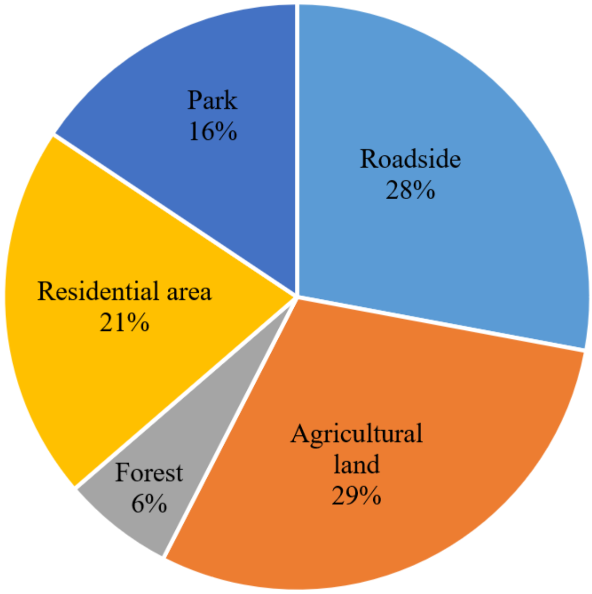

Figure 2. The amounts of microplastics in different terrestrial ecosystems.

established via the transmission of NPs to fish via the food chain (Barboza et al., 2018). However, determining the actual hazards and potential consequences that people may face from feeding marine species contaminated with NPs is important (Shen et al., 2019). The effects of MNPs on fish health can disrupt metabolic pathways, including catabolic processes, amino acid metabolism, and purine synthesis (Cheng et al., 2022), which may ultimately impact human health through the consumption of contaminated marine species.

3.2. The impacts of MNPs soil ecosystem

The contamination effects of MPs in terrestrial ecosystems may be 4-23 times greater than that of the oceanic environment (Horton et al., 2017). Figure 2 shows the level of microplastic contamination in different soil ecosystems which also indicates the highest level of microplastic contamination for the agricultural soils (Yoon et al., 2024).

Globally, large concentrations of MPs, ranging from 10 to 12,560 items, are found per kg of agricultural (Lv et al., 2019; Chen et al., 2020). Plastic items such as irrigation tubes, mulching films, silage films, boxes, packing materials, greenhouse or tunnel materials, harvesting nests, and plastic reservoirs are commonly found in agricultural soils (Bläsing and Amelung, 2018; Okeke et al., 2021). Additional sources include the use of intentionally plastic-containing goods, such as slow-release fertilizers or polymer-based insecticides (Kumar et al., 2020), polluted freshwater or cleansed wastewater for irrigation (Wang et al., 2021), and materials contaminated with MNPs, such as biosolids or organic fertilizers. These are all derived into soil when original components are utilized for agricultural activities. According to Bläsing and Amelung (2018), plastic contaminated with untreated and treated wastewater used for irrigation accounted for 1000–627,000 and 0–125,000 pieces m^{-3}, respectively, whereas compost and sewage sludge might contain 2.38–1200 and 1000–24,000 mg of MPs kg^{-1} of soil. According to Bläsing and Amelung (2018), the natural soil contamination resulting from floods with lake or river waters was responsible for 0.82–4.42 plastic fragments per m^{-3}.

These findings underscore the pervasive presence of microplastics in agricultural environments, raising concerns about their potential impact on soil health, crop productivity, and food safety, particularly as MPs and NPs can migrate from the topsoil where they accumulate and interact with plant roots into deeper soil layers through processes such as tillage, soil biota activities, and extensive fissures created by plowing (Rillig et al., 2017; Liu et al., 2018). The soil's water holding capacity may be adversely affected, microbial activity may be disturbed, a pH imbalance may arise, nutrient transfer may be interfered with, irrigation water permeability may be decreased, and soil structure may be harmed (Cao et al., 2017; Liu et al., 2018). Furthermore, interactions between soil microbiomes and MPs/NPs with smaller sizes and more concentrated regions affect the dynamics of soil nutrients and hinder their normal growth and function (Torres et al., 2021). For example, Lwanga et al. (2017) reported that earthworm development was severely inhibited and their death rate increased drastically (Qi et al., 2018). This is primarily due to the ingestion of microplastics, which can cause physical blockages in their digestive systems and introduce harmful chemicals, ultimately disrupting their physiological processes (Qi et al., 2018). Furthermore, MPs raise soil organic matter levels while simultaneously lowering soil organic nitrogen levels (Kim et al., 2021; Meng et al., 2022).

Since the early 1950s, plastics have increasingly been utilized in agriculture for various applications, such as improving crop yields, enhancing soil quality, and providing protective coverings for plants (Espi, 2006; Brodhagen et al., 2017). Mulch film sales were projected to exceed 83,000 tons in Europe in 2019 (Campanale et al., 2021) and will rise at a rate of 5.6% annually until 2030 (Huang et al., 2020). A landmark study assessing the use of plastics in agriculture to the end of 2021 was released by the Food and Agriculture Organization of the United Nations (FAO). In 2019, 12.5 million plastic goods were used in plant and animal production within agricultural value chains, and 37.3 million plastic products were used in food packaging. Industry analysts predict that between 2018 and 2030, the worldwide need for greenhouse, mulching, and silage films will increase by 50% between 2018 and 2030, from 6.1 to 9.5 million tons (FAO, 2021). Plastic mulching has become a popular method for protecting plants from severe weather conditions. It is mainly composed of low-density polyethylene (PE) and PP. Plastic mulch film has long been used to improve water consumption efficiency. Plastic mulch offers several financial benefits, but it remains in the soil after harvest, degrading soil quality and crop productivity (Liu et al., 2014; Yan et al., 2014). An immense quantity of plastic particles, classified as mega-, macro-, and MPs, are integrated into agricultural soils owing to the yearly introduction of new plastic leftovers and traditional tillage methods (Rillig et al., 2017). Practical challenges and high prices have impeded attempts to recycle plastic leftovers (Brodhagen et al., 2017).

3.3. Effects of MNPs on the plant's charachteristics

Different MNPs may cause different plant responses (De Souza Machado et al., 2019). The possible buildup of hazardous substances and MNPs in plant tissue in agricultural settings may affect human health as well as plant quality and productivity (Boots et al., 2019). The effects of micro and nanoplastics MNPs on plants are likely influenced by various factors, including the specific plant species, environmental conditions, and the type, size, and concentration of plastic particles present (Xu et al., 2019; De Souza Machado et al., 2019). According to Sun et al. (2021), MPs and NPs can accumulate in plants through the foliar and root absorption routes, respectively. Based on observations, MNPs may inhibit germination, impact plant's vegetative and reproductive development, induce genotoxicity and ecotoxicity, or otherwise encourage the growth of roots and shoots and an increase in biomass in general (Xu et al., 2019). Furthermore, according to Tian et al. (2021), MNPs may concentrate in plant roots before spreading to the leaves, flowers, and fruits of the plants. They may also encourage soil microbes to colonize roots (De Souza Machado et al., 2019).

Figure 3 shows that micro and nanoplastics can enter plants through various pathways. These particles can penetrate plant cells and be transported to other organs, such as stems and leaves, via the vascular system. In addition, nanoplastics can enter the plant through the leaf stomata and be translocated to other parts (Azeem et al., 2021). These plastic particles have various effects on plants. They can reduce photosynthetic parameters and chlorophyll content, induce oxidative stress, and alter the microbiological properties of the soil (Ren et al., 2021). Furthermore, they can block cell walls and limit the absorption of water and nutrients, potentially affecting plant growth and development (Larue et al., 2021).

MPs and NPs contaminate a wide range of primary agricultural crops, including cereals, oilseed crops, vegetables, and fruits (Table 1). Consequently, , these crops travel from farm to our plates, exposing humans to MPs and NPs. The largest concentrations of NPs have been found in apples and carrots (Conti et al., 2020). The data from tomato fruits showed that PS-NPs may being transported to plant stems and leaves through roots and accumulate in fruits so, endanger food safety(Gao et al., 2023).

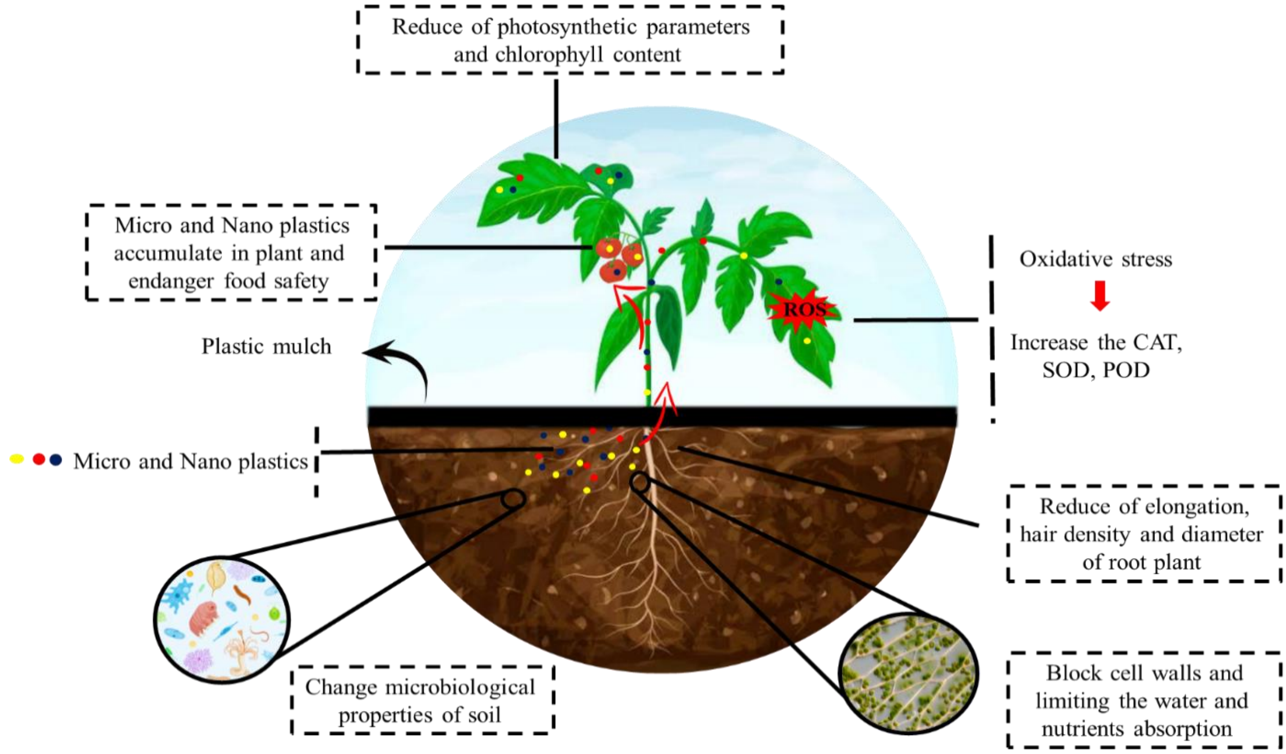

Figure 3. Pathways and impacts of micro- and nanoplastics on plant uptake and physiology.

MPs are easily absorbed on the surface of plant roots and seeds (Li et al., 2020b). For example, it has been discovered that MPs build up in the root surface of *Lepidium sativum*, a garden cress, and broad beans (*Vicia faba*) (Bosker et al., 2019). Furthermore, MPs can block cell walls or the connections of cells, limiting the quantity of water and nutrients absorption even if they are unable to penetrate into the cell walls themselves. However, Zhang et al. (2019) speculated that NPs are likely to pass through plant cell walls. Thus, NPs may be absorbed by vascular plants through their roots and other organs, a process known as "nutrient uptake" (Sun et al., 2021). The process by which these nanoparticles move from the plant cell wall to the apoplastic route by capillary action and osmotic pressure (Deng et al., 2014).

Furthermore, NPs may follow a simple route that involves ion transfer by endocytosis after interacting with membrane proteins, ion channels, and aquaporins (Tripathi et al., 2017). PS-NPs may enter tobacco cells by clathrin independent endocytosis (Bandmann et al., 2012). Some studies found that 100-nm PS-NPs (100 nm) may be taken up endocytotically by rice roots (Wu et al., 2021). Therefore, after entering plant roots, NPs can translocate to different organs, and the transpiration stream regulates how vigorously they do so. Similar results were reported by Li et al. (Li et al., 2020b), wherein a greater transpiration rate facilitated the absorption of plastic particles and, thus, caused their migration from the roots to the shoots. The stomata on plant leaves are another possible route through which nanoparticles might be absorbed (Lv et al., 2019). For example, stoma-entry-designed nanoparticles can reach various parts of the body via the apoplastic pathways of plants (Zhao et al., 2017). Lian et al. (2021) examined the relationship between plants and airborne NPs and found similar result. In this study, lettuce was treated topically with PS-NPs, which were then kept on them for a set period. Subsequently, microscopic analysis showed that PS-NPs traveled to the roots via the vascular bundle after entering the leaves through the stomata (Lv et al., 2019). Subsequent examination revealed a notable accumulation of NPs in the vicinity of the leaf stomata. Furthermore, another study clearly showed that PS (0.2 m) is mostly confined to the cortical tissue and xylem of wheat and lettuce roots, as well as in the leaves (Luo et al., 2022). The aforementioned observations demonstrate how readily NPs migrate along the vascular cylinder following the xylem, which carries nutrients and water to the shoot and leaves, once they have penetrated the vascular bundle of roots. However, NPs may also be transported by phloem, which is responsible for moving sugar and amino acids from leaves to other parts of the plant. This is demonstrated by the presence of NPs through the stomata on leaves. Furthermore, NPs can bind to proteins on cell membranes and enter cells. In particular, aquaporins are considered NP transporters within plant cells (Zhou et al., 2021).

Table 1. Effects of MPs or NPs on plant health of different species.

Common name	MPs or NPs	Plastic type	Size	Effect	Reference
Wheat	MPs	LDPE, Bio	Length: 6920000 ± 1470000 nm Width: 6100000 ± 1390000 nm	Root and shoot biomass, Leaf area, Number of leaves, Stem diameter ▼ Relative chlorophyll content ▲	Qi et al., 2018
Cucumber	NPs	PS	100, 300, 500, 700 nm	Mg, Ca, Fe ▼ MDA, Proline, Soluble protein ▲	Li et al., 2021
Cucumber	NPs	PS	100, 300, 500, 700 nm	Biomass plant, Chlorophyll a, Chlorophyll b, Soluble sugar, Carotenoid ▼ SOD, CAT, Vitamin C, Soluble protein ▲	Li et al., 2020a
Maize	NPs	$PS-NH_2$ PS-COOH	0, 10, 50, 100, 200, 400, 500 ng/spot	Fv/F0, qp, Rfd ▼ SOD, POD (Peroxidase), CAT, MDA, NPQ ▲	Sun et al., 2021
Maize	NPs	PS	10-100 $mg.L^{-1}$	Fresh weight, Growth, Root and shot length, SOD ▼ POD, CAT ▲	Wang et al., 2022
Tomato	NPs	PS	100 nm	Root and shoot length, Seed germination ▼ ROS, CAT, SOD ▲	Lakshmikanthan and Chandrasekaran., 2022
Tomato	MPs	MFB, MFL, LDPE	5 mm	Root: shoot ratio ▼ Chlorophyll content ▲	Weerasinghe and Madawala., 2022
Tomato	NPs	PS	60 nm	H_2O_2, MDA, ROS, SOD, CAT, POD ▲	Gao et al., 2023
Lettuce	MPs	PE	0.25,0.5,1 $mg.mL^{-1}$	Photosynthetic parameters, Chlorophyll content ▼ Antioxidant levels ▲	Gao et al., 2019
Lettuce	NPs	PS	0, 0.1, 1 $mg.L^{-1}$	Dry weight, Height, Leaf area, Chlorophyll a, b and carotenoid, Total antioxidant capacity ▼ EL ▲	Lian et al., 2021
Cress	MPs	Fluorescent	50, 500, 4800 nm	Germination rate, Root growth ▼	Bosker et al., 2019
Broad bean	MPs	PS	100 nm	CAT, Growth ▼ SOD, POD ▲	Jiang et al., 2019
Bean	MPs	LDPE, PLA	53000–1000000 nm	Chlorophyll content ▼ Root length, Leaf area ▲	Meng et al., 2021
Onion		PA	15000–20000 nm	Root length, Water content, Leaf nitrogen content▲ Root tissue density, Dry biomass, C/N ▼	de Souza Machado et al., 2019
		PES	8000 nm	Root length and colonization ,Dry biomass, C/N, Microbial activity▲ Water content, Leaf nitrogen content ▼	
		PEHD	643000 nm	Root length ▲	
		PP	624000 nm	Root length and colonization ▲ Water content ▼	
		PS	492000 nm	Root length ▲	
		PET	187000 nm	Root length and colonization ▲, Water content ▼	

▲ indicates an increase or enhancement; ▼ indicates a decrease or inhibition compared to the control. Microplastics (MPs), nanoplastics (NPs), low-density polyethylene (LDPE), polystyrene (PS), microfiber (MFB) microfilms (MFL), polyethylene (PE), polylactic acid (PLA), Polyester (PES), polyethylene high density (PEHD), polyethylene terephthalate (PET), magnesium (Mg), calcium (Ca), iron (Fe), malondialdehyde (MDA), superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), reactive oxygen species (ROS), hydrogen peroxide (H2O2), electrolyte leakage (EL).

3.3.1. Impact of MNPs on plant growth parameters

Plastic particles, particularly those sized between 500 and 4800 nm, can significantly lower water absorption and reduce the germination rates of soybean seeds (Li et al., 2021). El-Darier and Youssef (2000) emphasized that the presence of plastics in soil adversely modifies its environment, and affects seed germination. Notably, Gong et al. (2021) revealed varying degrees of vulnerability to PS exposure among different crop species. For instance, Italian lettuce exhibited the highest sensitivity, followed by radish, wheat, and maize. This variability can be attributed to genetic diversity among plant species, suggesting specialized detoxifying mechanisms or adaptive strategies to cope with environmental stressors (Chaves et al., 2002; Begum et al., 2011). The observed discrepancies in plant responses highlight the importance of considering multiple factors, such as MNPs size, polymer type, concentration, soil type, and specific plant species involved. For example, during early seedling development, root growth was significantly hindered in Italian lettuce, maize, and wheat, whereas radish showed minimal impact. This suggests that some crops may be more resilient to MNPs exposure due to their inherent biological traits.

Furthermore, an examination of root characteristics revealed that plants treated with PS experienced a marked reduction in root hair density. This decline has a negative impact on the root system, hindering the plant's ability to absorb water and nutrients, which can subsequently affect shoot growth and elongation. Weerasinghe and Madawala (2022) noted that in tomato plants, biomass allocation was skewed toward roots at low MNPs concentrations, likely as a strategy to enhance water uptake. Interestingly, while some studies have reported that MNPs can enhance soil aeration and promote aggregation (Khalid et al., 2020), De Souza Machado et al. (2019) found that PE fibers increased onion root and bulb weights by improving microbial activity and soil cohesion. These findings suggest that the effects of MNPs on plant growth are multifaceted and context-dependent, warranting further investigation. Despite these insights, a significant gap remains in our understanding of how different types of MNPs interact with various soil types and plant species. For instance, while polystyrene NPs have been widely studied, research on the effects of other common polymers, such as polyethylene, in agricultural systems is lacking. This knowledge gap is critical because it limits our ability to fully understand the ecological implications of plastic pollution in agriculture.

Li et al. (2020a) observed that cucumber plants exposed to 300 nm PS-NPs exhibited slower growth than those exposed to other sizes. This finding raises questions about the influence of particle size on plant metabolism, particularly regarding energy expenditure in breaking down soluble sugars. Notably, exposure to 700 nm PS-NPs did not significantly affect biomass, indicating that particle size may affect uptake versus degradation dynamics. The effects of PE and PVC on rice biomass further illustrate the unpredictable nature of MNPs impacts. Tong et al. (2023) reported that while these materials enhanced the above-ground biomass, they reduced the below-ground biomass. This variability could be influenced by differing soil properties, plant species responses, and polymer specific characteristics, underscoring the complexity of MNPs interactions in agricultural contexts. Lian et al. (2021) found that the antioxidant system in lettuce leaves exposed to PS-NPs was compromised, leading to leaf area and plant height reductions. Additionally, the introduction of varying quantities of plastic residue (0.1-1%) into the soil produced distinct effects on soybean growth throughout flowering and harvesting periods. Notably, while plant height increased in PE treatments before flowering, it dramatically declined after 80 days, particularly in treatments with 1% PE (Li et al., 2021b). Therefore, while the literature highlights various impacts of MNPs on plant growth, synthesizing these findings and identifying the moderating factors that contribute to such variability are crucial. Further research is needed to elucidate the mechanisms underlying these effects and to explore the interactions between different types of MNPs and agricultural practices.

3.3.2. Impact of MNPs on physiological parameters of plants

Exposure to MNPs has been shown to significantly affect plant physiological parameters. In cucumbers exposed to PS-NPs, there was a notable reduction in chlorophyll and carotenoid content and a decrease in the maximum quantum efficiency of photosystem II (Fv/Fm) (Li et al., 2020a). Under stressful conditions, ROS and MDA accumulation increases, leading to cellular membrane damage and a slowdown in photosynthesis (Alvarez et al., 1998). Further studies have indicated that plants treated with pure FluPS exhibited reduced chlorophyll concentrations across all treatments (Lakshmikanthan and Chandrasekaran, 2022). Wang et al. (2020) also reported that PLA led to a substantial reduction in chlorophyll content at higher concentrations, negatively impacting overall plant development. Conversely, PE did not exhibit similar effects. Interestingly, while tomato plants displayed concentration-dependent growth loss due to various MPs, no corresponding decrease in chlorophyll levels was observed (Weerasinghe and Madawala, 2022). This suggests that while MNPs may hinder growth, they do not necessarily impair the capacity of plants for photosynthetic processes, indicating a potential resilience or compensatory mechanism in some species.

The growth of *Cucurbita pepo* L. in soil contaminated with MPs made of PP, PE, PVC, and PBAT was expected to result in lower chlorophyll content and photosynthetic efficiency. Notably, the presence of PBAT MPs at 2.5

g·kg⁻¹ in soil negatively impacted the photosynthetic capacity of Arabidopsis plants through the release of adipic acid, phthalic acid, and butanediol, which are breakdown products of PBAT (Lian et al., 2022). Additionally, cucumber leaves exposed to 100 nm PS-NPs exhibited significantly lower proline levels than control leaves (Colzi et al., 2022; Li et al., 2020a). This suggests that the cucumber root system likely absorbed the 100 nm PS-NPs, which were then transported to the leaves via transpiration and root pressure. According to Li et al. (2020b), MNPs can cause organelle destruction in leaf tissue, and proline synthesis decreases as degradation increases, highlighting the stress response mechanisms in plants.

Moreover, understanding the relationship between oxidative stress and antioxidant enzyme activity is crucial for understanding plant responses to MNPs exposure. Tomato plants exhibiting higher levels of oxidative stress also showed increased CAT activity. The contact of coronated PS with seed cells significantly reduced enzyme activity, indicating that the nanoscale size of PS facilitates their infiltration into seed cells, where they generate ROS and weaken plant physiology. As the size of PS particles increases, along with the expansion of the eco-corona, the number of healthy cells, seed germination rates, ROS generation, and antioxidant enzyme activity also increase, making the NPs less permeable to seeds (Lakshmikanthan and Chandrasekaran, 2022). Furthermore, an increase in PS-NP concentration correlates with elevated SOD, POD, and CAT activities. These results indicate that plants exposed to PS-NPs experience oxidative stress, prompting an increase in antioxidant enzyme activity to mitigate ROS and a decrease in MDA levels to minimize oxidative damage (Gao et al., 2023). However, despite the identified responses, a significant gap in understanding the specific mechanisms by which different types of MNPs induce oxidative stress and how this varies among plant species remains. Dong et al. (2021) found that oxidative bursts occurred in carrot tissue cultured in hydroponic systems, with PS-MPs damaging the tertiary structure of carrot pectin methyl esterase. Additionally, the growth of tomato seedlings may have been adversely affected by a dose-dependent increase in hydrogen peroxide (H_2O_2) concentration due to PS-NP exposure (Gao et al., 2023). MDA levels increased following exposure to PS-NPs, indicating that PS-NPs accelerated lipid peroxidation in plant cell membranes. This suggests that the degree of lipid peroxidation worsens with higher PS-NP concentrations, leading to increased oxidative stress. Ultimately, while plants can mitigate some of the negative effects of high ROS levels through the production of antioxidant enzymes or antioxidants, the precise balance between ROS production and antioxidant response remains poorly understood. PS-NPs can induce oxidative stress in plants by promoting ROS production through electron transfer mechanisms (Gao et al., 2023). Further research is needed to elucidate these complex interactions and their implications for plant health and agricultural productivity.

3.4. Effect of MNPs on the human body

Ingestion of MNPs in terrestrial environments is a significant concern for human health. Individuals may consume between 39,000 and 52,000 MPs particles annually, depending on age and sex. When considering inhalation, this number rises to between 74,000 and 121,000 particles (Cox et al., 2019). Furthermore, individuals who drink bottled water may ingest up to 90,000 additional particles compared to those who only consume tap water, who may ingest an extra 4,000 particles (Cox et al., 2019). These findings underscore the alarming reality that a substantial proportion of the MPs consumed by humans originates from the food chain, highlighting the pervasive issue of terrestrial habitat pollution.

he presence of MPs in various food items, including table salt, honey, sugar, drinking water, and even traditional medicinal products derived from animals has been documented (Ding et al., 2020). This widespread contamination raises significant concerns regarding the potential impact of MNPs on human health (He et al., 2021). MNPs can adversely affect human health through mechanisms such as oxidative stress, inflammatory responses, genotoxicity, neurotoxicity, and mitochondrial dysfunction (Fournier et al., 2021). A recent investigation identified ingestion as the primary route of MNP exposure (Lehner et al., 2019). Ingestion of 150-m plastic particles measuring 150 μm can migrate from the stomach cavity into the circulatory system at a rate of 0.3% (Barboza et al., 2018). In a study by Leslie et al. (2022), the detection and quantification of plastic particles in human blood were reported for the first time, highlighting the severity of this issue.

Moreover, the accumulation of MPs/NPs in the human body has been linked to adverse inflammatory effects, increased lipid accumulation in the liver, and elevated activities of antioxidant enzymes, such as catalase (CAT) and superoxide dismutase (SOD), indicating oxidative stress (Lu et al., 2016). However, despite these findings, a significant gap remains in our understanding of the long-term implications of MNPs ingestion on human health. More research is needed to elucidate the underlying mechanisms of MNPs toxicity, particularly considering the chronic exposure scenarios that many individuals face (Campanale et al., 2020; Yee et al., 2021).

Table 2 summarizes the various impacts of MNPs on human health, emphasizing the need for further investigation into their physiological and biochemical effects. Addressing these knowledge gaps is crucial for developing effective public health strategies and regulatory measures to mitigate the risks associated with exposure to MPs.

Table 2. Effect of MPs or NPs on different aspects of human health.

Common name	MPs or NPs	Plastic type	Size	Effect	Reference
Embryonic kidney cells and hepatocellular	MPs	PS	1000 nm	Gene expression levels of the glycolytic enzyme, Glyceraldehyde-3-phosphate dehydrogenase, SOD, CAT ▼	Goodman et al., 2022
Peripheral blood lymphocytes	NPs	PS	50 nm	Chromosomal aberrations, such as chromosomal breaks and dicentric chromosomes, Nucleoplasmic bridge formation, Nuclear budding, Micronuclei formation and cytostasis% ▲	Sarma et al., 2022
Alveolar A549 cells	MPs	PS	1000, 10000 nm	Proliferation rate ▼ cell morphology Changes ▲	Goodman et al., 2021
Normal human intestinal CCD-18Co cells	NPs MPs	Fluorescent carboxylate-modified polystyrene beads	500, 2000 nm	Oxidative stress, Glycolysis ▲	Bonanomi et al., 2022
Hepatocellular carcinoma (HepG2) cell	NPs	PS-NH2	50 nm	SOD activity, GSH ▼ Oxidative stress, MDA ▲	He et al., 2020
Placental cells	NPs	PS	25, 50, 100, 500 nm	Reactive oxygen species, DNA damage, Lead to cell cycle arrest in G1or G2 phase, Inflammation and apoptosis ▲	Shen et al., 2022
Lung epithelial cells	NPs	PS	40 nm	Repair ability of the lung ▼ Matrix metallopeptidase, Surfactant protein A levels, Tissue damage, Cell death ▲	Yang et al., 2021
Hepatocellular carcinoma (HepG2)	NPs	PS	-	Adenosine triphosphate production, Mitochondrial membrane potentials, ROS ▼ Mitochondrial injuries, Upregulating dynamin-related protein 1 (DRP1) and P-DRP1 ▲	Li et al., 2023
CD34+ hematopoietic stem/progenitor cells (HSPCs)	NPs	PS	-	Cell viability, Pproliferation and differentiation of HSPCs, Metabolic activity ▼ Cell membrane damage ▲	Guo et al., 2023
Peripheral blood mononuclear cells (PBMCs)	NPs	PS	29, 44, 72 nm	PBMCs metabolic activity ▼ Single/double-strand break formation, Oxidized purines and pyrimidines, 8-oxo-2′-deoxyguanosine levels ▲	Malinowska et al., 2022
Bone marrow-derived mesenchymal stem cells (hBM-MSCs)	NPs	PS	-	HSP70 and XBP1 ▼ Proportion of cells in the S phase, Promoted cell proliferation, Adipogenic differentiation of hBM-MSCs ▲	

▲ indicates an increase or enhancement; ▼ indicates a decrease or inhibition compared to the control. Microplastics (MPs), nanoplastics (NPs), polystyrene (PS), superoxide dismutase (SOD), catalase (CAT), glutathione (GSH), malondialdehyde (MDA), reactive oxygen species (ROS).

4. Discussion

The findings of this study reveal critical insights into the pervasive issue of MNPs in both and terrestrial environments. As plastic pollution continues to escalate, the literature indicates several overarching patterns and trends that warrant further exploration.

A prominent trend observed across the reviewed studies are the increasing prevalence of MNPs in various ecosystems, driven largely by human activities. The fragmentation of larger plastic debris into MPs and NPs, along with their subsequent entry into soil systems, underscores the need for comprehensive waste management strategies (Andrady, 2011). Additionally, the studies indicate that MPs are not only ubiquitous in aquatic environments but are also being increasingly detected in terrestrial systems, highlighting the interconnectedness of these ecosystems. Furthermore, the bioaccumulation of MNPs in the food chain has potential implications for both aquatic organisms and humans. The ability of MPs and NPs to be ingested by a wide range of species raises concerns about their effects on biodiversity and ecosystem health, as well as the potential for these particles to enter human food systems, thereby posing health risks to consumers (Lusher et al., 2017).

Despite the growing body of research, significant knowledge gaps remain in the MNPs field. The lack of standardized methods for the extraction and analysis of MNPs from environmental matrices, particularly soil and water, is one of the most pressing issues. This inconsistency complicates comparisons across studies and hinders the development of a cohesive understanding of MNPs dynamics in different ecosystems. Moreover, the difficulty in studying NPs in complex environmental matrices presents a methodological challenge. The small size and varied chemical compositions of NPs complicate their detection and quantification, leading to uncertainties in assessing their ecological impacts. Addressing these methodological challenges is crucial for advancing the field and ensuring that future research can effectively inform policy and management strategies.

The presence of MNPs in agricultural and marine environments extends beyond ecological concerns; they also intersect with issues of agricultural sustainability and food security. As MNPs accumulate in soils and water systems, they may adversely affect soil health and crop productivity, compromising food systems that rely on healthy ecosystems (Rillig et al., 2017). The ingestion of MNPs by agricultural crops could lead to contamination of the food supply, raising public health concerns (He et al., 2021). Furthermore, the presence of MNPs in aquatic ecosystems poses risks to fisheries and aquaculture, which are vital for food security in many regions. As these particles accumulate in fish and shellfish, there is a risk of transferring contaminants up the food chain, ultimately affecting human consumers (Cedervall et al., 2012). This highlights the need for integrated approaches to environmental policy that consider the implications of plastic pollution on ecosystem health and food security. It is essential to develop and implement comprehensive policies aimed at reducing plastic waste and mitigating its impacts to address the challenges posed by MNPs. Strategies include promoting circular economy practices, enhancing waste management systems, and supporting research into biodegradable alternatives to conventional plastics. Additionally, regulatory frameworks should be established to monitor and manage MNP levels in agricultural and aquatic systems, ensuring that the health of both ecosystems and human populations is safeguarded. In conclusion, the synthesis of findings presented in this paper underscores the urgent need for a dedicated discussion on the implications of MNPs in our environment. By addressing the identified knowledge gaps and methodological challenges and by exploring the broader implications for agricultural sustainability and food security, future research and policy initiatives aimed at combating plastic pollution can be better informed.

5. Conclusions

The rising usage of micro and nanoplastics (MNPs) in today's society has brought forth new threats to the environment and human health. These particles pose significant hazards to various organisms, particularly fish, as they infiltrate both aquatic and terrestrial habitats. Moreover, health concerns regarding the absorption of MNPs by plants are growing, which can impact food safety and security. This review contributes to the field by synthesizing current knowledge on MNPs pollution, identifying critical research gaps, and highlighting the urgent need for comprehensive strategies to mitigate these risks. By emphasizing the interconnectedness of MNPs contamination across ecosystems, this study underscores the need for an integrated approach to environmental management and policy development. Several measures can be employed to reduce these hazards. Public awareness campaigns can inform consumers about the origins and potential effects of MNPs to positively influence consumer behavior. Additionally, the entry of microplastics (MPs) into agricultural lands and aquatic bodies can be diminished by supporting the use of organic fertilizers and soil additives, as well as promoting sustainable agricultural practices.

The development of environmentally friendly plastic substitutes and sustainable packaging materials is essential for reducing the release of MNPs into the environment. Governments play a critical role by enacting legislation and implementing regulations to restrict or prohibit the use of MNPs in cleaning supplies, personal hygiene products, and other consumer items. Policies that promote the use of biodegradable materials and regulate the industrial release of MNPs should also be prioritized. It is vital to urgently address MNPs contamination in agricultural systems, as these pollutants threaten soil health and crop productivity, directly impacting food security.

Future studies should focus on the health consequences of the consumption of MNPs in humans and animals, including potential adverse effects on the nervous, digestive, and respiratory systems. It is essential to develop sensitive and accurate methods for identifying and quantifying MNPs across various environmental media, including biological samples, soil, and water. Understanding the behavior, dispersal, and long-term fate of MNPs in diverse ecosystems, as well as their potential for bioaccumulation in the food chain, is crucial. Innovative technologies, such as advanced filtration systems and bioremediation techniques, should be prioritized for the extraction and cleanup of MNPs from environmental compartments. Finally, assessing the effectiveness of existing laws and policies aimed at reducing MP pollution and exploring avenues for creating new regulatory frameworks that comprehensively address this pressing issue are imperative. By concentrating on these research areas, we can enhance our understanding of MNPs pollution and develop practical strategies to mitigate its impacts on the environment and human health.

References

Alabi, O. A., Ologbonjaye, K. I., Awosolu, O., & Alalade, O. E. (2019). Public and environmental health effects of plastic wastes disposal: a review. Journal Toxicology and Risk Assessment, 5, 21. https://doi.org/10.23937/2572-4061.1510021.

Ali, I., Cheng, Q., Ding, T., Yiguang, Q., Yuechao, Z., Sun, H., Peng, C., Naz, I., Li, J., & Liu, Jing-Fu. (2021). Micro-and nanoplastics in the environment: Occurrence, detection, characterization and toxicity–A critical review. Journal of Cleaner Production, 313, 127863. https://doi.org/10.1016/j.jclepro.2021.127863.

Alvarez, M. E., Pennell, R. I., Meijer, P. J., Ishikawa, A., Dixon, R. A., & Lamb, C. (1998). Reactive oxygen intermediates mediate a systemic signal network in the establishment of plant immunity. Cell, 92, 773-784. https://doi.org/10.1016/s0092-8674(00)81405-1.

Andrady, A. L. (2011). Microplastics in the marine environment. Marine Pollution Bulletin, 62, 1596-1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Auta, H. S., Emenike, C. U., & Fauziah, S. H. (2017). Distribution and importance of microplastics in the marine environment a review of the sources, fate, effects, and potential solutions. Environment International, 102, 165–176. https://doi.org/10.1016/j.envint.2017.02. 013.

Azeem, I., Adeel, M., Ahmad, M. A., Shakoor, N., Jiangcuo, G. D., Azeem, K., Ishfaq, M., Shakoor, A., Ayaz, M., Xu, M., & Rui, Y. (2021). Uptake and accumulation of nano/microplastics in plants: a critical review. Nanomaterials, 11, 2935. https://doi.org/10.3390/nano11112935.

Bakhshaee, A., Babakhani, P., Ashiq, M. M., Bell, K., Salehi, M., & Jazaei, F. (2025). Potential impacts of microplastic pollution on soil–water–plant dynamics. Scientific Reports, 15, 9784. https://doi.org/10.1038/s41598-025-93668-0.

Bandmann, V., Müller, J. D., Köhler, T., & Homann, U. (2012). Uptake of fuorescent nano beads into BY2-cells involves clathrin-dependent and clathrin-independent endocytosis. FEBS Letters, 586, 3626–3632. https://doi.org/10.1016/j.febslet.2012.08.008.

Barboza, L. G. A., Vethaak, A. D., Lavorante, B. R., Lundebye, A. K., & Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. Marine Pollution Bulletin, 133, 336–348. https://doi.org/10.1016/j.marpolbul.2018.05.047.

Barceló, D., & Picó, Y. (2019). Microplastics in the global aquatic environment: analysis, effects, remediation and policy solutions. Journal of Environmental Chemical Engineering, 7, 103421. https://doi.org/10.1016/ j.jece.2019.103421.

Barría, C., Brandts, I., Tort, L., Oliveira, M., & Teles, M. (2020). Effect of nanoplastics on fish health and performance: A review. Marine Pollution Bulletin, 151, 110791. https://doi.org/10.1016/j.marpolbul.2019.110791.

Begum, P., Ikhtiari, R., & Fugetsu, B. (2011). Graphene phytotoxicity in the seedling stage of cabbage, tomato, red spinach, and lettuce. Carbon, 49, 3907–3919. https://doi.org/10.1016/j.carbon.2011.05.029.

Bhowmik, A., & Saha, G. (2025). Microplastics in our waters: insights from a configurative systematic review of water bodies and drinking water sources. Microplastics, 4, 24. https://doi.org/10.3390/microplastics4020024.

Bläsing, M., & Amelung, W. (2018). Plastics in soil: Analytical methods and possible sources. Science of The Total Environment, 612, 422–435. https://doi.org/10.1016/j.scitotenv.2017.08.086. https://doi.org/10.1016/j.ecolind.2023.109966.

Bonanomi, M., Salmistraro, N., Porro, D., Pinsino, A., Colangelo, A. M., & Gaglio, D. (2022). Polystyrene micro and nano-particles induce metabolic rewiring in normal human colon cells: A risk factor for human health. Chemosphere, 303, 134947. https://doi.org/10.1016/j.chemosphere.2022.134947.

Boots, B., Russell, C. W., & Green, D. S. (2019). Effects of microplastics in soil ecosystems: above and below ground. Environmental science & technology, 53, 11496–11506. https://doi.org/10.1021/acs.est.9b03304.

Bosker, T., Bouwman, L. J., Brun, N. R., Behrens, P., & Vijver, M. G. (2019). Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant Lepidium sativum. Chemosphere, 226, 774–781. https://doi.org/10.1016/j.chemosphere.2019.03.163. https://doi.org/10.1016/j.jhazmat.2020.123590.

Brandts, I., Teles, M., Tvarijonaviciute, A., Pereira, M. L., Martins, M. A., Tort, L., & Oliveira, M. (2018). Effects of polymethylmethacrylate nanoplastics on Dicentrarchus labrax. Genomics, 110, 435-441. https://doi.org/10.1016/j.ygeno.2018.10.006.

Brodhagen, M., Goldberger, J. R., Hayes, D. G., Inglis, D. A., Marsh, T. L., & Miles, C. (2017). Policy considerations for limiting unintended residual plastic in agricultural soils. Environmental Science & Policy, 69, 81e84. https://doi.org/10.1016/j.envsci.2016.12.014.

Campanale, C., Galafassi, S., Savino, I., Massarelli, C., Ancona, V., Volta, P., & Uricchio, V.F. (2021). Microplastics pollution in the terrestrial environments: Poorly known diffuse sources and implications for plants. Science of The Total Environment, 805, 150431. https://doi.org/10.1016/j.scitotenv.2021.150431.

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Uricchio, V. F. (2020). A detailed review study on potential effects of microplastics and additives of concern on human health. International Journal of Environmental Research and Public Health, 17, 1212. https://doi.org/10.3390/ijerph17041212.

Cao, D., Wang, X., Luo, X., Liu, G., & Zheng, H. (2017). Efects of polystyrene microplastics on the ftness of earthworms in an agricultural soil. IOP Conference Series: Earth and Environmental Science, 61, 012148. https://doi.org/10.1088/1755-1315/61/1/012148.

Cedervall, T., Hansson, L. A., Lard, M., Frohm, B., & Linse, S. (2012). Food chain transport of nanoparticles affects behaviour and fat metabolism in fish. PLoS One, 7, 1–6. https:// doi.org/10.1371/journal.pone.0032254.

Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osório, M. L., Carvalho, I., Faria, T., C., P., 2002. How plants cope with water stress in the field. Photosynthesis and growth. Ann. Bot. 89, 907–916

Chen, Y., Leng, Y., Liu, X., & Wang, J. (2020). Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. Environmental Pollution, 257, 113449. https://doi.org/10.1016/j.envpol.2019.113449.

Cheng, H., Duan, Z., Wu, Y., Wang, Y., Zhang, H., Shi, Y., Zhang, H., Wei, Y., & Sun, H. (2022). Immunotoxicity responses to polystyrene nanoplastics and their related mechanisms in the liver of zebrafish (Danio rerio) larvae. Environment International, 161, 107128. https://doi.org/10.1016/j.envint.2022.107128.

Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: a review. Marine Pollution Bulletin, 62, 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Colzi, I., Renna, L., Bianchi, E., Castellani, M. B., Coppi, A., Pignattelli, S., Loppi, S., & Gonnelli, C. (2022). Impact of microplastics on growth, photosynthesis and essential elements in Cucurbita pepo L. Journal of Hazardous Materials, 423, 127238. https://doi.org/10.1016/j.jhazmat.2021.127238.

Conti, G. O., Ferrante, M., Banni, M., Favara, C., Nicolosi, I., Cristaldi, A., Fiore, M., & Zuccarello, P. (2020). Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population. Environmental Research, 187, 109677. https://doi.org/10.1016/j.envres.2020.109677.

Cox, K. D., Covernton, G. A., Davies, H. L., Dower, J. F., Juanes, F., & Dudas, S. E. (2019). Human consumption of microplastics. Environmental Science & Technology, 53, 7068-7074. https://doi.org/10.1021/acs.est.9b01517.

Deng, T. H. B., Cloquet, C., Tang, Y. T., Sterckeman, T., Echevarria, G., Estrade, N., Morel, J. L., & Qiu, R. L. (2014). Nickel and zinc isotope fractionation in hyper accumulating and non accumulating plants. Environmental Science & Technology, 48, 11926–11933. https://doi.org/10.1021/es5020955.

de Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., & Rillig, M. C. (2019). Microplastics can change soil properties and affect plant performance. Environmental Science & Technology, 53, 6044-6052. https://doi.org/10.1021/acs.est.9b01339 .

Ding, L., Zhang, S. Y., Wang, X. Y., Yang, X. M., Zhang, C. T., Qi, Y. B., & Guo, X. T. (2020). The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in north-western China. Science of the Total Environment, 720, 137525. https://doi.org/10.1016/j.scitotenv.2020.137525.

Dong, Y., Gao, M., Qiu, W., & Song, Z. (2021). Uptake of microplastics by carrots in presence of As (III): Combined toxic effects. Journal of Hazardous Materials, 411, 125055. https://doi.org/10.1016/j.jhazmat.2021.125055.

El-Darier, S. M., & Youssef, R. S. (2000). Effect of soil type, salinity, and allelochemicals on germination and seedling growth of a medicinal plant Lepidium sativum L. Annals of Applied Biologyl, 136, 273e279. https://doi.org/10.1111/j.1744- 7348.2000.tb00035.x

Espi, E. (2006). PLastic films for agricultural applications. Journal of Plastic Film & Sheeting, 22, 85-102. http://dx.doi.org/10.1177/8756087906064220.

FAO. (2021). Assessment of agricultural plastics and their sustainability. A call for action. Rome, Italy. https://doi.org/10.4060/cb7856en.

Fournier, E., Etienne-Mesmin, L., Grootaert, C., Jelsbak, L., Syberg, K., Blanquet-Diot, S., & Mercier-Bonin, M. (2021). Microplastics in the human digestive environment: A focus on the potential and challenges facing in vitro gut model development. Journal of Hazardous Materials, 415, 125632. https://doi.org/10.1016/j.jhazmat.2021.125632.

Gao, M., Liu, Y., & Song, Z. (2019). Effects of polyethylene microplastic on the phytotoxicity of di-n-butyl phthalate in lettuce (Lactuca sativa L. var. ramosa Hort). Chemosphere, 237, 124482. https://doi.org/10.1016/j.chemosphere.2019.124482.

Gao, S., Mu, X., Li, W., Wen, Y., Ma, Z., Liu, K., & Zhang, C. (2025). Invisible threats in soil: microplastic pollution and its effects on soil health and plant growth. Environmental Geochemistry and Health, 47, 158. https://doi.org/10.1007/s10653-025-02464-2.

Gao, M., Wang, Z., Jia, Z., Zhang, H., & Wang, T. (2023).

Brassinosteroids alleviate nanoplastic toxicity in edible plants by activating antioxidant defense systems and suppressing nanoplastic uptake. Environment International, 174, 107901. https://doi.org/10.1016/j.envint.2023.107901.

Gigault, J., Halle, A. T., Baudrimont, M., Pascal, P. Y., Gauffre, F., Phi, T. L., El Hadri, H., Grassl, B., & Reynaud, S. (2018). Current opinion: What is a nanoplastic? Environmental Pollution, 235, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024.

Gong, W., Zhang, W., Jiang, M., Li, S., Liang, G., Bu, Q., & Lu, A. (2021). Species-dependent response of food crops to polystyrene nanoplastics and microplastics. Science of the Total Environment, 796, 148750. https://doi.org/10.1016/j.scitotenv.2021.148750.

Goodman, K. E., Hare, J. T., Khamis, Z. I., Hua, T., & Sang, Q. X. A. (2021). Exposure of human lung cells to polystyrene microplastics significantly retards cell proliferation and triggers morphological changes. Chemical Research in Toxicology, 34, 1069-1081. http://dx.doi.org/10.1021/acs.chemrestox.0c00486.

Goodman, K. E., Hua, T., & Sang, Q. X. A. (2022). Effects of polystyrene microplastics on human kidney and liver cell morphology, cellular proliferation, and metabolism. ACS Omega, 7, 34136-34153. http://dx.doi.org/10.1021/acsomega.2c03453.

Guo, X., Cheng, C., Cao, C., Li, D., Fan, R., & Wei, X. (2023). Metabolomic characteristics in human CD_{34}^{+} hematopoietic stem/progenitor cells exposed to polystyrene nanoplastics. Food and Chemical Toxicology, 177, 113817. https://doi.org/10.1016/j.fct.2023.113817.

He, Y., Li, J., Chen, J., Miao, X., Li, G., He, Q., Xu, H., Li, H., & Wei, Y. (2020). Cytotoxic effects of polystyrene nanoplastics with different surface functionalization on human HepG2 cells. Science of the Total Environment, 723, 138180. https://doi.org/10.1016/j.scitotenv.2020.138180.

He, D., Zhang, Y., & Gao, W. (2021). Micro (nano) plastic contaminations from soils to plants: human food risks. Current Opinion in Food Science, 41, 116-121. https://doi.org/10.1016/j.cofs.2021.04.001.

Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Science of The Total Environment, 586, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190.

Huang, Y., Liu, Q., Jia, W., Yan, C., & Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environmental Pollution, 260, 114096. https://doi.org/10.1016/j.envpol.2020.114096.

Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., & Klobučar, G. (2019). Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. Environmental Pollution, 250, 831–838. https://doi.org/10.1016/j.envpol.2019.04.055.

Khalid, N., Aqeel, M., & Noman, A. (2020). Microplastics could be a threat to plants in terrestrial systems directly or indirectly. Environmental Pollution, 267, 115653. https://doi.org/10.1016/j.envpol.2020.115653.

Kim, S. W., Jeong, S. W., & An, Y. J. (2021). Microplastics disrupt accurate soil organic carbon measurement based on chemical oxidation method. Chemosphere, 276, 130178. https://doi.org/10.1016/j.chemosphere.2021.130178.

Kochanek, A., Grąz, K., Potok, H., Gronba-Chyła, A., Kwaśny, J., Wiewiórska, I., Ciuła, J., Basta, E., & Łapiński, J. (2025). Micro- and nanoplastics in the environment: current state of research, sources of origin, health risks, and regulations—a comprehensive review. Toxics, 13, 564. https://doi.org/10.3390/toxics13070564.

Koelmans, A. A., Besseling, E., Shim, & W. J. (2015). Nanoplastics in the aquatic environment.Critical review. In: Marine anthropogenic litter. Springer. pp. 325-340. https://doi.org/10.1007/978-3-319-16510-3_12.

Kumar, M., Xiong, X., He, M., Tsang, D. C., Gupta, J., Khan, E., Harrad, S., Hou, D., Ok, Y. S., & Bolan, N. S. (2020). Microplastics as pollutants in agricultural soils. Environmental Pollution, 265, 114980. https://doi.org/10.1016/j.envpol.2020.114980.

Lakshmikanthan, D., & Chandrasekaran, N. (2022). Humic acid alleviates the toxicity of nanoplastics towards Solanum lycopersicum. Agronomy, 12, 2787. https://doi.org/10.3390/agronomy12112787.

Lambert, S., & Wagner, M. (2016). Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere, 145, 265–268. https://doi.org/10.1016/J.CHEMOSPHERE.2015.11.078.

Larue, C., Sarret, G., Castillo-Michel, H., & Pradas del Real, A. E. (2021). A critical review on the impacts of nanoplastics and microplastics on aquatic and terrestrial photosynthetic organisms. Small, 17, 2005834. https://doi.org/10.1002/smll.202005834.

Lehner, R., Weder, C., Petri-Fink, A., & Rothen-Rutishauser, B. (2019). Emergence of nanoplastic in the environment and possible impact on human health. Environmental Science & Technology, 53, 1748–1765. https://doi.org/10.1021/acs.est.8b05512.

Leslie, H. A., Van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantifcation of plastic particle pollution in human blood. Environment International, 163, 107199. https://doi.org/10.1016/j.envint.2022.107199.

Li, Y., Guo, M., Niu, S., Shang, M., Chang, X., Sun, Z., Zhang, R., Shen, X., & Xue, Y. (2023). ROS and DRP1 interactions accelerate the mitochondrial injury induced by polystyrene nanoplastics in human liver HepG2 cells. Chemico-Biological Interactions, 379, 110502. https://doi.org/10.1016/j.cbi.2023.110502.

Li, Z., Li, Q., Li, R., Zhao, Y., Geng, J., & Wang, G. (2020b). Physiological responses of lettuce (Lactuca sativa L.) to microplastic pollution. Environmental Science and Pollution Research, 27, 30306–30314. https://doi.org/10.1007/s11356-020-09349-0.

Li, Z., Li, Q., Li, R. Zhou, J., & Wang, G. (2021). The distribution and impact of polystyrene nanoplastics on cucumber plants. Environ Sci Pollut Res, 28, 16042–16053. https://doi.org/10.1007/s11356-020-11702-2

Li, Z., Li, R., Li, Q., Zhou, J., & Wang, G. (2020a). Physiological response of cucumber (Cucumis sativus L.) leaves to polystyrene nanoplastics pollution. Chemosphere, 255, 127041. https://doi.org/10.1016/j.chemosphere.2020.127041.

Lian, J., Liu, W., Meng, L., Wu, J., Chao, L., Zeb, A., & Sun, Y. (2021). Foliar-applied polystyrene nanoplastics (PSNPs) reduce the growth and nutritional quality of lettuce (Lactuca sativa L.). Environmental Pollution, 280, 116978. https://doi.org/10.1016/j.envpol.2021.116978.

Lian, Y., Liu, W., Shi, R., Zeb, A., Wang, Q., Li, J., Zheng, Z., & Tang, J. (2022). Effects of polyethylene and polylactic acid microplastics on plant growth and bacterial community in the soil. Journal of Hazardous Materials, 435, 129057. https://doi.org/10.1016/j.jhazmat.2022.129057.

Liu, E., He, W., & Yan, C. (2014). 'White revolution'to 'white pollution'dagricultural plastic film mulch in China. Environmental Research Letters, 9, 091001. http://dx.doi.org/10.1088/1748-9326/9/9/091001.

Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Cao, C., Shi, H., Yang, X., & He, D. (2018). Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. Environmental Pollution, 242, 855–862. https://doi.org/10.1016/j.envpol.2018.07.051.

Lu, Y., Zhang, Y., Deng, Y., Jiang, W., Zhao, Y., Geng, J., Ding, L., & Ren, H. (2016). Uptake and accumulation of polystyrene microplastics in zebrafsh (Danio rerio) and toxic efects in liver. Environmental Science & Technology, 50, 4054–4060. https://doi.org/10.1021/acs.est.6b00183.

Lusher, A. L., Hollman, P. C. H., & Mendoza, H. (2017). Microplastics in fisheries and aquaculture: Status of knowledge on their occurrence and implications for aquatic organisms and food safety. FAO Fisheries and Aquaculture Technical Paper, 615.

Luo, Y., Li, L., Feng, Y., Li, R., Yang, J., Peijnenburg, W. J., & Tu, C. (2022). Quantitative tracing of uptake and transport of submicrometre plastics in crop plants using lanthanide chelates as a dual-functional tracer. Nature Nanotechnology, 17, 424–431. https://doi.org/10.1038/s41565-021-01063-3.

Lv, W., Zhou, W., Lu, S., Huang, W., Yuan, Q., Tian, M., Lv, W., & He, D. (2019). Microplastic pollution in rice-fish co-culture system: a report of three farmland stations in Shanghai, China. Science of the Total Environment, 652, 1209–1218. https://doi.org/10.1016/j.envpol.2022.120656.

Lwanga, E. H., Gertsen, H., Gooren, H., Peters, P., Salánki, T., van der Ploeg, M., Besseling, E., Koelmans, A., & Geissen, V. (2017). Incorporation of microplastics from litter into burrows of Lumbricus terrestris. Environmental Pollution, 220, 523–531. https://doi.org/10.1016/j.envpol.2016.09.096.

Malinowska, K., Bukowska, B., Piwoński, I., Foksiński, M., Kisielewska, A., Zarakowska, E., Gackowski, D., & Sicińska, P. (2022). Polystyrene nanoparticles: the mechanism of their genotoxicity in human peripheral blood mononuclear cells. Nanotoxicology, 16, 791-811. https://doi.org/10.1080/17435390.2022.2149360.

Mattsson, K., Jocic, S., Doverbratt, I., & Hansson, L. A. (2018). Nanoplastics in the aquatic environment. in microplastic contamination in aquatic environments; Elsevier: Amsterdam, The Netherlands, pp. 379–399. https://doi.org/10.1016/B978-0-12-813747-5.00013-8.

Meng, F., Yang, X., Riksen, M., Xu, M., & Geissen, V. (2021). Response of common bean (Phaseolus vulgaris L.) growth to soil contaminated with microplastics. Science of the Total Environment, 10, 142516. https://doi.org/10.1016/j.scitotenv.2020.142516.

Meng, F., Yang, X., Riksen, M., & Geissen, V. (2022). Efect of diferent polymers of microplastics on soil organic carbon and nitrogen–A mesocosm experiment. Environmental Research, 204, 111938. https://doi.org/10.1016/j.envres.2021.111938.

Nizzetto, L., Futter, M., & Langaas, S. (2016). Are agricultural soils dumps for microplastics of urban origin? Environmental. Science. Technology. 50, 10777-10779. https://doi.org/10.1021/acs.est.6b04140.

Okeke, E. S., Okoye, C. O., Atakpa, E. O., Ita, R. E., Nyaruaba, R., Mgbechidinma, C. L., & Akan, O. D. (2021). Microplastics in agroecosystemsimpacts on ecosystem functions and food chain. Resources, Conservation and Recycling, 177, 105961. https://doi.org/10.1016/j.resconrec.2021.105961.

Prata, J. C., da Costa, J. P., Girão, A. V., Lopes, I., Duarte, A. C., & RochaSantos, T. (2019). Identifying a quick and efficient method of removing organic matter without damaging microplastic samples. Science of the Total Environment, 686, 131–139. https://10.1016/j.scitotenv. 2019.05.456.

Qi, Y., Yang, X., Pelaez, A. M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., & Geissen, V. (2018). Macro- and micro- plastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth. Science of the Total Environment, 645, 1048-1056. https://10.1016/j.scitotenv.2018.07.229.

Rakesh, S. S., Ramasamy, M., Ramesh, P. T., Maheswari,

M., Shri Rangasami, S. R., & Yuvaraj, M. (2020). Nanoplastics in 21st Century. Biotica Research Today, 2, 356-358.
Ren, X., Tang, J., Wang, L., & Liu, Q. (2021). Microplastics in soil-plant system: effects of nano/microplastics on plant photosynthesis, rhizosphere microbes and soil properties in soil with different residues. Plant and Soil, 462, 561-576. https://doi.org/10.1007/s11104-021-04869-1.
Rillig, M. C., Ingraffia, R., & Machado, A. A. D. (2017). Microplastic incorporation into soil in agroecosystems. Frontiers in Plant Science, 8, https://doi.org/10.3389/fpls.2017.01805.
Sarma, D. K., Dubey, R., Samarth, R. M., Shubham, S., Chowdhury, P., Kumawat, M., Verma, V., Tiwari, R. R., & Kumar, M. (2022). The biological effects of polystyrene nanoplastics on human peripheral blood lymphocytes. Nanomaterials, 12, 1632. https://doi.org/10.3390/nano12101632.
Shen, F., Li, D., Guo, J., & Chen, J. (2022). Mechanistic toxicity assessment of differently sized and charged polystyrene nanoparticles based on human placental cells. Water Research, 223, 118960. https://doi.org/10.1016/j.watres.2022.118960.
Shen, M., Zhang, Y., Zhu, Y., Song, B., Zeng, G., Hu, D., Wen, X., & Ren, X. (2019). Recent advances in toxicological research of nanoplastics in the environment: a review. Environmental Pollution, 252, 511–521. https://doi.org/10.1016/j.envpol.2019.05.102.
Song, Y. K., Hong, S. H., Eo, S., Han, G. M., & Shim, W. J. (2020). Rapid production of micro-and nanoplastics by fragmentation of expanded polystyrene exposed to sunlight. Environmental Science & Technology, 54, 11191-11200. https://doi.org/10.1021/acs.est.0c02288.
Sun, H., Lei, C., Xu, J., & Li, R. (2021). Foliar uptake and leafto-root translocation of nanoplastics with diferent coating charge in maize plants. Journal of Hazardous Materials, 416, 125854. https://doi.org/10.1016/j.jhazmat.2021.125854.
Thompson, R. C., Swan, S. H., Moore, C. J., & vom Saal, F. S. (2009). Our plastic age. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 364, 1973-1976. https://doi.org/10.1098/rstb.2009.0054.
Tian, L., Jinjin, C., Ji, R., Ma, Y., & Yu, X. (2021). Microplastics in agricultural soils: Sources, effects, and their fate. Current Opinion in Environmental Science & Health, 25, 100311. https://doi.org/10.1016/j.coesh.2021.100311.
Tong, Y., Ding, J., Xiao, M., Shahbaz, M., Zhu, Z., Chen, M., Kuzyakov, Y., Deng, Y., Chen, J., & Ge, T. (2023). Microplastics affect activity and spatial distribution of C, N, and P hydrolases in rice rhizosphere. Soil Ecology Letters, 5, 220138. https://doi.org/10.1007/s42832-022-0138-2.
Torres, F. G., Dioses-Salinas, D. C., Pizarro-Ortega, C. I., & De-la-Torre, G. E. (2021). Sorption of chemical contaminants on degradable and non-degradable microplastics: Recent progress and research trends. Science of the Total Environment, 757, 143875. https://doi.org/10.1016/j.scitotenv.2020.143875.
Tripathi, D. K., Singh, S., Singh, S., Srivastava, P. K., Singh, V. P., Singh, S., Prasad, S. M., Singh, P. K., Dubey, N. K., Pandey, A. C., & Chauhan, D. K. (2017). Nitric oxide alleviates silver nanoparticles (AgNps)-induced phytotoxicity in Pisum sativum seedlings. Plant Physiology and Biochemistry, 110, 167–177. https://doi.org/10.1016/j.plaphy.2016.06.015.
Vance, M. E., Kuiken, T., Vejerano, E. P., McGinnis, S. P., Hochella, M. F. J., Rejeski, D., & Hull, M. S. (2015). Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory. Beilstein Journal of Nanotechnology, 6, 1769–1780. https://doi.org/10.3762/bjnano.6.181.
Wang, W., Yuan, W., Xu, E. G., Li, L., Zhang, H., & Yang, Y. (2021). Uptake, translocation, and biological impacts of micro (nano) plastics in terrestrial plants: Progress and prospects. Environmental Research, 203, 111867. https://doi.org/10.1016/j.envres.2021.111867.
Wang, F., Zhang, X., Zhang, S., Zhang, S., & Sun, Y. (2020). Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere, 254, 126791. https://doi.org/10.1016/j.chemosphere.2020.126791.
Weerasinghe, T., & Madawala, H. (2022). Potential impacts of two types of microplastics on Solanum lycopersicum L. and arbuscular mycorrhizal fungi. Ceylon Journal of Science, 51, 137. https://doi.org/10.4038/cjs.v51i2.8008.
Wolff Leal, T., Tochetto, G., Lima, S. V. M., de Oliveira. P. V., Schossler. H. J., de Oliveira. C. R. S., & da Silva Júnior, A, H. (2025). Nanoplastics and microplastics in agricultural systems: effects on plants and implications for human consumption. Microplastics, 4, 16. https://doi.org/10.3390/microplastics4020016.
Wong, J. K. H., Lee, K. K., Tang, K. H. D., & Yap, P. S. (2020). Microplastics in the freshwater and terrestrial environments: Prevalence, fates, impacts and sustainable solutions. Science of the Total Environment, 719, 137512.
Wu, J., Liu, W., Zeb, A., Lian, J., Sun, Y., & Sun, H. (2021). Polystyrene microplastic interaction with Oryza sativa: Toxicity and metabolic mechanism. Environmental Science: Nano, 8, 3699–3710. https://doi.org/10.1039/D1EN00636C.
Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., Wang, H., Lu, Z., Brookes, P. C., Tang, C., Gan, J., & Xu, J. (2019). Microplastics in the soil environment: Occurrence, risks, interactions and fate–A review.

Critical Reviews in Environmental Science and Technology, 50, 2175–2222. https://doi.org/10.1080/10643389.2019.1694822.
Yan, C., He, W., & Turner, N. (2014). Plastic-film mulch in Chinese agriculture: importance and problems. World Agriculture, 4, 32e36.
Yang, S., Cheng, Y., Chen, Z., Liu, T., Yin, L., Pu, Y., & Liang, G. (2021). In vitro evaluation of nanoplastics using human lung epithelial cells, microarray analysis and co-culture model. Ecotoxicology and Environmental Safety, 226, 112837. https://doi.org/10.1016/j.ecoenv.2021.112837.
Yee, M. S. L., Hii, L. W., Looi, C. K., Lim, W. M., Wong, S. F., Kok, Y. Y., Tan, B. K., Wong, C. Y., & Leong, C. O. (2021). Impact of microplastics and nanoplastics on human health. Nanomaterials, 11, 496. https://doi.org/10.3390/nano11020496.
Yoon, J. H., Kim, B. H. & Kim, K. H. (2024). Distribution of microplastics in soil by types of land use in metropolitan area of Seoul. Applied Biological Chemistry, 67, 15. https://doi.org/10.1186/s13765-024-00869-8.
Zhang, S., Wang, J., Liu, X., Qu, F., Wang, X., Wang, X., Li, Y., & Sun, Y. (2019). Microplastics in the environment: A review of analytical methods, distribution, and biological efects. TrAC Trends in Analytical Chemistry, 111, 62–72. https://doi.org/10.1016/j.trac.2018.12.002.
Zhao, J., Ren, W., Dai, Y., Liu, L., Wang, Z., Yu, X., Zhang, J., Wang, X., & Xing, B. (2017). Uptake, distribution, and transformation of CuO NPs in a foating plant Eichhornia crassipes and related stomatal responses. Environmental Science & Technology, 51, 7686–7695. https://doi.org/10.1021/acs.est.7b01602.
Zhou, C. Q., Lu, C. H., Mai, L., Bao, L. J., Liu, L. Y., & Zeng, E. Y. (2021). Response of rice (Oryza sativa L.) roots to nanoplastic treatment at seedling stage. Journal of Hazardous Materials, 401, 123412. https://doi.org/10.1016/j.jhazmat.2020.123412.