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REVIEW

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Micro/Nanoplastics in plantation agricultural products: behavior process, phytotoxicity under biotic and abiotic stresses, and controlling strategies

Zhihao Lin[1†], Donghui Xu[1*†], Yiming Zhao[1], Bin Sheng[3], Zhijian Wu[4], Xiaobin Wen[3], Jie Zhou[1], Ge Chen[1], Jun Lv[1], Jing Wang[2*] and Guangyang Liu[1*]

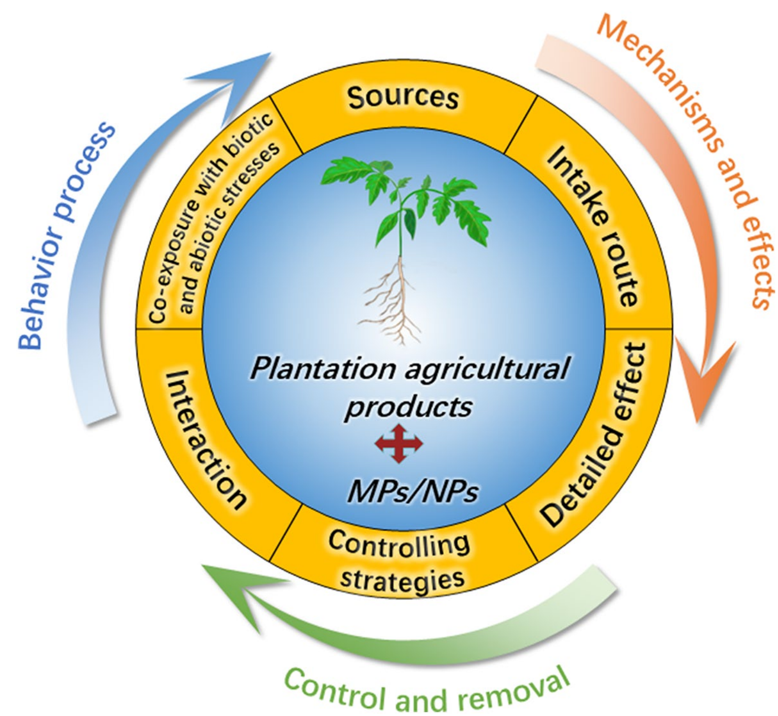
Abstract
With the extensive utilization of plastic products, microplastics/nanoplastics (MPs/NPs) contamination not only poses a global hazard to the environment, but also induces a new threat to the growth development and nutritional quality of plantation agricultural products. This study thoroughly examines the behavior of MPs/NPs, including their sources, entry routes into plants, phytotoxicity under various biotic and abiotic stresses (e.g., salinity, polycyclic aromatic hydrocarbons, heavy metals, antibiotics, plasticizers, nano oxide, naturally occurring organic macromolecular compounds, invasive plants, *Botrytis cinerea mycorrhizal fungi*.) and controlling strategies. MPs/NPs in agricultural systems mainly originate from mulch, sewage, compost fertilizer, municipal solid waste, pesticide packaging materials, etc. They enter plants through endocytosis, apoplast pathways, crack-entry modes, and leaf stomata, affecting phenotypic, metabolic, enzymatic, and genetic processes such as seed germination, growth metabolism, photosynthesis, oxidative stress and antioxidant defenses, fruit yield and nutrient quality, cytotoxicity and genotoxicity. MPs/NPs can also interact with other environmental stressors, resulting in synergistic, antagonistic, or neutral effects on phytotoxicity. To address these challenges, this review highlights strategies to mitigate MPs/NPs toxicity, including the development of novel green biodegradable plastics, plant extraction and immobilization, exogenous plant growth regulator interventions, porous nanomaterial modulation, biocatalysis and enzymatic degradation. Finally, the study identifies current limitations and future research directions in this critical field.

†Zhihao Lin and Donghui Xu Co first authors.

*Correspondence:
Donghui Xu
xudonghui@caas.cn
Jing Wang
w_jing2001@126.com
Guangyang Liu
liuguangyang@caas.cn

Full list of author information is available at the end of the article

Graphical Abstract



Keywords Agroecosystems, Emerging pollutants, Environmental behavior, Influencing mechanism, Phytoremediation strategies, Stressors

Introduction

Plastic items have been extensively utilized worldwide since their creation in the 1950s [1]. By 2060, the projected amount of plastic garbage is expected to >1.5 billion tons [1, 2]. Micro/nanoplastics (MPs/NPs) have been detected in various regions worldwide, including locations with high human activity [1–4]. This widespread distribution underscores the escalating severity of global plastic pollution. Plastic trash can break down into smaller particles due to external factors such as light, mechanical forces, chemical reactions, and biological processes [5, 6]. In 2004, the term "microplastics" was coined to describe plastic particles that are smaller than 5 mm [7], and the definition was followed by the National Oceanic and Atmospheric Administration (NOAA) as well [8]. Subsequently, some researchers have discovered plastic particles with even smaller particle sizes, defining plastic particles (<100 nm) as NPs [9, 10]. Alternatively, some individuals classify plastic particles with dimensions <1 μm as NPs [11]. The EU categorizes plastics based on their size: MPs (1 μm –5 mm), sub-MPs (100 nm–1 μm), and NPs (1–100 nm) [9]. Hence, MPs have a widely accepted definition based on their sizes after NOAA and EU standard, but there has not been clearly recognized international definitions for NPs.

As an emerging pollutant, MPs/NPs are extensively found in various mediums such as freshwater bodies, oceans, lakes, atmosphere and agricultural fields [9, 12]. Plantation agricultural products (vegetables, crops and fruits), rich in essential carbohydrates, vitamins, inorganic salts and dietary fiber, are a major part of the food composition in our daily diet. Recently, more and more studies have reported that MPs/NPs could be enriched and migrated in plantation agricultural products (barley [13], peanut [14], rice [14], strawberry [15]), which presents a possible hazard to the quality and safety of agricultural products. MPs/NPs could be uptaken and accumulate in cells and alter cellular activity, affecting the growth of cucumber [16], wheat [17] and lettuce [17]. During the process of seed germination and root growth, MPs/NPs have the potential to disrupt crucial physiological processes by obstructing the pores in the cell wall, so restricting the absorption of water and nutrients in corn [18], lettuce [19] and wheat [20]. Due to their hydrophobic nature and large surface area, MPs/NPs can adsorb a wide range of biotic and abiotic stressors, including heavy metals [21–26], antibiotics [27, 28], plasticizers [29], polycyclic aromatic hydrocarbons (PAHs) [30–33], humic acid [34], invasive plants (*Canadian goldenrod*) [35], *Botrytis cinerea mycorrhizal fungi* [36, 37]. This adsorption occurs through various mechanisms such as electrostatic interactions, van der Waals forces, hydrogen bonding, halogen bonding, hydrophobic interactions, micropore filling, and π-π interactions [30–34]. Co-exposure to these stressors induces complex toxicity, posing significant ecological risks and adversely affecting the growth and quality of agricultural products [29–33]. Therefore, it's critical to understand the behavior process, phytotoxicity under biotic and abiotic stresses on plantation agricultural products, which is advantageous for evaluating the hazards presented by MPs and NPs.

While there have been reviews discussing the impact of MPs on aquatic and terrestrial plants, there is still limited understanding of the behavior process (sources and intake route), the phytotoxicity of individual and co-exposure to MPs/NPs under biotic and abiotic stresses in the growth of agricultural products, and the strategies for controlling and removing MPs/NPs. These areas of research are still in their early stages. Only in the past six years have scientists begun to steadily focus on the impact of MPs/NPs on the growth of agricultural products in the plantation industry. Up to November 1, 2024, a search on Web of Science for "microplastics" or "nanoplastics" and "fruits" or "vegetables" or "crops" returned 605 publications from 2018 to 2023 (Fig. 1). The field is receiving more and more attention every year (Fig. 1a), with China has published research far more than other countries (Fig. 1b). However, only about 8.3% and 9.5% of the publications dealt with plant science and agriculture, respectively (Fig. 1c), especially the impact of MPs/NPs on plantation agricultural products (151 articles).

This study aims to analyze the advancement and boundaries in understanding the environmental behavior of MPs/NPs, the phytotoxicity resulting from co-exposure to biotic and abiotic stressors, and the regulated measures employed in plantation agricultural goods. The primary goals of this review are to: (1) Delineate the origins of MPs/NPs in agricultural planting systems

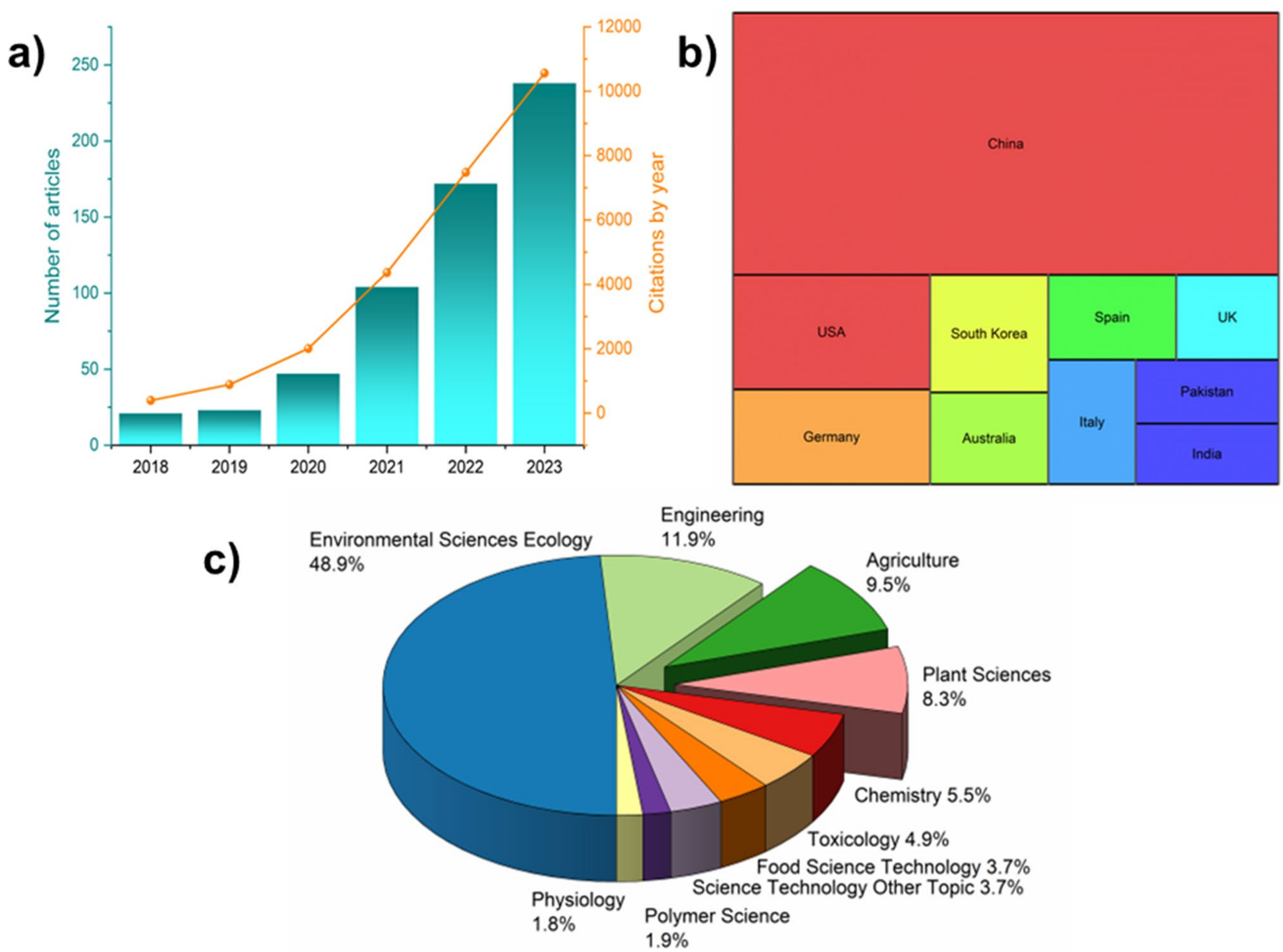


Fig. 1 Publication analysis of research topics related to "microplastics" or "nanoplastics" and "fruits" or "vegetables" or "crops" (pale green bars) and citations received per each year considered (orange points) (**a**), the publication quantity in the most active countries (The area of the rectangle is proportional to the percentage of publications in each country) (**b**), and the publication quantity each year and the percentage in each research field (**c**), respectively. The data is obtained from Web of Science, Nov. 1st, 2024

and their uptake by plants; (2) Analyze the impact of MPs/NPs on plants, including the molecular mechanisms involved and the variables that influence them; (3) Examine the interactions between MPs/NPs and other biotic and abiotic stresses, and the resulting phytotoxicity caused by their combined exposure on plants; (4) Present the potential controlling strategies for MPs/NPs of plantation agricultural products in the cultivation process, especially the latest perspectives on MPs/NPs mitigants (phytohormones, novel porous nanomaterials, etc.). Finally, we discuss the shortcomings and challenges of current research and provide an outlook on future directions, contributing to ensure improved growth and yield of agricultural products in MPs/NPs contaminated areas globally.

Sources of MPs/NPs in plantation agricultural products

Since their inception, plastic products have been extensively integrated into modern agricultural systems due to their ability to enhance crop yields, improve product quality, and reduce production costs [5, 38]. For example, plastic films are widely employed for their thermal insulation and moisture retention properties, which effectively conserve soil nutrients and mitigate the incidence of diseases and pests [39]. Similarly, plastic pipes have supplanted traditional metal materials in irrigation and greenhouse construction, significantly lowering associated costs [10, 12, 40]. However, under the combined effects of environmental factors such as ultraviolet radiation, mechanical abrasion, chemical oxidation, and biodegradation, plastic waste undergoes fragmentation into particles of specific size ranges, thereby forming MPs or

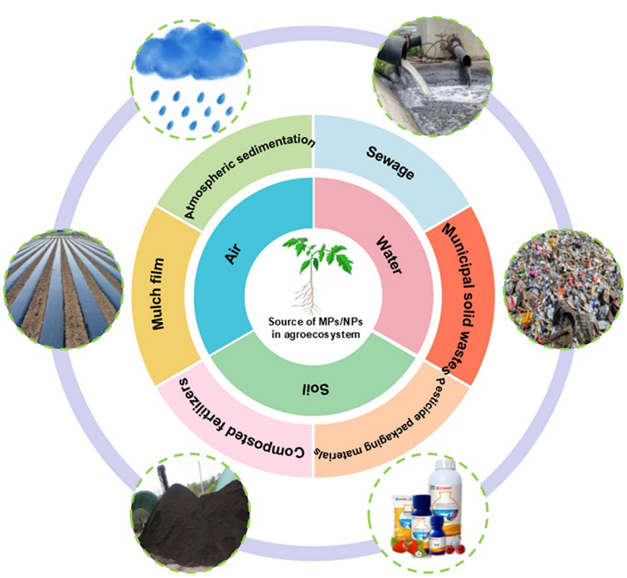


Fig. 2 Sources of MPs/NPs in plantation agricultural products [12, 41–43, 51–61]

NPs [5]. The degree of degradation is affected by plastic type, radiation, precipitation, heat, soil properties, mechanical stress, microbial activity and so on [5, 40, 41]. The predominant types of MPs/NPs utilized in agricultural production are polyacrylonitrile (PAN), polybutylene terephthalate (PBT), polyethylene (PE), polyethylene terephthalate (PET), polylactic acid (PLA), polymethylmethacrylate (PMMA), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC) [42]. The state of large-sized plastics in the environment is generally related to their density and shape [43]. When plastic particles reach the micron scale, MPs may combine with heavy metals or microorganisms to alter their buoyancy [44]. And at the nanoscale, collisions of NPs with water molecules and other ions could cause NPs to float in water without settling [45, 46]. Either MPs/NPs drift away with the atmosphere, or they are adsorbed in the soil and interact with soil microorganisms [47, 48]. NPs, characterized by their nanoscale dimensions, extensive specific surface area, and enhanced surface reactivity, exhibit dynamic environmental behaviors. These particles can experience multifaceted transformation pathways through processes such as: (1) physical modification via aggregation or fragmentation, (2) interfacial interactions with organic macromolecules, (3) redox-mediated chemical conversion, and (4) biologically induced alterations mediated by environmental factors [9, 49, 50]. During the growth process, MPs/NPs could contaminate agricultural products (fruits, vegetables, cereal crops, commercial crops, etc.) through water [51], air [52] and soil [53], which are mainly derived from mulch film [54], sewage [55], composted fertilizers [56], municipal solid wastes [43, 57], pesticide packaging materials [58], and so on (Fig. 2). The sources of MPs in agricultural production systems were well reviewed recently [12, 41, 42, 59–61]. Therefore, we do not elaborate more, but focus on the pathways by which MPs/NPs enter agricultural products and associated impacts.

Uptake and translocation pathways of MPs/NPs in plantation agricultural products

Currently, the main modes of MPs/NPs entry into plantation agricultural products are endocytosis [14, 18, 62], apoplast pathway [15, 63–65], Crack-entry mode [16, 17, 66] and stomata in leaves [19, 67] (Fig. 3). Nevertheless, there is a scarcity of studies regarding the absorption and transportation of MPs/NPs and their accumulation in produced agricultural products. When released into the environment, MPs/NPs can be internalized by plants through multiple uptake pathways. These pathways are influenced by both plant physiological characteristics and the physicochemical properties of the particles, including their size distribution, surface charge, and morphological features [18, 66]. Upon entering the plant via the routes

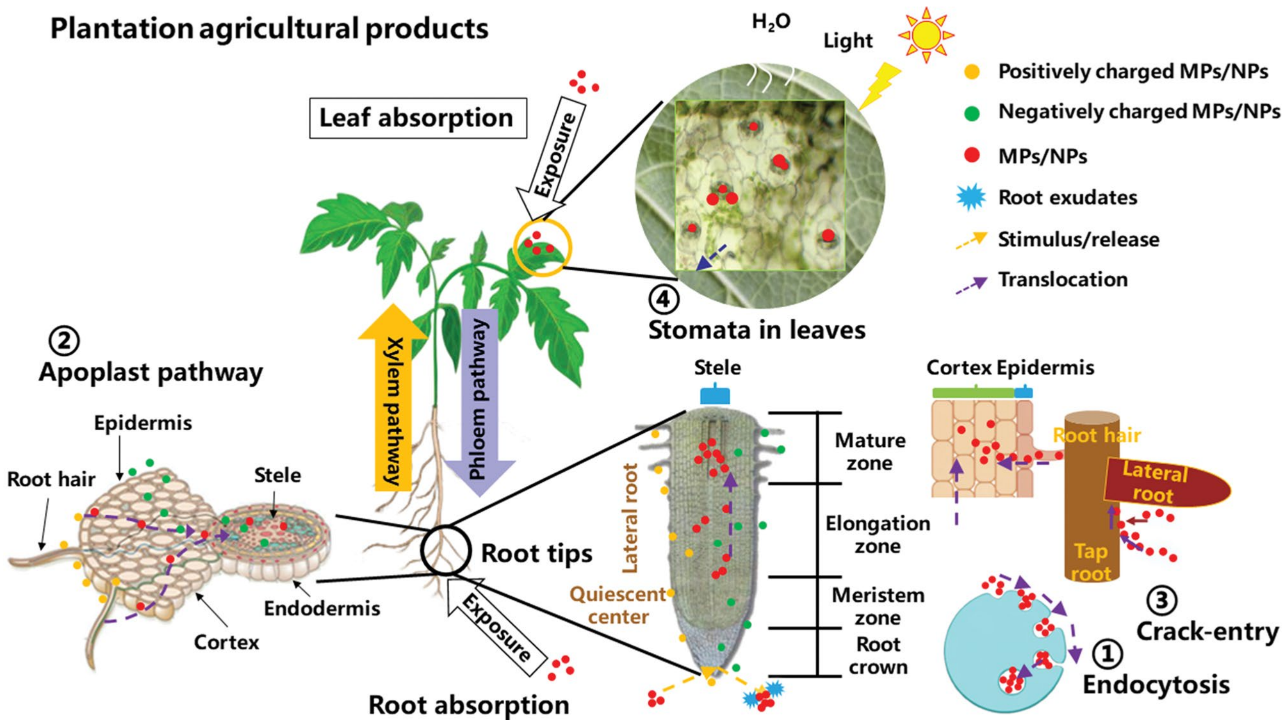


Fig. 3 Mechanisms of MPs/NPs uptake and transport in plantation agricultural products [14–19, 39, 59, 62–67, 74, 77]

above, MPs/NPs are carried either by following the roots in an upward direction and propelled by the forces of transpiration and root pressure [15, 62, 63, 66], or by moving through the vascular bundles from the leaves in a downward direction [19, 67]. With the migration over time, MPs/NPs could be enriched in roots, stems, leaves, seeds and fruits, respectively [14, 16]. Among them, commercial fluorescently labeled PS solutions as model MPs microspheres, combined with laser confocal microscopy, are often used to study the pathways of MPs/NPs into plants [15, 62, 65]. The main factors affecting the entry of MPs/NPs into plantation agricultural products are particle size [14, 63, 68], particle concentration [69], different functional groups [19, 20], growing environment [17, 70], exposure duration [15, 16, 71] and aging time [66, 72, 73]. Typically, when particles are smaller [68] and their concentration is higher [69], they are more readily absorbed by plants, hence posing a greater risk to plant health. Plant cell membranes and walls typically have a negative charge [74, 75]. Positively charged MPs/NPs have a higher likelihood of being adsorbed by plant cells compared to other charged ions [76], due to their competition for adsorption sites (Fig. 3). However, their entry into the plant becomes more challenging. On one side, plants exhibited a higher absorption rate of -NH2 modified MPs/NPs compared to -COOH modified MPs/NPs [19, 20]. On the other side, positively charged MPs/NPs were mainly concentrated in root hair, root cap, cortex, cell membrane and cell wall, while negatively charged MPs/NPs were concentrated in root hair, cortex, column, xylem and phloem (Fig. 3).

Endocytosis

Currently, it has been found that MPs/NPs can enter the root cells of peanut [14], corn [18], sweet potato [62] and rice [68] by endocytosis. Wu et al. (2021) demonstrated in a hydroponic experiment that PS-100 nm initially attached to the root hairs of rice and then entered the mature zone of the root, rather than being taken up at the root crown via endocytosis [68]. The primary function of the root cap's marginal cells is to secrete root secretion and mucilage, which serve as crucial barriers to prevent the plant from absorbing MPs. Concurrently, invaginations of the plasma membrane and multivesicular bodies (MVBs) that included intraluminal vesicles were seen in the root cells by the researchers [74, 78]. Act as a defensive barrier, the cell wall theoretically permits nanoparticles with diameters between 5 and 20 nm to cross the cell wall [10, 59, 61]. In this case, PS-NPs first adhered to the surface of root tissues and then penetrated the core of the roots by endocytosis in maize seedlings [18]. The size of particles is a crucial component that affects the transportation of MPs/NPs from the bottom-up. PS-100 nm and PS-300 nm induced a more severe disruption of subcellular structure and cellular morphology than PS-500 nm in the root [68]. There are two potential mechanisms for this [68, 79]: one possibility is that NPs might promote the rupture of cell walls and increase the number of pores; another possibility is that particles can infiltrate root cells via roots that are sick or have physical wounds. In addition to NPs, the root epidermal cells could internalize PE-5 μm through endocytosis [62]. It moved slowly towards the inner part of the brain and upwards via the stele. PE was mostly found in the cortical tissues of roots and stems, but did not translocate into the leaves. Subsequently, Jiang et al. (2023) conducted a soil-cultivation experiment for 125d and found that PS-80 nm were enriched in peanut roots with increasing exposure concentration [14]. With plant growth, it was first found that MPs/NPs could be enriched in the fruits. Currently, research on the mechanism of endocytosis is still in its infancy. In the future, it is necessary to integrate in vivo experiments with separate cell cultures and mixed designs. Additionally, real-time monitoring of the migration distribution of MPs/NPs using dynamic tracer technology is required to gain a clearer understanding of the position of endocytosis in the uptake process of MPs/NPs in agricultural products.

Apoplast pathway

In contrast to endocytosis, apoplast pathway is the main mode of MPs/NPs transported from the roots into the plant. Currently, the plantation agricultural products that have been reported to enter the plant by means of apoplast transport include grain crops (rice [14, 65, 76, 80–82], wheat [20, 83, 84], barley [13], maize [85]), commercial crops (cotton [86], *Solanum nigrum* [87]), vegetables (lettuce [63, 64], carrot [70], water spinach [71], onion [69]), fruits (strawberry [15]), and so on. Among them, rice, wheat and lettuce were reported more. Exosomes may transport particles ranging in size from 20 nm to 1 μm into the roots. The reported particles include PS, PE, and PMMA. Upon entering the root tip cells, they may be transported in an upward direction via the xylem, and become concentrated in the roots, stems, leaves, fruits, and seeds.

After entering plant roots, MPs/NPs are trapped by the mucus layer, which is a highly hydrated polysaccharide. This layer concentrates the particles on the surface of the root and subsequently moves them into plant tissues through the apoplast route [20, 34, 64, 74, 75]. The primary factor driving the apoplast route is transpiration pull, which greatly aids in the dispersion of granular polymers throughout plant tissues [59, 74, 78]. The movement of endosomes from the cortex to the vascular bundles is obstructed by the endodermal Kasparian band, which prevents the entry of pollutants [16, 42, 77, 88, 89]. Therefore, MPs/NPs pass through the endodermal plasma and enter the root cells from the apoplast pathway. Initially, Li and colleagues (2019) found that PS-200 nm particles were able to penetrate the root cortex and mid-column of lettuce roots by utilizing the free space within the cellular interstitials and bypassing the plasmalemma barrier [63]. However, PS-1 μm particles were unable to be absorbed by lettuce roots through plasmalemma transport. This was primarily attributed to the cell wall acting as a barrier that prevented the entry of larger-sized PS particles. Contrarily, Liu et al. (2022) discovered that PS-1 μm may be transported to the circulatory system of plant tissues [81]. This transportation mostly occurs inside the cell wall and intercellular zone of root columns, stem vascular bundles, and leaf veins. Furthermore, these particles had the ability to move upwards towards the branches. Subsequently, scientists found that neither PS-5 μm could be taken up by the roots of maize [85] and carrots [70] through soil cultivation experiments, further substantiating that plastic particles beyond 1 μm cannot be internalized. When the particle size is less than 1 μm, the more MPs/NPs enter the plant tissue and cell as the exposure concentration increases, inducing more inhibitory effect [65, 69]. Zhu et al. found that PS-NH_2 entered wheat root tissue cells more readily than PS-COOH, which was more conducive to its tissue/cell translocation [20]. The internalization of PS-NPs in wheat root cells is controlled by a combination of particle size and surface functional groups, with particle size being the main influencing factor. In view of exposure time, Zhang et al. (2023) exposed strawberry seedlings to PS-100 nm and PS-200 nm for 3, 7, 14 and 21 d [15]. It was found that PS-100 nm could migrate upward through the xylem into stem and leaf tissues with the extension of exposure time after 14 d, while PS-200 nm could only migrate into the stem but not further into the petiole. Recent research has discovered that PS- 80 nm had the ability to penetrate rice grains during the early grain setting stage and subsequently accumulated in the starch granules of mature rice after the filling stage [14]. This indicates that nanoparticles could migrate into agricultural products intended for consumption and potentially pose a hazard to these products. Moreover, the presence of several plastic polymers characterized by long chain fatty acids, larger molecular weights and high hydrophobicity poses challenges for plant absorption via the apoplast transport pathway [59, 74]. Although the particle size may be sufficient to fulfill the criteria for plant absorption, it is possible that the molecular structure of the plastic may not be sufficient to meet the needs for uptake. As a result, the physical and chemical characteristics of the plastic particles are directly connected to the absorption of plastic particles by plants via the process of apoplast transport. The influencing factors are complex and need to be further investigated for understanding.

Crack-entry mode

Furthermore, apart from endocytosis and apoplast transport from the root tip to the cell, it is possible for

MPs/NPs to be absorbed by the root via the Crack-entry method originating from the lateral root. Typically, plant cell walls include holes with dimensions of 3.5–5 nm and intercellular linking filaments with diameters of 50–60 nm [90]. As a result, nanoparticles larger than 5 nm cannot pass through the cell wall, and those larger than 60 nm cannot spread into the intercellular space [59]. Nevertheless, particulate plastics of significant size had the ability to infiltrate the cell wall by passing through the mucus of the root cap, so being trapped inside the cell wall of the root [16, 66, 91]. During the process of cell division, the apical meristem has a high level of porosity, which enables the diffusion of granular plastic across it [17, 92]. Furthermore, during the process of cell separation, it is possible for fissures to form between the epidermal cells and the lateral root loci [17]. These cracks may serve as pathways for micron-sized plastics to enter the stele. Once within the mesocosm, tiny plastic particles may be carried from the xylem to the aboveground sections of plants by the process of transpiration (Fig. 3). There have been reports indicating that MPs/NPs are capable of entering the lateral root cells of several plants, including cucumber [16], wheat [17], lettuce [17], spinach [66], and cress [91], via the gaps or openings. The size of these particles typically falls within the range of 30–4800 nm.

In cress germination experiments, Bosker et al. (2019) initially found that sub-micron and micron-sized particulate plastics could pass through the seed coat by means of fissures into endosperm cells within 24 h [91]. Although MPs/NPs could be progressively enriched in the root hairs, leaves and seed coat over time, the related mechanism is not clear. Further, with the aid of SEM and LSCM systems, Li et al. (2020) revealed the mechanism of plant uptake of PS and PMMA, observing that particulate plastics could bypass the endocytosis and apoplast pathways to enter the cleavage physical channels in wheat and lettuce roots [17]. PS (100–700 nm) could adhere to lateral roots and then enter the epidermal cell wall tissue cells through cracks [16]. Additionally, increased transpiration rates facilitated the absorption of MPs/NPs. Huang and co-workers (2024) discovered that MPs/NPs have the ability to be carried by water and nutrient flow, and may subsequently travel into the stems and leaves [66]. It is crucial to note that although larger particles cannot traverse the pores of cell walls and intercellular junctions, certain intrinsic properties, such as the low stiffness of plastic particles, may result in their expulsion and deformation during cellular uptake [39, 74, 77]. The pliability of granular plastics is crucial for their ability to be absorbed via the Crack-entry mode. Additional study is required to fully understand the method by which nanoparticles enter plants via cracks. Various possible mechanisms may simultaneously influence the absorption of MPs/NPs by plants, necessitating the inclusion of a broader spectrum of MPs/NPs and plant species in future research.

Stomata in leaves

The primary route for MPs/NPs to enter leaf tissues and then go to the vascular system is via stomatal opening, which occurs mostly during foliar replenishment [19]. Atmospheric deposition speeds up the attachment of MPs/NPs to plant leaves [12, 93]. According to reports, MPs were found to make up 28% of the particulate matter that sticks to leaves [94]. This indicates that the deposition of MPs from the atmosphere is a significant way in which leaves absorb MPs. Sun et al. (2021) observed the absorption of positively or negatively charged PS-NPs by the stomata of maize leaves [19]. They also found that the primary route for the movement of NPs from the leaves to the roots is via the vascular bundles. As time goes on, NPs start to get together, which limits their movement to the root system. It is necessary to conduct mechanistic research to investigate the process of MPs/NPs being deposited on leaves, the absorption of atmospheric MPs/NPs by leaves, and the movement and distribution of MPs/NPs inside plants [67].

Currently, MPs/NPs have been detected in the edible portion of plantation agricultural products, which could affect the content of nutrients such as polyphenols, flavonoids, polysaccharides, vitamins and proteins, inducing related food safety problems [14, 15, 95, 96]. However, the mechanism by which MPs/NPs move across different tissues is still not well understood. Hence, it is important to examine the methods by which MPs/NPs move across various plant tissues, particularly in the edible sections of plants. While the importance of plant tissue fluids in the movement of MPs/NPs is well recognized, there is a limited amount of research on the interactions between MPs/NPs and plant tissue fluids.

Impact of MPs/NPs on cultivated agricultural products

Upon entering the plant, MPs/NPs elicit various effects on the plant's phenotype, metabolism, enzymes, transcription, and genetics. These effects include seed germination, metabolism and growing development, photosynthesis, oxidative stress and antioxidant defenses, fruit yield and nutritional quality, as well as cytotoxicity and genotoxicity (Fig. 4). These negative effects may be based on the following reasons [39, 41, 59, 74, 77]: (1) MPs/NPs physically obstruct the openings in the outer layer of the seed, causing damage to the plant's root system and hindering the absorption and transportation of essential nutrients and water; (2) MPs/NPs reduce plant photosynthesis by disrupting the structure of the cyst-like bodies and inhibiting energy trapping in the leaves; (3) MPs/NPs are cytotoxic or genotoxic to the plant,

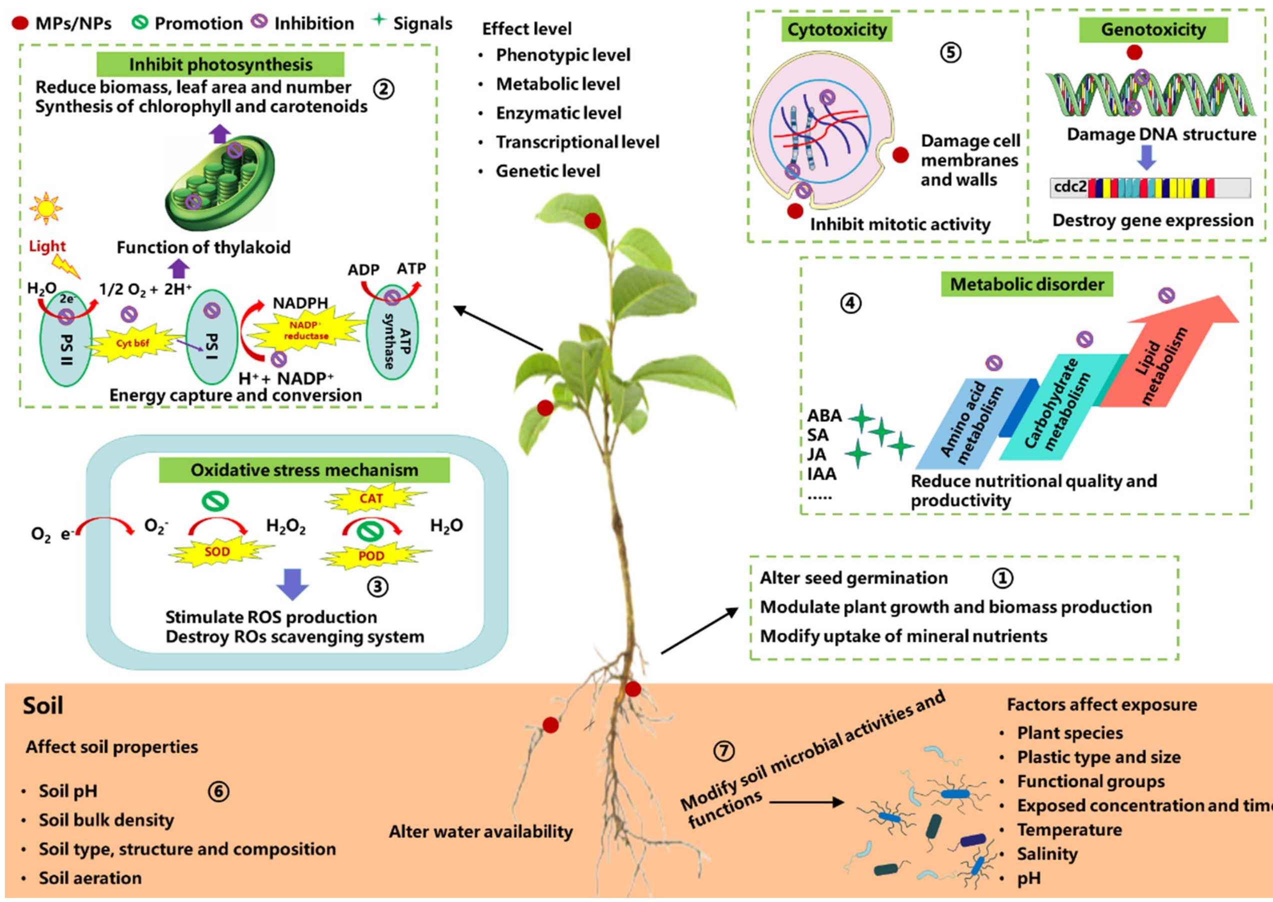


Fig. 4 Impacts and mechanisms of MPs/NPs on plantation agricultural products [39, 41, 59, 74, 77]

leading to metabolic disorders; and (4) MPs/NPs indirectly induce changes in the plant's growing environment (soil physicochemical properties and microflora structure, etc.). Currently, the design of the trials is based on soil cultivation [62, 97–99], hydroponics [76, 82, 100, 101] and foliar spraying [19, 67]. The relevant plantation agricultural products are mainly grain crops (rice [76, 82, 97, 98], wheat [100, 102], maize [67, 103, 104], barley [13, 101, 105], soybean [101, 106], buckwheat [107], sweet potato [62]), vegetables (Chinese cabbage [99, 108–110], lettuce [19, 64, 111], cucumber [16, 112, 113], tomato [114–116], onion [69, 117], garden cress [72, 73], cress [91], common bean [118], broad bean [119], baby marrow [120], savoy cabbage [121], coriander [122], spinach [66, 123], water spinach [71], turnip [124], chili [125]), commercial crop (peanut [14, 126], cotton [86], *Torreya grandis* [127], *Orychophragmus violaceus* [128], *Impatiens balsamina* [128], *Trifolium repens* [128], dandelion [129], woad [130]), fruits (strawberry [15], melon [131]). The impact of MPs/NPs on agricultural products mostly depends on factors such as plant species, plastic type, plastic particle size, particle surface charge, various modified functional groups, concentration of exposed plastic particles, ambient temperature, salt, and pH (Fig. 4).

Impact of MPs/NPs on seed germination

Seed germination is a crucial step in the life cycle of plants and has significant biological importance. It serves as a vital indication for determining the phytotoxicity of MPs/NPs [69, 83, 91]. The excessive buildup of MPs/NPs in the environment and their attachment to the surface of seeds during germination obstruct the stomata and restrict the absorption of nutrients and water, thereby impeding seed germination [69, 91, 132]. In their study, Bosker et al. (2019) examined the impact of MPs on the germination of kale seeds. They discovered that within 24 h, MPs accumulated on the seed coat, obstructing pores, reducing nutrient absorption, and temporarily impeding seed germination [91]. During the later phases of seed germination (at 48 and 72 h), the substance mostly accumulated on root hairs and did not have any impact on the process of seed germination. Lian et al. (2020) demonstrated that PS-100 nm had a notable effect on enhancing water absorption in seeds, resulting in fast swelling and subsequent restoration of basic metabolism [83]. This led to a considerable improvement in seed viability. Later on, the scientists discovered that PS-50 nm, PS-200 nm, and PP-MPs (< 500 μm) did not have a notable impact on the process of seed germination for onion

[69], wheat [65], and tomato [132], respectively. Span et al. (2022) found that PS-50 nm had a detrimental impact on rice germination [80]. This negative effect is likely caused by oxidative damage resulting from the absorption of PS-NPs into the rice plants.

The type and exposure concentration of MPs/NPs had different effects on seed germination [116, 123, 128, 130, 131]. For example, Sridharan et al. (2023) found that PVC inhibited the germination of Coriander seeds more than PP and PLA through soil cultivation experiments [122]. The presence of PS, PP, and PE particles of a size smaller than 100 nm hindered the germination of tomato seeds as the quantity of these MPs/NPs rose [116]. MPs/NPs decreased the ability of seeds to sprout and the speed at which they sprouted, and this harmful impact may be influenced by the selectivity and specificity of MPs/NPs [131]. However, Yang et al. (2022) discovered that PS-NPs enhanced the germination of woad seeds when exposed to doses of 10-1000 mg/kg in a soil-cultivation experiment [130]. Aging of MPs/NPs affects seed germination. Pflugmacher et al. conducted a study where they evaluated the impact of fresh and old PC particles, as well as their leachate, on watercress germination [72, 73]. They discovered that aging PCs reduced negative germination effects due to hazardous compound release. Thus, the impact of MPs/NPs on seed germination is contingent upon the specific characteristics of the MPs/NPs, such as its kind, particle size, aging period, as well as the growth environment, exposure concentration, and plant species.

At the initial stage of seed germination, MPs/NPs may inhibit later growth by blocking internal activities through the blockage of stomata [91]. Conversely, seeds easily take in significant quantities of water that contains dissolved poisons via their stomata [5, 73]. The impact of MPs/NPs on seed germination is contingent upon timing, species, and dosage. MPs/NPs present in soil may have both physical and chemical impacts on several phases of seed germination. Films and fibers include harmful monomers that may release colorants, plasticizers, heavy metals, and pathogens into water. These leached chemicals pose additional risks to seed viability. Further research is needed to elucidate the specific mechanisms and impacts of MPs/NPs on agricultural seed germination under diverse growing conditions and environmental factors.

Impact of MPs/NPs on photosynthesis

Photosynthesis is essential for plants, and the amount of chlorophyll in plants indicates their development rate and nutritional value [133–135]. Chlorophyll is a major participant in plant photosynthesis, and changes in chlorophyll a/b values under unfavorable conditions can be used to assess plant self-protection against unfavorable environments [136–138]. Exposure to MPs/NPs may interfere with the process of chlorophyll generation in leaves and shoots, leading to a decrease in photosynthesis [67, 106, 108]. Members of MPs/NPs hindered the process of photosynthesis in plants by reducing the transport of electrons and the functioning of Cyt b6f and $NADP^+$ reductase enzymes [77]. In their study, Liao et al. (2019) discovered a correlation between the content of PS-MPs and the levels of leaf photosynthetic pigments in wheat [100]. Specifically, they observed an initial rise followed by a subsequent drop in the pigments when the PS-MPs content rose. Lower concentrations of MPs/NPs treatment have a positive impact on enhancing the photosynthesis of wheat leaves. However, higher concentrations of MPs/NPs may disrupt the photosynthetic pathway of leaves, hinder protein synthesis, trigger oxidative stress, and have a more pronounced toxic effect on the leaves [15, 83, 100, 123]. Further, Wang et al. (2022) examined the impact of various functional groups of PS-NPs on photosynthesis [76]. They discovered that PS-NH_2 had a more pronounced effect on reducing the photosynthetic capability and chlorophyll concentration of rice compared to PS and PS-COOH. Sun and Zhang et al. also both found that PS-NH_2 presented stronger photosynthetic toxicity through their studies on maize [67] and Chinese cabbage [108], respectively, but the related mechanisms were not effectively explored. A study found that the decomposition of PS releases Benzene rings, which are likely the primary component influencing chlorophyll and sugar metabolism in cucumber leaves [112]. The type of MPs/NPs also has a greater effect on photosynthesis. Li et al. (2023) discovered that PVC had a greater impact on the structure of PSII in soybean chloroplasts compared to PE [106]. This resulted in a decrease in the ability of soybean PSII to absorb, transport, and dissipate energy, thus affecting the process of photosynthesis. It is well known that different plastics have different structural properties and electron-conducting abilities, and environmental ageing can significantly alter the properties of plastics. Both new and old computers decreased the levels of chlorophyll a and b in watercress, mostly due to the progressive release of bisphenol A [73]. From the perspective of the whole growth cycle, according to Yang et al. (2023), varying concentrations of PE had distinct impacts on photosynthetic pigments and photosynthesis throughout various development stages (seedling, flowering, and fruiting) of Chilli [125]. PE, at a dosage of 50 mg/kg, hindered the production of photosynthetic pigments during the seedling stage. However, at a concentration of 2500 mg/kg, it stimulated the production of photosynthetic pigments during the blooming stage.

MPs/NPs induce stomatal closure by indirectly reducing water efficiency, resulting in limitations on photosynthetic stomatal activity [13, 77]. The blockage of cell walls and water channel proteins in the roots hinders the absorption of water [39]. Moreover, alterations in MPs inside the soil may modify the water cycle and impact the process of root water absorption [59]. To clarify the relevant mechanism, Wang et al. (2022) discovered that PS-NPs had a notable impact on Rubisco activity and ATP production [13]. This led to a restriction of photosynthetic carbon assimilation in barley under low temperature conditions, leading to a decrease in both photosynthesis and carbonylation in barley leaves. Zhang et al. (2023) found that the up-regulation of DEG was mainly related to photosynthetic metabolism and PE interfered with buckwheat leaf carbon fixation and ATP → ADP + Pi processes [107]. The promotion effect of PE on photosynthesis of buckwheat leaves may be at the expense of morphological advantage. By enhancing the activity of antioxidant enzymes, more energy is supplied to activate the antioxidant system in the leaves.

Thus, the presence of MPs/NPs in soil may greatly enhance the levels of plant photosynthetic pigments and impact the photosynthetic ability of plants. It seems that MPs/NPs had a negative effect on the reaction centers of photosystem II, and this effect increased with the dosage (Fig. 4). Primarily, it impacts the effectiveness of converting light energy by reducing the rate of electron transfer and the maximal quantum efficiency (Fv/Fm). This results in the buildup of electrons in the cysts and a rise in oxidative stress [77, 106, 107]. Previous research has investigated the function of MPs/NPs at the physiological and biochemical levels. Nevertheless, the precise biochemical processes by which MPs/NPs impact photosynthesis remain unclear. A complete molecular investigation is essential to explore the impact of MPs/NPs on photosynthesis. The impact of these changes on plant photosynthesis are not well determined. Further research is needed to determine if MPs/NPs' effects on photosynthesis vary between C3 and C4 plants due to their distinct photosynthesis processes.

Impact of MPs/NPs on growing development and metabolism

MPs/NPs cause changes in plant morphology that disrupt and inhibit plant growth and metabolism [68, 82, 100, 114, 139]. MPs/NPs have exerted many effects on the development and metabolism of plants, including the accumulation of biomass, elongation of roots and stems, enhancement of root vitality, inhibition of leaf stomata, alteration of micronutrient levels, modulation of energy metabolism, and modification of amino acid metabolism [83, 84, 108, 124, 125, 140]. At first, Qi et al. (2018) conducted a study on the impact of MPs on wheat growth [103]. Their findings revealed that both macro- and micro- plastic residues had detrimental impacts on both the above-ground and below-ground components of wheat, affecting both nutrient uptake and reproductive growth. The toxicity of PS-5 µm was greater than that of PS-100 nm in terms of the elongation of roots and stems in wheat [100]. MPs/NPs had the ability to decrease the emissions of NH_3 and N_2O from the soil and modify the composition of microorganisms and variety of soil bacteria. This may be achieved by targeting the cell wall pores and root hairs, resulting in reduced transpiration, nutrient absorption, and root respiration, ultimately inhibiting plant development [68, 83, 99, 122, 124, 132, 139] (Fig. 4). The application of PS-NPs resulted in a decrease in the length of rice roots produced in a hydroponic system and hindered the absorption of nutrients. Consequently, this stimulated the development of lateral roots and led to an increase in their quantity, which served to fulfill the plant's nutritional requirements [68, 82]. The plant growth metabolism was impacted by the characteristics of MPs/NPs, including their kind, concentration, and size [112, 116, 123]. In their study, Sridharan et al. (2023) discovered that PLA had a more negative impact on the root length of coriander seedlings compared to PP and PVC [122]. Furthermore, they observed that the inhibitory effect was more pronounced in the field than in the greenhouse. Additionally, it has been shown that MPs stimulate root development in spinach and rice [65, 123]. PS affected the metabolic profiles of rice in a dosage-dependent manner. Amino acid metabolism was more apparent in the leaves than in the root system [68]. Some studies also reported that MPs did not affect plant growth [84, 108, 140]. Li and teammates (2023) discovered that PS-200 nm did not have a noteworthy impact on the development and physiology of wheat seedlings cultivated hydroponically [84]. This finding aligns with the outcome observed in Chinese cabbage during the establishment phase of dark morphogenesis [108]. Therefore, the specific effects should be determined in relation to the specific plant and exposure concentration.

MPs/NPs could interact with the growth medium and combine to affect the overall growth status of the plant [109, 111, 118, 121]. According to Yang et al. (2021), the presence of MPs in the soil decreased the amount of nutrients available, resulting in a decrease in the weight of cabbage [109]. PE caused higher growth metabolism impacts than PS, and the risk was higher for smaller MPs than for larger MPs [109]. Unlike non-biodegradable MPs, the biodegradable MPs made of PBAT did not have any major harmful impacts on soil and seaweed due to their own disintegration [110]. The effects produced by MPs on seaweed vary dynamically on plant physiological indices as the self-regulation diminishes in plant. Another study found that LDPE-MPs did not have any impact on the aboveground and root biomass. However, Bio-MPs drastically decreased the aboveground and root biomass [118]. Shorobi and co-workers (2023) examined the impact of PP-MPs on nutrient absorption in several tomato cultivars, discovering that PP stimulated root elongation in cherry tomatoes and hindered the transportation of a significant quantity of nutrients from the roots to the stems [132]. Recently, Lian and colleague (2024) derived an equation that described the impact of rhizosphere microorganisms on lettuce development when paired with MPs [111].

In order to provide a more comprehensive understanding of the impact of MPs/NPs on plant development and metabolism, researchers have carried out a number of investigations focusing on several elements including phenotypic, metabolism, enzyme activity, cellular functions, and transcriptional processes [13, 18, 76, 86, 97, 124]. MPs/NPs have the potential to enhance the levels of amino acids, reduce the amounts of ascorbic acid, soluble sugars, and soluble proteins, trigger significant alterations in defense mechanisms, signal transmission, hormone processing, interactions between plants and pathogens, and the production of phenylpropanoids, as well as hinder gene expression [76, 97, 131, 139]. Through a field trial, Wu and colleagues (2022) discovered that PS-MPs had the ability to disrupt the accumulation of metabolites and energy consumption pathways in various types of rice [97]. They analyzed the rice varieties at the transcriptomic level and observed differences among them. Specifically, the metabolites of Y900 were suppressed, while those of XS123 were promoted. Cells were triggered by stress stimuli, leading to the activation of MAPK cascade pathways, which had the potential to impact crucial signal transduction pathways in plants by modifying receptors that come before them and target components that come after them. For example, they may trigger processes such as cell proliferation, cell differentiation, and stress responses. Various functional categories of PS influenced metabolic processes and gene expression in rice seedlings [76]. PS, PS-COOH, and PS-NH_2 were implicated in the RNA metabolism, ion transport and terpene biosynthesis, and macromolecule synthesis, respectively. PS suppressed carbohydrate metabolism in barley leaves at low temperature, resulting in a significant reduction in the activity of crucial enzymes associated with sucrose solubilization, glycolysis, and starch metabolism pathways [13]. By utilizing analysis alongside multi-omics tools, Yu et al. discovered the molecular reaction of Tephrosia shoots to PS-100 nm. They observed that NPs heightened the levels of thiobarbituric acid actives, while reducing the concentrations of iron, sulfur, and zinc. Additionally, NPs had an impact on the quantities of small RNAs, transcripts, proteins, and metabolism, which in turn could regulate the biosynthesis of terpenoids and flavonoids [127]. PS-NPs have the potential to influence the processes of DNA repair, membrane protein transport, and hormone generation and response [139]. The presence of PS-5 μm had a detrimental impact on the production of ATP and NADPH. On the other hand, PS-1 μm controlled the intercellular CO_2 content via influencing the expression of PEPCK and PEPC genes [113]. The tomato root system exhibited resilience to MPs stress by releasing substantial quantities of low molecular weight organic acids (LMWOAs). Furthermore, the tomato plants experienced more significant metabolic reprogramming when exposed to PS and PP [115], as to found in spinach [66]. Furthermore, the PS-NPs that were aged caused changes in certain pathways, namely the synthesis of aminoacyl-tRNA and phenylpropanoid. On the other hand, the pristine PS-NPs altered pathways associated with sulfur metabolism, the synthesis of unsaturated fatty acids, and tryptophan metabolism [66].

The impact of MPs/NPs on the development and metabolism of agricultural products in the plantation is deep and multifaceted. While numerous studies have employed various histological tools for analysis, the specific regulatory mechanisms underlying these effects remain poorly understood. To completely assess the possible dangers of MPs/NPs and implement appropriate intervention measures, it is essential to enhance research on the processes and impacts of MPs/NPs on plant development and metabolism.

Effect of MPs/NPs on fruit yield and nutritional quality

Exposure to the environment, MPs/NPs could affect the nutritional quality of plant over time and gradually enrich in fruits as plant growth, thereby reducing taste and flavor [14, 16, 19, 97, 98, 118]. Table S1 summarized the effects of MPs/NPs on the nutritional quality of plantation agricultural products. Initially, Meng and colleagues (2021) conducted a comparison of the impacts of several kinds of MPs on the fruit production of common bean [118]. They discovered that LDPE-MPs did not have any influence on the biomass of cauliflower fruits, while Bio-MPs significantly decreased the fruit biomass. Regarding the possible impacts of airborne MPs/NPs, Lian et al. sprayed PS-NPs on the foliar surface of lettuce, and found that PS-NPs decreased the amount of dry weight, height of the plant, area of the leaves, pigmentation content of micronutrients, and essential amino acid content of lettuce, which affected lettuce growth, fruit biomass and nutrient quality [19]. Additionally, PS-NPs led to a rise in the concentration of soluble proteins in cucumber fruits, while causing a substantial drop in the levels of Mg, Ca, and Fe [16]. In contrast, Greenfield et al. demonstrated that the inclusion of PE and PHBV did not impact the yield or microbial community composition of winter barley [101]. Hence, the impact of MPs/NPs on the crop yield of plantation product is contingent upon the specific plant species and the kind of MPs/NPs involved.

Jiang and colleagues (2022) conducted the impact of soil MPs on fruit yield by adding 250 mg/kg of PS-80 nm into the soil [14]. The study revealed that the presence of PS-80 nm resulted in an increase in the number of rice grains with empty shells, a drop in the fruiting rate, and a reduction in the average weight of peanut kernels by 3.45%. The presence of PS-NPs had an impact on the equilibrium of trace elements in peanut and rice, resulting in a decrease in the levels of mineral elements, amino acids, and unsaturated fatty acids [14]. Furthermore, it disrupted the synthesis and storage of fatty acids in peanut, ultimately leading to a negative effect on the nutritional quality. For different rice varieties, Wu and co-workers indicated that PS acted on the quality of Y900 and XS123 to different degrees in rice by interfering with metabolite accumulation and energy consumption pathways [97]. The monocot yield of Y900 decreased by 10.62% and that of XS123 increased by 6.35%. In the fruiting period, PE-MPs inhibited plant height, fresh mass and phosphorus content. reducing chili yield by up to 42.86% per plant [125]. The suppressive impact of PE-MPs on pepper output was more pronounced at low doses than to high values. As the concentration of PE-MPs rose, the agglomerates became larger, resulting in less interaction with the root system of peppers. This hindered the absorption of nutrients by the PE-MPs and ultimately weakened their impact on the production of peppers. The extended growing period of plantation agricultural products results in a limited number of research examining the impact of MPs/NPs on fruit output and nutritional quality. Moreover, the relevant mechanism of regulation is unknown. Therefore, it is necessary to conduct constant research on the impact of MPs/NPs on fruit and nutritional quality, which may be achieved by using different plant kinds and various histology and analytical quantitative detection techniques, aiming is to guarantee the quality and safety of agricultural goods.

Impact of MPs/NPs on oxidative stress and antioxidant defensive systems

Oxidative stress is a primary method by which plants are harmed (phytotoxicity) [77]. Electrons present in chloroplasts, mitochondria, and plasma membranes of plants can be transferred to oxygen, resulting in the formation of reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2), superoxide anion ($\bullet O_2^-$), hydroxyl radical ($\bullet OH$), and singlet-linear oxygen ($^1O_2$). This process can lead to oxidative stress, which causes permanent damage [39, 77, 139]. Due to their detectability, H_2O_2 and $\bullet O_2^-$ are often used as markers of the buildup of ROS [82]. The presence of oxidative stress in plants is determined by the generation of ROS and the effectiveness of their removal by the antioxidant enzyme system [67, 68, 141]. MPs/NPs induced toxicity leads to oxidative stress, which disrupts the antioxidant enzyme system and alters ROS levels. As a result, the buildup of ROS causes damage to cellular components, with lipid membrane peroxidation serving as an indicator of oxidative stress [15, 86, 139]. To counteract the harmful effects of ROS, plants have developed a range of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), dehydroascorbate reductase (DHAR), monodehydrated ascorbate reductase (MDHAR), and glutathione peroxidase (GSH-PX). Additionally, nonenzymatic antioxidants like ascorbic acid (AsA) and glutathione (GSH) play a crucial role in the plant's defense mechanisms by scavenging ROS [15, 18, 111]. Oxidative damage arises when the generation of ROS surpasses the ability of the antioxidant defense system to neutralize them [69, 111, 130].

Oxidative stress may lead to lipid peroxidation, a process in which ROS interact with large molecules like phospholipids in the cell membrane. This interaction decreases the flexibility and permeability of the cell membrane, resulting in the inhibition of cell activity and function [10, 41, 61]. Malondialdehyde (MDA), a byproduct of lipid peroxidation, is well recognized as a primary marker of cellular oxidative stress in this particular situation [68]. According to Wu et al. (2021), their research revealed that PS induced oxidative stress and modifies metabolic profiles in rice [68]. Specifically, they observed that PS-100 nm caused greater levels of MDA in the roots compared to PS-1 μm. The physiological reactions and capacity of plants to remove ROS in response to MPs/NPs may be influenced by factors such as the composition, dimensions, amount, functional groups, and morphology of the polymers [76, 106, 112, 122, 123, 131, 141]. Li et al. (2020) discovered that PS-NPs had an impact on the antioxidant system of cucumber leaves [112]. They observed a progressive rise in the enzyme activities of CAT and SOD as the particle size of PS-NPs rose. The treatment with positively charged PS-NH2 had a more pronounced effect on stimulating the activity of the antioxidant system of maize, compared to the negatively charged PS-COOH [67]. PVC-MPs induced stronger oxidative stress than PE-MPs in soybean leaves [106]. Low levels of MPs enhanced the activity of antioxidant enzymes, while high levels of MPs had a detrimental impact on the antioxidant defense system of plants [82]. This indicates that excessive exposure to high levels of MPs overwhelms the plant's ability to regulate the balance of ROS through its antioxidant defenses [69, 82, 84, 100, 130]. Conversely, when the PVC concentration increased, the activity of CAT in melon roots and the presence of ROS steadily decreased [131]. Pehlivan and colleagues (2021) discovered that smaller particle sizes of MPs caused a possible redox relaxation in maize. Additionally, they observed that bigger particle sizes of MPs resulted in greater cellular recovery from the exogenous stress damage generated by MPs [141]. POD1 and HSP1 were pivotal elements in the MPs-induced transduction of ROS into expression of gene transcripts. The size of the PE had a more significant impact on the generation of ROS, MDA, and ASA compared to the addition of PE on water spinach roots [71]. It is worth noting that the general trend of increasing and then decreasing in CAT, SOD and H_2O_2 contents in Clover, Orchidum and Bromeliad was in accordance with the "Plant-ES" equation [128].

Overproduction of ROS actively inhibits antioxidant defenses and leads to membrane oxidative damage [13, 80]. Damage to the membranes of mitochondria decreases the activity of mitochondrial dehydrogenase and hinders the function of respiration (Fig. 4). Span` and co-workers (2022) found that PS exposure internalization caused oxidative damage to seedlings by disrupting H_2O_2 homeostasis and membrane damage, exhibiting different oxidative contingencies [80]. The impact of PS-NPs on the cellular biology and physiology of rice seedlings may be attributed not only to the direct impacts of PS-NPs, but also to the modification of ROS generation and diffusion at the tissue and cellular level. PS-NPs had a strong inhibitory effect on the activities of SOD, APX, and CAT in chloroplasts at low temperatures. Additionally, PS-NPs also lowered the activities of APX and CAT in mitochondria [13].

The oxidative stress caused by MPs may be reduced by the plant's synthesis of antioxidants such as flavonoids, ascorbic acid, glutathione, and carotenoids, which helped remove ROS from the cells [10, 41, 61, 77]. Hua et al. (2024) showed that PS-MPs caused oxidative stress in the roots and leaves of lettuce. They also found that both CAT and SOD activities were significantly increased to reduce oxidative stress [64]. Oxidative stress in dandelion varied by MPs type and concentration [129]. PS and PP induced membrane lipid peroxidation, resulting in higher levels of O_2^- and H_2O_2 in seedlings. Additionally, they raised the activities of SOD, POD, and CAT enzymes. Therefore, O_2^-, CAT, and proline were identified as sensitive biomarkers for dandelion plants polluted with MPs. Li et al. found that there was a correlation between phytohormone concentrations and enzyme activities in spring barley, which induced different strategies of glycolysis regulation in leaves and roots [105]. Some studies have reported that an ecological corona effect can reduce the PS-induced oxidative stress [117], but the related research mechanism needs to be further explored.

Plants employ antioxidant enzymes and specific ROS as signaling molecules to activate defense gene expression under stress conditions. To fully elucidate these mechanisms, further research is essential to investigate the effects of MPs/NPs on diverse crop species. Such studies will improve risk assessment of MPs/NPs and help ensure the safety and quality of agricultural products.

MPs/NPs induce cytotoxicity and genotoxicity

Cytogenetic effects result from the oxidative damage to cells, which inhibits cell cycle and repair-regulated genes [69, 77, 117]. Oxidative stress induced by MPs/NPs could disrupt cellular structures including membranes, walls, and DNA strands, which might contribute to the cytotoxicity and genotoxicity of plant tissues [77, 119, 129]. MPs/NPs are genetically and cytogenetically toxic to plants by altering the nucleus and chromosomes (Fig. 4). Traditionally, toxicological investigations have used primary plastic microspheres as a standard for exposure trials. However, the findings from these studies have shown discrepancies when compared to the results obtained by employing secondary plastic microspheres of different shapes and sizes found in the natural environment [39, 61]. There is a lack of research on the uniformity of primary and secondary MPs in relation to their phytotoxic effects. In addition, increased cytotoxicity could be determined by a decrease in mitotic index (MI) [77]. Effects on root growth are often used as biomarkers of cytotoxic and genotoxic effects [68, 100, 117]. Micronucleus (MN) frequency is alternative measure applied to determine the extent of oxidative damage in plants [61]. During cell division, chemical pollutants block chromosome replication and movement, and these damaged chromosomes (segments) form MNs. When exposed to PS-100 nm, the development of faba bean roots reduced and the cytotoxicity increased, as shown by a drop in MI [119]. Nevertheless, the MN test and antioxidant enzyme activity indicated that PS-100 nm induced more genotoxicity and oxidative damage in faba bean compared to PS-5 μm.

The quantity of proteins that govern plant growth and development is determined by the levels of gene expression. As external abiotic stressors, MPs had an impact on the expression of genes and regulatory networks in plants [117, 141]. Advancements in metabolomics and genomics technology have enabled several research to uncover the genetic and metabolic processes via which MPs exert toxicity on plants [77, 141, 142]. Genotoxic effects include chromosomal abnormalities (CA) and nuclear abnormalities (NA) [69]. MPs/NPs have cytotoxic and genotoxic effects on plants, especially at high concentrations, associated with toxicity from chemicals absorbed from the particle surface, such as organic and inorganic pollutants [39, 69, 77]. Expose to MPs/NPs will disrupt the cell cycle by stimulating the overproduction of ROS damage and altering gene expression, leading to genetic abnormalities and structural damage in plant cells [39, 61, 69]. Giorgetti et al. (2020) documented the harmful effects on cell division (decrease of mitotic index) and genetic material (induction of cytogenetic abnormalities and micronuclei) in the rapidly dividing tissues of plant roots, even at the lowest dose [69]. However, in the absence of oxidative stress, the MI of onion root cells was reduced and cytotoxicity was independent of ROS production [117]. Irrespective of their surface charge, the pristine PS-NPs in *Allium cepa L.* exhibit varying amounts of cell mortality, oxidative stress generation, and antioxidant enzyme activity [117]. The concentrations were positively correlated with the rise in values. The inhibitory effect of plastic particles on mitochondria may be linked to their ability to suppress cell cycle regulators and DNA replication, particularly via the regulation of cyclin-dependent kinase (CDK2). The gene expression was diminished, and PS directly affected the G2/M transition by inhibiting G2 phase cells and decelerating all mitotic processes. Furthermore, the harmful effects may arise from the direct interaction with compounds that internalize particles or leak from their surfaces [117]. At the same time, soil extracellular polymers (EPS) formed an ecological corona on PS-NPs, and crowned PS-NPs tended to aggregate, reducing their uptake in onion cells and further decreasing oxidative stress and toxic effects [75, 117]. NPs is more likely to generate genotoxicity than MPs because it has a greater propensity to interact with interior tissues. Furthermore, the presence of NA seems to be influenced by both time and dosage, with NA becoming increasingly detrimental with time and with higher dosages of NPs. For relevant mechanism, Pehlivan et al. (2021) showed that POD1 and HSP1 were pivotal elements in the transduction of ROS into expression of gene transcripts in MPs-exposure maize [141]. Later, Lian et al. (2022) used a combination of DEGA and WGCNA methodologies to explore the molecular processes behind the phytotoxic effects of PS-NPs [142], discovering that exposure to PS-NPs led to substantial alterations in the expression patterns of wheat genes, with a tissue-specific impact. In addition, WGCNA identified four potential modules and their corresponding crucial genes linked to phytotoxicity.

Currently, although transcriptome analysis provided the basis for molecular studies of plant-microplastic interactions, the understanding of plant stress response to MPs/NPs was limited to detected transcriptome data. It mainly for that the identification of MPs/NPs associated genes required the construction of transgenic lines and the validation of downstream protein functions, a time-consuming and cumbersome process. To get a deeper comprehension of the harmful effects of MPs/NPs on plants and the precise molecular pathways involved, it is imperative that more research be conducted with a special emphasis on identifying and describing the functions associated with MPs/NPs.

MPs/NPs under biotic and abiotic stresses

As environmental pollutants, under biotic and abiotic stresses, MPs/NPs have the potential to interact with other stressors [28], such as saline and alkaline stress [123], polycyclic aromatic hydrocarbons (PAHs) (phenanthrene, pyrene) [30–33], heavy metal (Cd, As, Cr, Cu, Pb, Hg, Zn) [21–26], antibiotics (norfloxacin, enrofloxacin, doxycycline, doxycycline, ibuprofen, simazine, sertraline, amoxicillin, florfenicol) [27, 28, 143, 144], plasticizers (di-n-butyl phthalate (DBP)) [29], metal oxide nanoparticles (ZnO, Fe_2O_3) [34, 145], natural organic macromolecular compounds (humic acids) [34], invasive plants (Canadian goldenrod) [35], Botrytis cinerea mycorrhizal fungi [36, 37]. Such interactions could be summarized as synergistic, antagonistic and non-effect (Fig. 5).

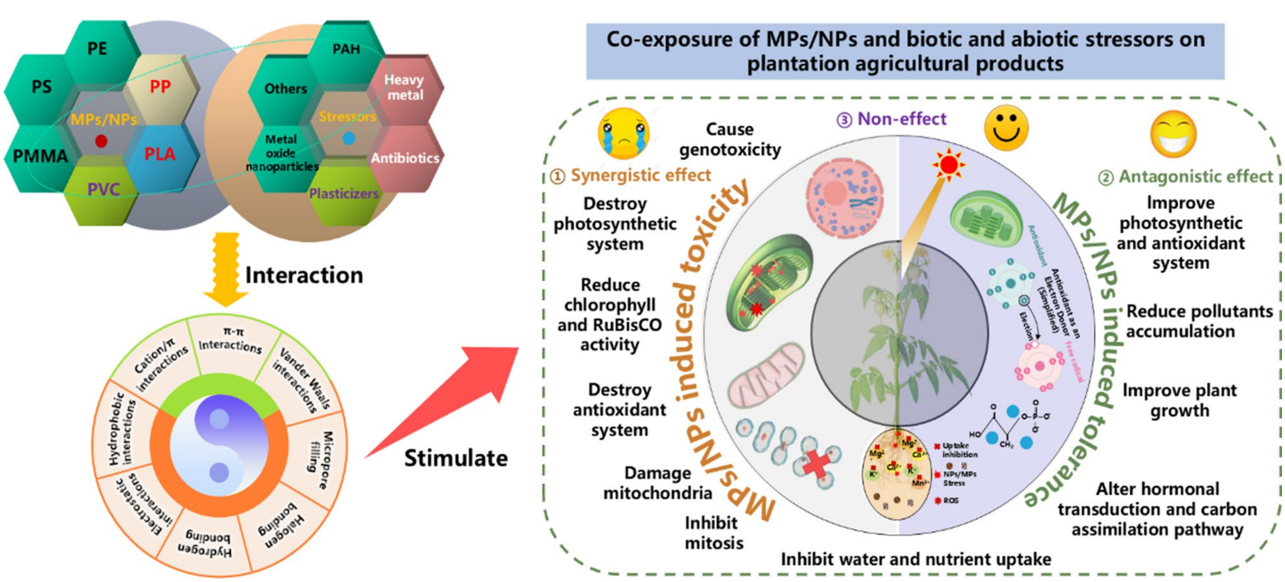


Fig. 5 Combined effects of MPs/NPs with biotic and abiotic stressors on plantation agricultural products [21–28, 30–37, 39, 77, 144, 145]

Due to the inherent physicochemical properties, MPs/NPs could bind soil contaminants, potentially increasing or reducing plant stress. During the process of aging, weathering, and photolysis of plastics, plastic additives such as As, Cr, Pb, DBPs and PAHs are released into the soil or air environment [146]. Studies have indicated that smaller particles of MPs heighten the likelihood of plastic additives being released, which is a primary cause of the phytotoxicity associated with MPs [29]. Owing to large surface area, high hydrophobicity and rich and diverse functional groups, MPs/NPs are carriers of co-existing stressors and pose a combined risk to plants [147]. Co-existing stressors interact with MPs/NPs through various mechanisms, including electrostatic or van der Waals force interactions, hydrogen bonding, halogen bonding, hydrophobic force interactions, micropore filling, and π-π interactions (Fig. 5), altering the physicochemical properties of the stressors and their bioavailability to plants [147]. On the one hand, acted as carriers of abiotic stressors, MPs/NPs facilitated stressors co-transport to the plant roots and increased phytotoxicity, which manifested itself as oxidative stress, inhibition of seed germination, disruption of pectin structure in plant roots, and reduced biomass, photosynthetic pigments, and gas exchange characteristics, in turn reducing growing development and nutrition quality (Fig. 5) [23, 24, 146, 148–150]. On the other hand, MPs/NPs might cut down the bioavailability and translocation of co-existing pollutants to plants by adsorption of the co-existing stressors and thus reduce their phytotoxicity [21, 23, 32, 33, 151, 152]. Simultaneously, MPs/NPs may not contribute to the buildup of pollutants in plants, having a non-impact on the phytotoxicity caused by stressors [147, 153, 154].

Synergistic effect

Currently, MPs/NPs co-exist with most stressors, mainly in the form of synergistic toxic effects on plant growth, exacerbating the hazards to agricultural product. Plastic additives, a contaminant that unavoidably co-existed with MPs/NPs, have been of environmental concern since 2020 [77]. Gao et al. (2019) found that PE-MPs + DBP treatment reduced growth parameters and photosynthesis parameters of lettuce, exacerbating the effects of DBP on lettuce photosynthesis and cellular damage of root tissues with increasing levels of PE-MPs [29]. As an important stressor in soil, heavy metals continuously affected plant growth, and their interactions with MPs/NPs on plant growth had been reported more. MPs/NPs generally facilitate the accumulation of metal ions, such as Cu^{2+}, Cr^{6+}, As^{3+}, and Pb^{2+}, in plants [148–150, 155]. Wang and co-workers (2020) first discovered that the interaction between MPs and Cd might modify maize production and root symbiosis, observing the impact of green biodegradable PLA on Cd bioavailability was more significant than that of PE [153]. Later, Zhang et al. (2023) discovered that PE exhibited greater accumulation of Cr and caused more harm to cucumber plants cultivated hydroponically compared to PA and PLA, which attributing to the ability of MPs to adsorb Cr^{6+} [26]. The impact of the kind of MPs on the accumulation of Cr in plants and their development was more significant compared to the effects of MP size and concentration, depending on the dosage of Cr and MPs [156]. To elucidate the interaction mechanism, a recent study showed that PS could promote As accumulation by inhibiting abscisic acid content and iron plaque formation, significantly increasing the phytotoxicity of As^{3+} by 9.4 ~ 22.8% [157]. Simultaneously, PS-NPs hindered the rice's antioxidant system, disturbed the metabolism of salicylic acid (SA), jasmonic acid (JA), and GSH in rice, and amplified the sequestration of As vesicles and its efflux. This study provides the initial evidence that the "Trojan horse effect" does not play a role in the increased accumulation of As when exposed to NPs. Furthermore, the presence of As^{3+} may enhance the negatively charged region of the plant cell wall, leading to twisting and deformation. This thus enables the infiltration of larger PS-MPs into the roots and leaves of carrots, eventually causing oxidative damage to the carrot tissues and exacerbating the decline in their quality [70]. As MPs/NPs age, the surface of PVC-MPs undergoes natural photolysis, resulting in the breaking of C-Cl bonds and the formation of C = O bonds. This leads to an increase in the hydrophilicity of the PVC-MPs surface. The adsorption of Cd on the aged PVC-MPs is enhanced, leading to an increase in the bioconcentration of Cd in wheat [147]. Dong and colleagues (2022) discovered that the simultaneous exposure to MPs and Cd resulted in a decrease in fruit yield [22]. They also observed that PS-MP and PTFE-MP directly caused damage to the tertiary structure of decreased hemoglobin, whereas As increased the quantity of hemoglobin in rice by stimulating the production of ROS. Under mixed exposure circumstances, there was an observed additive effect, meaning that the combined impact of the conditions was equal to the sum of their individual effects. Specifically, the activities of rice kernel soluble starch synthase and pyrophosphorylase were suppressed, leading to a reduction in starch accumulation. This decrease in starch accumulation resulted in a decrease in rice biomass and yield. Furthermore, it has been recently reported that MPs (PS, PVC, PMF) and Cd had the ability to synergistically enhance seed germination and seedling growth, increase antioxidant enzyme activities, and improve photosynthesis in wheat and lettuce [151, 154, 158]. This exacerbates their ability to increase phytotoxicity when amalgamated with heavy metals. Hence, the precise synergistic impacts of MPs/NPs in conjunction with heavy metals are contingent upon the kind of heavy metal, the type of MPs/NPs, the administered dosage, the concentration of exposure, and the length of exposure.

Substances such as pesticides and antibiotics are inevitably used to control pests and diseases during plant growth. Guo et al. (2022) demonstrated that the combination of hygromycin and PE-MPs caused phytotoxicity, resulting in decreased plant height and biomass. Additionally, this combination dramatically elevated carotenoid content and POD activity, and caused changes in organic acid and sugar metabolic pathways in wheat leaves [144]. The synergistic effect between MPs and antibiotics may vary depending on the type of MPs [28]. Based on cooccurrence network analyses, it is suggested that composite pollution can hinder the growth of wheat and maize seedlings and affect the composition of soil metabolites, such as sugars, organic acids, and amino acids. It is achieved by simplifying the connections between soil bacteria and metabolites and changing the prevalence of certain genera [27]. PAHs are hydrophobic persistent environmental pollutants that are genotoxic, mutagenic, and carcinogenic to plant growth, etc. For the first time, Liu and co-workers (2021) conducted a novel study examining the impact of co-pollution from PE-MPs and phenanthrene (Phe) on agricultural goods [32]. Their findings revealed that the combined contamination had a more hazardous effect on wheat seedlings, such as disrupting the leaf photosynthetic system and hindering the development of the seedlings. Over the years, metal nanoparticles have been widely used in agricultural production, especially metal based nano-fertilizers [159]. The physicochemical qualities and bioavailability of substances are greatly influenced by several soil environmental conditions, including soil pH, soil composition, and the presence of plants [34]. During the process of environmental transport and transformation, excessive use unavoidably leads to the release of substances into the environment, which may cause environmental pollution [160, 161]. Primitively, Gong et al. (2022) discovered that PS-100 nm exacerbated the harmful effects of Fe_2O_3 on lettuce by causing significant oxidative stress, root deformation, and the spread of injured cells from the xylem to the epidermis [34]. PS-100 nm interacted with Fe_2O_3 to form heterogeneous aggregates that favored the leaching of Fe ions and increased Fe accumulation in roots and leaves, thereby exacerbating the toxic effects. In addition, the simultaneous application of PS-MPs and alkali stress resulted in a decrease in the activities of SOD and POD, as well as a reduction in the chlorophyll content of spinach seedlings [123]. Invasive plants provide a growing danger to the functioning and biodiversity of terrestrial ecosystems. These effects are mediated through modifications to root composition and architecture in the soil, alterations in leaf morphology (including length, width, and diameter), and disruptions to plant growth via changes in physiological and metabolic processes [162]. Unlike PE-MPs, Iqbal et al. (2024) discovered that treatments involving the invasive plant *Solidago canadensis L* and PE-MPs had a significant impact on rice leaf biomass, carbon, nitrogen, and phosphorus levels [35]. These treatments also led to a decrease in APX and CAT activities and elevated levels of POD, SOD, and ROS content, causing oxidative stress and changes in the metabolic spectrum of rice leaves.

Antagonism

In addition to the synergistic effect, when MPs/NPs are co-exposed with stressors, they also partially present antagonistic effects and reduce the harm caused by MPs/NPs to plants. One study demonstrated that the interaction between PS and heavy metals resulted in a decrease in the buildup of ROS in wheat seedlings [151]. Specifically, PS decreased the accumulation of Cd and Cu in wheat seedlings, and exhibited properties that mitigated the bioavailability and toxicity of Cd and Cu. On the one hand, PS mitigated the detrimental impact of Cd on the germination potential, vigor index, shoot length, and biomass of wheat seeds [155]. On the other hand, Cd^{2+} mitigated the toxicity of PVC and PE leachate on wheat seedlings [158]. Furthermore, PS-MP and PTFE-MP had the ability to engage with the secretions of rice roots via van der Waals forces [22]. This interaction leads to a decrease in the presence of *Geobacteria* and *Anaeromyxobacter*, resulting in a reduction of iron plaques on the surface of the roots and the absorption of As by rice. Plants may adjust to the simultaneous exposure to MPs and As by controlling antioxidant enzymes and the AsA-GSH cycle [148]. While the concentration in rice leaves increased, the PS-82 nm and PS-200 nm promoted and dropped, respectively in As build-up of rice leaves [148]. Although both amounts of MPs/NPs reduced the harmful effects of As on rice seedling growth, the simultaneous exposure had a more negative impact on the root activity and chlorophyll content of the seedlings.

PE and PLA could reduce the phytotoxicity of hygromycin on *Brassica napus* with antagonistic effects [163]. Hygromycin combined with degradable PLA-MPs produced greater toxic effects on Brassica napus than non-degradable PE. With the deterioration of climate and soil erosion, saline and alkaline soils seriously constrained the development of high-quality agricultural products in the plantation industry [123, 164]. The addition of PS-MPs to alkali stress resulted in a considerable improvement in the germination rate, germination index, germination potential, and vigor index of seeds [123]. It also encouraged the growth of spinach seed roots and shoots, hence reducing the negative effects of alkali stress. For PAHs, PS decreased the build-up of Phe in the roots and stems of rice plants by modifying the processes of photosynthesis and energy metabolism, which in turn enhanced the pathways for carbon sequestration and hormone signaling [30]. Further, the study conducted by Chen et al. (2023) shown that the application of PE resulted in a decrease in the buildup of Phe in both maize plants and soil [31]. Furthermore, it was observed that PE with bigger particle sizes mitigated the harmful effects of Phe on maize growth. Simultaneously, MPs modified the composition of the bacterial community in the roots of maize, decreasing the prevalence of certain bacteria that degrade PAHs, and diminishing the ability of rice plants to accumulate pyrene, hence mitigating the harmful effects of pyrene on the growth of rice seedlings [33]. In terms of metal oxide, 0.5% PE alleviated the toxicity of ZnO to a certain extent, had an antagonistic effect, but did not promote the biotransformation of ZnO to Zn in maize stems [145]. Through the examination of oxidative reactions, phototoxicity, and molecular metabolism, it has been shown that PS has the ability to mitigate the adverse impacts of florfenicol on photosynthesis, growth metabolism, and oxidative stress in rice seedlings [143]. Humic acid (HA) is a large organic compound that is often present in nature. According to Gong et al. (2022), HA has been shown to efficiently decrease the clumping together of PS particles and the release of iron ions, reducing the harmful effects of PS on lettuce [34].

Congenial mycorrhizal fungi are common microorganisms in plant-growing soil environments, playing an important role in regulating soil stability [165]. Several studies have indicated that the presence of ascomycetous mycorrhizal fungi (AMF) does not have a significant impact on the absorption of PMMA-MPs by lettuce in soil [37]. However, mycorrhizal fungi may enhance the uptake of phosphorus by modifying the chemical characteristics of MPs, decreasing their binding with nutrients, and trapping PMMA particles in the vesicles of AMF and fungal hyphae within the roots. This enhancement consequently improves lettuce's resistance to MPs and reduces MPs translocation into its edible tissues. AMF decreased oxidative stress by enhancing antioxidant enzymes, ascorbic acid, glutathione pools, and the glyoxalase system, so alleviating the negative impacts of MPs on soybean growth and physiology [36]. The effects of AMF on the growth and physiology of soybean could be reduced by PMMA particles in the vesicles and root mycelium. Under MPs stress, AMF treated plants with upregulated expression of heavy metal related genes is a good way to mitigate MPs-induced phytotoxicity [39, 77]. In the future, it is important to prioritize the study of MPs/NPs' impact on root secretion release and the subsequent rhizosphere behavior, since this is a critical factor in determining the phytotoxicity of MPs/NPs. Furthermore, it is crucial to comprehend the behavior of coexisting stressors, particularly plastic additives, in terms of their release, adsorption, and desorption on plant rhizosphere MPs/NPs, as well as their combined phytotoxicity.

Non-effect

The interaction between MPs/NPs and environmental contaminants may vary based on the specific characteristics of the MPs/NPs and the kind of plant. The primary emphasis of relevant research was on heavy metals, whereas the effects of MPs/NPs and stressors on plants were mostly synergistic and antagonistic. Non-effect was typically seen only in relation to certain physiological and biochemical markers. Wang and co-workers (2020) demonstrated that PLA, PVC, and PE did not influence the concentration of Cd in maize and lettuce [153, 154]. In addition, Gu et al. (2021) discovered that both new and weathered PVC-MPs had no impact on the toxicity of Cd to wheat leaves [147]. However, the relevant mechanisms of influence have not been effectively studied.

Strategies to mitigate the detrimental effects induced by MPs/NPs

As an abiotic stress, currently, most of the studies mainly focus on the ecological and safety issues linked to the phytotoxicity of MPs/NPs. While significant research has focused on removing MPs/NPs from water, fruits, and vegetable juices [95, 166, 167], there remains a critical gap in developing strategies to mitigate their adverse effects on plantation agricultural goods. It is imperative to not only implement source control measures to prevent MPs/NPs from entering soil, water, and air systems but also to design effective remediation strategies for addressing existing contamination. In the last decade, the United Nations and the EU have developed a series of guidelines for managing plastic waste in response to MPs/NPs pollution, which is crucial for controlling plastics and the resulting MPs/NPs pollution [77, 168]. Meanwhile, the strategies to reduce the harmful effects of MPs/NPs on plants primarily involve the development of novel green biodegradable plastics, phytoextraction and immobilization, exogenous plant growth regulator intervention, modulation by porous nanomaterials, biocatalysis and enzymatic degradation (Fig. 6).

Development of novel green biodegradable plastics

In the field of agricultural production, a significant quantity of engineering equipment and plastic films are composed of non-biodegradable polymers. This poses a hindrance to the advancement of sustainable eco-agriculture [9, 12]. Although there are a range of biodegradable plastic films used in agriculture, some studies found potential bioaccumulation and significant toxicity of biodegradable MPs on the biota, even comparable to the normal plastic polymers [103, 114, 118, 126]. This is mainly for that these biodegradable films require harsh

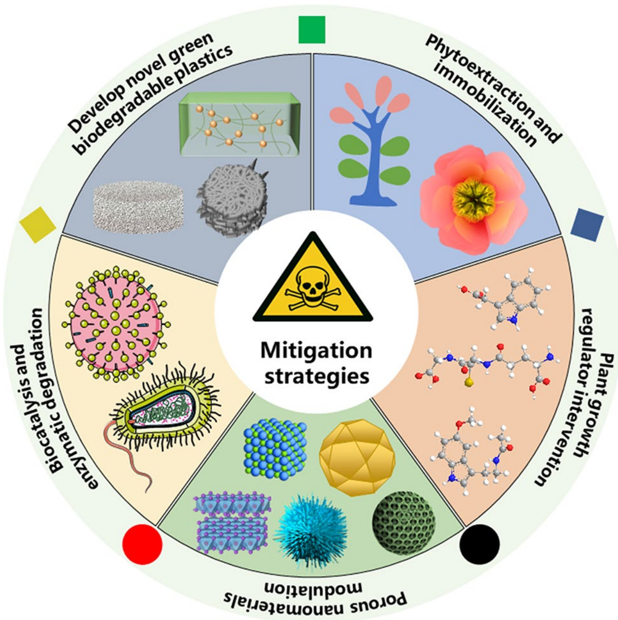


Fig. 6 Mitigation strategies for phytotoxic effects of MPs/NPs

degradation temperatures, specific microorganisms, pH, etc., and the degree of degradation varies significantly depending on the type of plant grown [12, 102, 103, 110]. Hence, research and development of novel green degradable plastics are conducive to reducing plastic pollution at source. According to the EU, the market proportion of green biodegradable plastics is about > 2 million tons by 2023 [12]. If green biodegradable plastics replace synthetic plastics, it will create a safer environment for agricultural cultivation, with less or no synthetic plastic wastes and impacts, and control the production of MPs/NPs. Currently, it has been reported that novel green degradable plastics could be prepared using starch [169, 170], plant and animal derived proteins [171, 172], cellulose [173, 174], chitosan [175, 176], and plant-derived biomass (sugarcane, coffee grounds, cassava roots, etc.) [177, 178]. Table S2 provides a comprehensive comparison of biodegradable plastics and synthetic plastics, focusing on their material characteristics, degradation mechanisms, benefits, drawbacks, and commercial viability. Green and biodegradable polymers, which are cost-effective, biodegradable, and compatible with current bioplastics manufacturing facilities, offer a diverse variety of uses and pose less harm to the food chain, thereby being considered the future trend for plastic goods.

Phytoextraction and immobilization

Phytoextraction and immobilization are ecologically sustainable methods for reducing the pollution caused by MPs/NPs, in which the key lies in how to economically select and excavate plants that can be highly enriched in MPs/NPs [77, 179, 180]. While MPs/NPs exhibit resistance to degradation, they may be absorbed by plant roots and then transferred to plants above the earth [63, 80]. Hence, MPs/NPs may be remediated by either root fixation or extraction from the soil into aboveground plants. Root-fixation does not eliminate MPs/NPs from the environment, but it does decrease their movement and availability, hence lowering their ecological hazard [77, 179]. There have been studies indicating that aquatic plants, including duckweed, have the potential to absorb and enhance the concentration of MPs/NPs in their tissues [181]. However, there is a lack of research on the immobilization of MPs/NPs in plantation crops, and the capacity of terrestrial plants to immobilize MPs/NPs in soil remains unclear [77]. Adsorbed MPs/NPs have the potential to enhance plant metabolism by interacting with functional enzymes, leading to the conversion of MPs/NPs into plant biomass carbon or their mineralization into inorganic products like CO_2 and CH_4 [16, 77]. The immobilization of MPs/NPs with plant extracts may enhance plant biomass and photosynthetic carbon sequestration, while concurrently mitigating global warming caused by greenhouse gas emissions. Hence, the impact of MPs/NPs on the equilibrium of various carbon reservoirs within the ecosystem, particularly in the phytoremediation system of MPs, is of utmost importance. The related research is still in the gap and needs to be further strengthened. To be attention, it is necessary to investigate whether the plastic additives will be extracted and fixed together, or will they cause secondary risks to the growth and metabolism of the plants? Some studies have reported that NPs could increase the ecotoxicity of plastic additive release more than MPs on plant metabolism [12, 77], while Zhou et al. (2024) extracted Hg using *Pennisetum giganteum* [179]. It is vital to controlling the release of plastic additives by selecting suitable plants for phytoextraction and immobilization, which requires large-scale field trials. On the one hand, phytoextraction and immobilization may benefit from the knowledge gained by using phytoextraction to remediate common contaminants such heavy metals, insecticides, and biotoxins [179, 180]. On the other hand, enhancing our comprehension of phytotoxicity and the phytoremediation process for MPs/NPs contamination necessitates the utilization of diverse histology methodologies, including genomics, metabolomics, proteomics, and transcriptomics. Ultimately, it is essential to synthetically evaluate the capacity of plants to endure, collect, and process MPs/NPs. It's exciting that if we incorporate phytoremediation into the landscape and regional functional design of a site, which will achieve production while restoring the environment.

Exogenous plant growth regulator interventions

Plant growth regulators (PGRs) are tiny molecules that function as messengers to regulate plant stress tolerance, controlling stress-adaptive responses and plant growing development [38, 182]. Therefore, exogenous PGRs could be utilized to alleviate MPs/NPs stress. Currently, exogenous PGRs that intervene in MPs/NPs stress mainly include brassinosteroids [183], strigolactones [184], indole-3-acetic acid (IAA) [185], melatonin (MT) [186], glutathione [187], and related studies are in infancy.

Brassinosteroids is a stress-regulating hormone that promoted plant growth and conferred plant resistance. Gao et al. (2023) demonstrated that the application of brassinosteroids at a concentration of 50 nM increased the expression of fatty acids and NIP1-2 [183]. This was achieved by suppressing the expression of genes related to water channel proteins, while simultaneously enhancing amino acid metabolism and synthesis. As a result, the accumulation of PS-NPs in tomato fruits was inhibited, leading to improved plant growth, increased fresh weight, and taller plants, effectively reducing the phytotoxic effects caused by NPs.

Strigolactones, a kind of plant hormone, when applied, activates the antioxidant defense system and reduces oxidative stress in maize, thereby decreasing the build-up of PS-NPs and enhancing the stress resistance [184]. Multi-omics technology analysis showed that solanum lactone application altered gene expression patterns and the rate of metabolic reactions in PS-NPs-treated maize, contributing to enhance molecular mechanisms of tolerance. The initiation of stress and immunological responses by strigolactones is indicated by the activation of signal transduction and defense-related pathways/genes.

Indole-3-acetic acid (IAA) activates ATPase at the plasma membrane, stimulates hydrogen ion efflux out of the cell, lowers medium pH, activates related enzymes to hydrolyze polysaccharides, resulting in softening cell wall and expansion [188, 189]. Xu et al. (2023) found that IAA synergistically inhibited NPs distribution, maintained rice redox homeostasis, enhanced the production of tetrapyrrole compounds, reducing the harmful effects caused by PS-NH_2 in rice [185]. However, relevant genes and pathways involved in the detoxification of PS-NH_2 were still unknown.

Melatonin (MT), a plant hormone, has garnered interest due to its capacity to mitigate abiotic stressors in crops [39]. The application of exogenous MT reduced the uptake and toxicity of PS-NPs in roots by modulating the expression of aquaporin genes. Specifically, MT upregulated the expression of tonoplast intrinsic proteins and plasma membrane intrinsic proteins in both leaves and roots, thereby decreasing NPs absorption in roots and limiting their translocation to stems [186]. MT stimulated the ROS scavenging mechanism, maintained a more balanced redox equilibrium, and mitigated the adverse impacts of PS-NPs on glucose metabolism, leading to greater plant growth and increased resilience to NPs toxicity.

Glutathione (GSH) is critical in maintaining and regulating several interrelated cellular processes of metabolism [68, 187, 190]. GSH works along with ascorbic acid to control the process of lipid peroxidation and effectively regulate lipoxygenase activity and the buildup of H_2O_2 [191, 192]. GSH application improved physiological traits impaired by PET and PE, such as chlorophyll content, transpiration, gas exchange, biomolecules and ion content, thereby promoting growth and yield in rice [187]. This phenomenon may be partially attributed to the distribution of GSH in the mitochondria, where a greater concentration of GSH allows for more effective removal of ROS, hence reducing the negative impact of ROS on photosynthesis. Furthermore, an increased buildup of GSH in the cytosol mitigated the adverse impacts of ROS on the outflow of cations, such as K^+ and Ca^{2+}.

In conclusion, PGRs could effectively regulate the poisonousness of MPs/NPs and improve plant metabolism and immune resistance in plant within the appropriate dosage range, which provides a new idea for MPs/NPs-induced phytotoxicity in sustainable agriculture. Apart from understanding the related mechanisms, large-scale implementation and feasibility of the multi-omics approach can be quite challenging. But it definitely has great potential in the future.

Porous nanomaterials modulation

Utilizing nanobiotechnology to breed genetically modified crops with enhanced stress tolerance is a potentially secure and environmentally-friendly approach to boost agricultural productivity [193]. Some porous nanomaterials with unique physicochemical properties could promote plant growth and improve plant resistance to MPs/NPs stress [24, 194, 195]. Currently, the porous nanomaterials that have been documented for their use in modulating plant resistance to MPs/NPs stress mostly consist of biochar [195], TiO_2 [24], Fe_2O_3@GO [196], FeO [197]. The use of biochar in agricultural soils has been suggested as a strategy to mitigate MPs/NPs stress by enhancing soil enzyme activities, microbial diversity, nutrient retention, N and C cycles, amino acid and carbohydrate metabolism [74, 195, 198–200]. For instance, Ran et al. (2023) showed that the alteration of biochar improved the development of bacteria resistant to PP in soils. Specifically, the *Massilia*, *Lysobacter*, and *Terrimonas* spp. were shown to stimulate the growth of chilli plants [201]. Furthermore, the introduction of biochar enhanced the prevalence of genes associated with bacterial amino acid and carbohydrate metabolism in soils polluted with MPs. Additionally, it promoted the cycling of nitrogen and phosphorus metabolism in plants growing in soils contaminated with MPs. Li et al. (2023) conducted a study on the impact of corncob biochar (CCBC) on the phytotoxicity of PVC-MPs [200]. They discovered that CCBC effectively decreased the levels of H_2O_2, ROS, and MDA in lettuce, which helped mitigate the toxicity of PVC-MPs on lettuce seedlings and minimize the negative effects of PVC-MPs on crop yield. The stimulatory effect might be related to nutrient release from CCBC, changes in medium pH, and reduction of PVC-MP exposure through adsorption. These first results indicate that the processes by which biochar affects the phytotoxicity of MPs are intricate and need additional in-depth investigation. Biochar enhanced root development in Vicia faba by boosting the mitotic index and reducing the proportion of aberrant root tip cells, resulting in increased fresh and dried weights of the roots [202]. To summarize, biochar enhances plant development in the presence of several stressors by directly influencing plant growth and indirectly influencing soil fertility and production.

When it comes to abiotic stressors like drought and salinity, only a few metal oxide nanoparticles have been applied to mitigate MPs/NPs stresses [24, 194, 196, 197]. Arikan et al. (2022) found that Fe_2O_3@GO had an excellent antioxidant capacity to effectively scavenge ROS, and maintained biochemical responses to photosynthesis, thereby eliminating the PS adverse effects on wheat development [196]. In response to PS-NPs induced growth inhibition, TiO_2 regulated C and N metabolism in maize through melatonin signaling, demonstrating enhanced rates of photosynthesis, sucrose synthesis, and protein synthesis, and modulating the antioxidant system to mitigate oxidative damage [194]. For combined stresses, AL-Huqail et al. (2024) demonstrated that the addition of TiO_2 enhanced cell segregation and reduced the negative effects of growth toxicity caused by the combination of PVC and Hg by lowering proline metabolism and AsA-GSH cycling [24]. The combined virulence of PVC and As could be reduced to wheat seedlings by coating wheat seeds with FeO [197], which provides a new approach to address the contamination of heavy metals and MPs.

As abiotic stress, MPs can induce the production of excessive ROS in plants, disrupt the homeostasis of ROS in plants, thus impairing plant growth. The strategies for enhancing crop stress resistance based on nanomaterials mainly include the use of porous nanomaterials to simulate the characteristics of ROS scavenging enzymes and the use of nanomaterials to stimulate and induce plants to produce immune memory resistant to ROS [193]. Therefore, porous nanomaterials have a wide potential for mitigating the elimination of MPs/NPs-induced phytotoxicity, which needs to be further investigated. It is important to note that if the crops are genetically modified to tolerate MPs, could this approach also lead to new invasive plants/crops with further ecological implications? For example, there is a need to assess the impact of nanomaterials and modified plants on non-target biota and to study the bioaccumulation of nanomaterials in the food chain. Importantly, nanomaterials can degrade themselves after mitigating MPs toxicity, and no secondary risk has been reported so far.

Biocatalysis and enzymatic degradation

As a safe and green method, biocatalysis and enzymatic degradation are of great research value for the removal of MP/NPs. Various strains of fungus and bacteria may facilitate the breakdown of microplastics and nanoparticles by using their own amino acid catalytic sites. This process involves transforming the chemical structure of the microplastics and nanoparticles from being composed of multiple units to being composed of single units [12]. Microbial biodegradation primarily happens via two mechanisms: internal degradation and extracellular degradation [48, 203]. During intracellular degradation, bacteria form aggregates on the surface of the MPs/NPs and break down the MPs/NPs into shorter chains by hydrolysis. Bacteria secrete extracellular enzymes, such as hydrolases, to break down complex polymers into smaller units. These units are then transformed into end products, such as CO_2, H_2O, or CH_4, by either anaerobic or aerobic metabolism. For example, *Bacillus gottheilii* mediated chemical changes and bond breaks that subsequently reduced the bioavailability of PE, PET, PP, and PS [204]. Nitrogen-fixing bacteria enhance the breakdown of MP/NPs by increasing the population of fungi, speeding up the action of enzymes that degrade plastics, and establishing or interacting with communities of fungi that degrade plastics [203, 205]. The development of the microbial degradation of MP/NPs depends on the microorganisms excavated. Jeon et al. (2021) found that strain JJY0216 effectively degraded PE and PP in soil, reducing the degradation rate by about 4% and 9%, respectively, within 26 days [206].

Since most of the MPs/NPs are present in the soil, their catalytic degradation could be achieved with the help of rhizosphere microorganisms by using microorganisms or enzymes with high efficiency in the catalytic degradation of MPs/NPs in plant roots [77, 88, 207]. For example, rhizosphere -specific bacteria could efficiently catalyze the degradation of PS-MPs with aromatic structures [88]. The rhizosphere soil may be degraded by bacteria (*Serratia plymuthica*) and fungus (*Laccaria Laccata*), causing the breakdown of PLA and PET [207]. Within the soil around the roots, the release of root exudates, specifically low molecular weight organic acids, may serve as a source of nutrition for microorganisms [115, 208]. This, in turn, enhances the process of breaking down

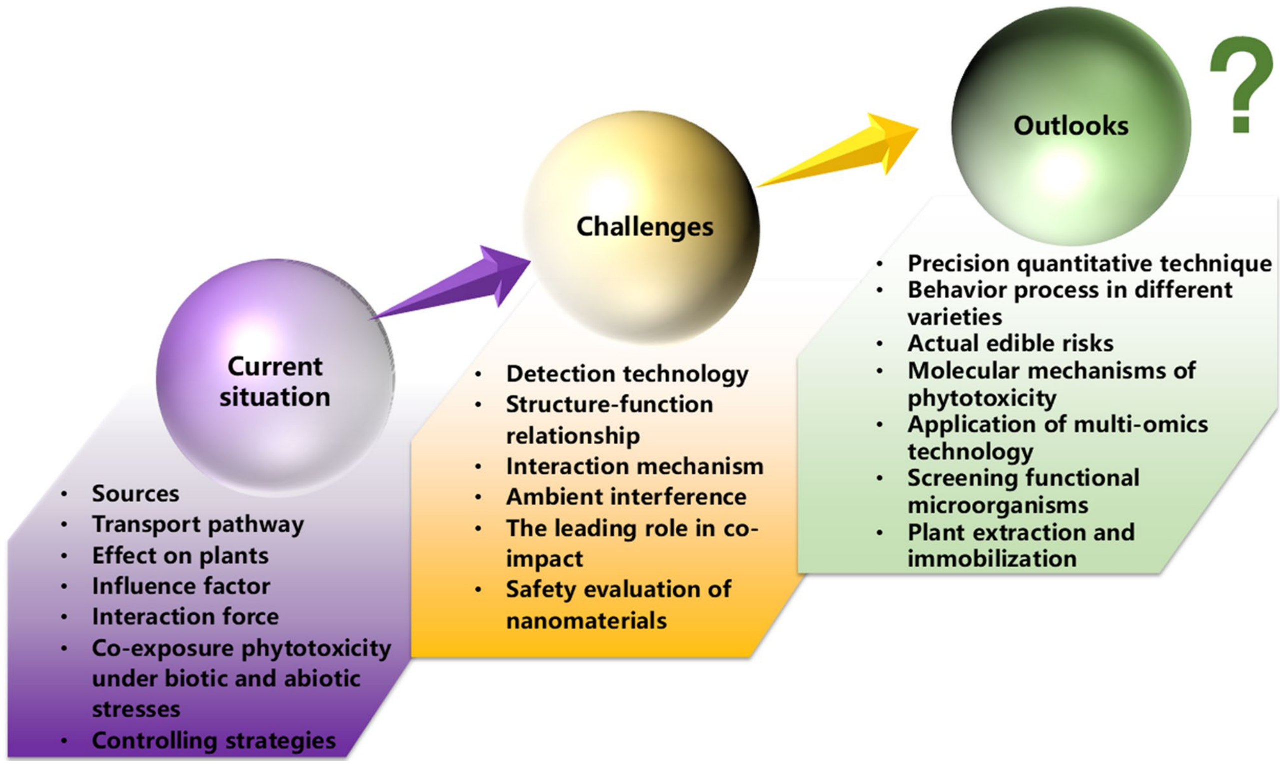


Fig. 7 Current situation, challenges and outlooks of MPs/NPs in plantation agricultural products

persistent plastics that are challenging to decompose. Moreover, many active biological enzymes present in root secretions contribute to the oxidation-reduction and hydrolysis processes of MPs/NPs, hence promoting the breakdown of MPs/NPs in the area between plant roots [209, 210]. Rhizosphere or endophytic microbes promote plant development and enhance plant health, playing a crucial role in plant detoxification and the breakdown of pollutants such as MPs/NPs in the rhizosphere region [77, 211]. Therefore, rhizoremediation of MPs/NPs stress could be achieved with the help of functional microorganisms and rhizosphere secretions, which has a great potential for application.

Conclusions

This study conducted a comprehensive analysis of the origins, absorption, movement, and buildup of MPs/NPs in agricultural products within the plantation industry. It also examined the impact of MPs/NPs on plant growth and development, compared the effects of simultaneous exposure to MPs/NPs and other environmental stresses on plants, and discussed strategies for controlling and reducing their effects. The primary major discoveries of this investigation are as follows (Fig. 7): (1) The sources of MPs/NPs in plantation agricultural products include mulch, sewage, compost fertilizer, municipal solid waste, pesticide packaging materials, etc. Then, they contact with plants through growth media such as the atmosphere, water, and soil. (2) MPs/NPs can adhere to plant roots and enter the stele via endocytosis or the apoplast pathway. Alternatively, they may penetrate the cortical tissue through fissures in lateral root cells and subsequently be transported from belowground to aboveground tissues through xylem conduits. Conversely, MPs/NPs present in the environment can also enter leaf stomata, infiltrate leaf vein tissues, and be translocated from the top to the bottom of the leaf via the phloem. (3) Once internalized, MPs/NPs can exert multifaceted impacts on plants, spanning phenotypic, metabolic, enzymatic, transcriptional, and genetic levels. These effects include inhibition of plant growth and seed germination, disruption of nutrient metabolism, reduction in chlorophyll content, suppression of photosynthesis, induction of cytotoxicity and genotoxicity, and induction of oxidative stress and metabolic disorders. Collectively, these adverse effects lead to diminished fruit yield and reduced nutritional quality. (4) The extent of harm caused by MPs/NPs to cultivated agricultural products is modulated by a range of factors. These include the properties of MPs/NPs (e.g., type, size, shape, aging degree, surface charge, exposure duration, and concentration), plant characteristics (e.g., species, age, and tissue type), cultivation practices, and environmental conditions (e.g., soil microbial communities and the presence of other stressors). (5) MPs/NPs, as natural carriers, could undergo a series of interactions (electrostatic or van der Waals force interactions, hydrogen bonding, halogen bonding, hydrophobic forces, micropore filling and π-π interactions, etc.) with other abiotic stresses (salinity stress, PAHs, heavy metals, antibiotics, plasticizers, nano-oxidants, naturally occurring organic macromolecule compounds, invasive plants, Botrytis cinerea mycorrhizal fungi, etc.) together, co-affecting plant growth. The combined phytotoxicity are summarized as synergistic, antagonistic and non-effect, which is not a simple "1 + 1 = 2". (6) There are some strategies used to ameliorate MPs/NPs-induced toxicity of cultivated agricultural products, mainly including the development of novel green biodegradable plastics, phytoextraction and immobilization, intervention by exogenous plant growth regulators, modulation of porous nanomaterials, biocatalysis and enzymatic degradation.

Challenges

Although some progresses have been made on the behavior process, phytotoxicity under biotic and abiotic stresses and controlling strategies of MPs/NPs in agricultural products, a series of problems and deficiencies still exist (Fig. 7):

Challenge 1

Further investigation is required to examine the correlation between the absorption, transportation, and structural impacts of MPs/NPs in various cultivated agricultural products. For example, are the transport and translocation patterns of root, leaf and organ consistent in cruciferous vegetables? Factors and mechanisms affecting the uptake and transport capacity of MPs/NPs need to be further explored.

Challenge 2

The analysis of MPs/NPs in agricultural systems faces significant challenges, including the complexity of soil physicochemical properties and matrix interference, as well as limitations in detection methods. Are the specific concentrations of MPs/NPs in the relevant organ tissues of plantation products, particularly in the edible portions, a potential risk to human health? There is still a research gap in this area. Furthermore, most of the studies were carried out in controlled laboratory settings, where PS/PE particles of the same size and shape were used. This approach overlooks the crucial influence of the environment and the variability of MPs/NPs in their potential harm to plants and the ecological risks they pose.

Challenge 3

Although MPs/NPs inhibit seed germination, disrupt antioxidant systems, and restrain plant growth metabolism and photosynthesis, the molecular mechanisms of their phytotoxicity remain to be elucidated, e.g., changes in plant hormone responses and mRNA transcription of pollutant transporter protein genes.

Challenge 4

Recent studies have explored the co-exposure phytotoxicity of MPs/NPs under biotic and abiotic stresses, but the relevant interactions mechanisms and the conformational relationships of the co-impact induced toxicity need to be further elucidated. Which pollutant plays a dominant role under combined stress conditions?

Challenge 5

The investigation of the inhibitory effects of plant growth regulators, namely brassinosteroids, strigolactones, biochar, and FeO, on the absorption of MPs/NPs via influencing the expression of water-channel protein-responsive genes is now underway. Studying the interaction between plant growth regulators and bionanoparticles and how it influences the harmful effects of MP/NPs-induced phytotoxicity is important. However, this mechanism has not been fully tested by cytological and genetic analyses. Currently, there is a lack of knowledge on the impact of phytohormones and nanomaterials on the absorption, movement, and distribution of MPs and NPs inside different plant organs, particularly the parts that are consumed as food. Do hormones and metal ions cause residues and secondary contamination? Relevant research data are still lacking.

Challenge 6

In plant extraction and immobilization, there has been no terrestrial plants identified that could efficiently adsorb and remove MPs/NPs. It is necessary to consider whether their growth will interfere with the growth and development of plantation agricultural product.

Challenge 7

In biocatalysis and enzymatic degradation, there is a lack of enzymes with efficient degradation properties for different types of MPs/NPs and high resistance to matrix interference, while economic costs and usage scenarios need to be considered.

Future prospects

To address the current research gaps and comprehensively reveal the phytotoxicity of MPs/NPs and their related mechanisms in plantation agricultural products, and to further safeguard the food safety on the tip of the tongue, future studies should focus on the following key areas (Fig. 7): (1) Develop robust pretreatment and analytical techniques to accurately detect and quantify MPs/NPs in diverse soil environments and agricultural products at environmentally relevant concentrations. This will enable precise assessment of their environmental behavior and associated risks. (2) Investigate the absorption, translocation, and structural impacts of MPs/NPs in various crops, identifying factors influencing their bioavailability. Assess their uptake rates, bioaccumulation potential, and transmission through the food chain to evaluate human health risks. (3) Conduct field studies to examine the interactions and ecological effects of MPs/NPs with varying properties during aging. Employ advanced data analysis tools, such as machine learning, to predict dietary health risks and establish safety thresholds. Utilize stable isotope labeling and metabolic flux analysis to trace their propagation through food webs. (4) Explore the role of phytohormones and porous nanomaterials in modulating the uptake and distribution of MPs/NPs in plants. Employ high-throughput omics approaches (proteomics, metabolomics, and transcriptomics) to unravel the molecular mechanisms of phytotoxicity. (5) Investigate the potential of plant growth regulators and porous nanomaterials to alleviate the synergistic phytotoxicity of MPs/NPs in edible crops. Identify safe and effective materials while ensuring no secondary contamination. (6) Develop MPs/NPs-resistant crop varieties using genetic engineering to minimize their accumulation in edible parts and ensure food safety. (7) Enhance understanding of MPs/NPs interactions with rhizosphere microorganisms using advanced histological techniques. Promote plant extraction and immobilization strategies to mitigate pollution. (8) Screen and engineer functional microorganisms with high biocatalytic degradation efficiency for MPs/NPs using directed biosynthesis technology, enabling cost-effective and sustainable rhizosphere remediation.

In summary, current research has yet to fully elucidate the phytotoxicity of MPs/NPs and their underlying mechanisms. This study aims to assess agricultural and food safety by comprehensively investigating the transport and behavior of MPs/NPs in crop systems. The findings provide a foundation for future research, advancing our understanding of the impacts of MPs/NPs on plants and contributing to the quality and safety assurance of agricultural products.

Abbreviations

AMF	Arbuscular Mycorrhizal Fungi
APX	Ascorbate Peroxidase
AsA	Ascorbic Acid
CAT	Catalase
CCBC	Corncob Biochar
DBP	Di-n-Butyl Phthalate
DC	Doxycycline
DHAR	Dehydroascorbate Reductase
ENR	Enrofloxacin
EPS	Extracellular Polymeric Substances
GR	Glutathione Reductase
GSH	Glutathione
GSH-PX	Glutathione Peroxidase
HA	Humic Acid
IAA	Indoleacetic Acid
JA	Jasmonic Acid
LMWOAs	Low molecular Weight Organic Acids
MDA	Malondialdehyde
MDHAR	Monodehydroascorbate Reductase
MT	Melatonin
NOR	Norfloxacin
OTC	Oxytetracycline
PA	Polyamide
PAN	Polyacrylonitrile
PBAT	Polybutylene Terephthalate-Adipate
PBT	Polybutylene Terephthalate
PC	Polycarbonate Granulate
PE	Polyethylene
PET	Polyethylene Terephthalate
PGR	Plant Growth Regulator
PHBV	Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate)
Phe	Phenanthrene
PLA	Polylactic Acid
PMF	Polyester Microfibers
PMMA	Polymethylmethacrylate
Pn	Photosynthesis Rate
POD	Peroxidase
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
ROS	Reactive Oxygen Species
SA	Salicylic Acid
SOD	Superoxide Dismutase

Supplementary Information

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Supplementary Material 1

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Author contributions

Z.H.L., J.W., G.Y. L. and D.H.X. conceived the idea, designed the experiment, wrote and reviewed the manuscript; B.S., Y.M.Z., X.B.W., Z.J.W. conducted experiments and data analysis; J.Z., J. L., G.C. participated in data collection and discussion.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors have provided consent for the manuscript to be published in Journal of Nanobiotechnology.

Competing interests

The authors declare no competing interests.

Author details

[1]State Key Laboratory of Vegetable Biobreeding, Institute of Vegetables and Flowers, Key Laboratory of Vegetables Quality and Safety Control, Chinese Academy of Agricultural Sciences, Ministry of Agriculture and Rural Affairs of China, Beijing 100081, China

[2]Key Laboratory of Agro-Product Quality and Safety, Institute of Quality Standards & Testing Technology for Agro-Products, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[3]College of Horticulture, Shenyang Agricultural University, Shenyang 110866, China
[4]College of Horticulture, Hunan Agricultural University, Hunan 410125, China

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