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Microplastic/nanoplastic toxicity in plants: an imminent concern

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Abstract The toxic impact of microplastics/nanoplastics (MPs/NPs) in plants and the food chain has recently become a top priority. Several research articles highlighted the impact of MPs/NPs on the aquatic food chain; however, very little has been done in the terrestrial ecosystem. A number of studies revealed that MPs/NPs uptake and subsequent translocation in plants alter plant morphological, physiological, biochemical, and genetic properties to varying degrees. However, there is a research gap regarding MPs/NPs entry into plants, associated factors influencing phytotoxicity levels, and potential remediation plans in terms of food safety and security. To address these issues, all sources of MPs/NPs intrusion in agroecosystems should be revised to avoid these hazardous materials with special consideration as preventive measures. Furthermore, this review focuses on the routes of accumulation and transmission of MPs/NPs into plant tissues, related aspects influencing the intensity of plant stress, and potential solutions to improve food quality and quantity. This paper also concludes by providing an outlook approach of applying exogenous melatonin and introducing engineered plants that would enhance stress tolerance against MPs/NPs. In addition, an overview of inoculation of beneficial microorganisms and encapsulated enzymes in soil has been addressed, which would make the degradation of MPs/NPs faster.

Keywords Germination · Phytotoxicity · Mucilage · Translocation · Ecocorona · Remediation

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Introduction

In 2004, tiny plastics < 5 mm in size were termed microplastics (MPs) (Thompson et al., 2004), and later, plastic particles ranging between 1 nm and 1 μm in size were considered nanoplastics (NPs) (Frias & Nash, 2019). However, due to their pernicious consequences on the environment, both MPs and NPs have become an imminent concern for the research community. The primary sources of MPs/NPs are plastic particles from the textile industry, plastic manufacturing industry, cosmetics, and scrubbing agents, while fragmented plastic particles produced via weathering are coined as secondary MPs/NPs (Tang et al., 2019). Therefore, the plethora of MPs/

NPs in the soil is enumerated to be 4 to 23 times higher than that in the ocean (Nizzetto et al., 2016). In the soil environment, plastic mulching, landfilling of plastic wastes, utilization of sludge, wastewater irrigation, and atmospheric deposition are the prominent sources of MPs/NPs and ultimately affect biodiversity (Nizzetto et al., 2016; Horton et al., 2017; Chae & An, 2018; He et al., 2018). Aside from direct entry of MPs/NPs via plastic mulching, wastewater irrigation, and plastic-contaminated sludge or biosolids are potential sources of MPs/NPs into crop fields (Sanchez et al., 2020). Each year, approximately 0.8 to 2.5 million tons of MPs are discharged into water bodies via wastewater treatment plants, with 95% of these plastic particles carried in the form of biosolids (Boucher & Friot, 2017; Ziajahromi et al., 2016). As a result, the direct utilization of such wastewater and biosolids in the form of irrigation and the application of plastic-coated fertilizers are endangering agricultural land (Mohapatra et al., 2016). Simultaneously, the results from the recent studies also revealed that the MPs/NPs in the wastewater, organic fertilizers, and sewage sludges are the major sources of plastic particles in the terrestrial environment and ultimately responsible for poisoning the agricultural land (Harley-Nyang et al., 2022; Zheng et al., 2022).

Once MPs/NPs amalgamate into the topsoil (grater hub of nutrients and hold plant roots), they may travel into deeper soil via tillage as well as activities of soil biota and large cracks due to the plowing of agricultural soils (Liu et al., 2018; Rillig et al., 2017). As plants serve basic living components from the pristine period, understanding the interactions between MPs/NPs and plants is a crucial aspect of risk assessment (Li et al., 2020a). Regarding plant growth, diverse impacts of MPs/NPs have been identified, including direct absorption and accumulation into plant cells and alteration of different cellular activities in plants (Li et al., 2019; Qi et al., 2020; Rillig et al., 2019). Moreover, regarding seed germination and root growth, MPs block the cell wall pores and hinder water and nutrient uptake, resulting in interference with physiological processes (Bosker et al., 2019; Jiang et al., 2019); thus, both above and below ground biomass productions are affected simultaneously (Zhang et al., 2020). Investigation from early studies has also proven that MPs/NPs hinder the growth of wheat (Liu et al., 2021), corn (Wang et al., 2020a, b), cress, and tomatoes (Bosker et al., 2019) and are highly noxious to the seedlings of rice (Dong et al., 2020). Recently, the observations from different studies of MPs/NPs reveals their noxious effects on major crops which may be a potential threat to the assurance of food security in the long run. For example, the observation from a recent study reveals that polystyrene-nanoplastics (PS-NPs) affect the physiology of rice seedlings, impede normal RNA biosynthesis, and hinder the plants' responses to external stresses (). Moreover, the intensity of toxicity depends on some other factors, such as polyvinyl chloride-based MPs (PVC-MPs) showing a more devastating impact compared to PS-MPs in the metabolism, ionic homeostasis, and growth of crop plants (Ma et al., 2022). However, these interpretations may only mirror the direct impact of MPs/NPs in plants. Additionally, alterations in soil properties also indirectly affect plant growth. Specifically, MPs/NPs can rupture the soil structure, diminish the permeation of rainwater as well as irrigation water, negatively affect the water holding capacity of the soil, disturb microbial activity in the soil, cause pH imbalance, and disrupt nutrient transfer (Cao et al., 2017; Li et al., 2021a, b, c, d; Liu et al., 2018). MPs/NPs with smaller sizes and larger specific areas interact with soil microbiomes, reduce their normal growth and function, and interrupt nutrient dynamics in soils (Torres et al., 2021). In addition, MPs have been observed to create a strong disturbance in carbon and nitrogen cycling in soil by declining both organic nitrogen (DON) and dissolved organic carbon (DOC), enhancing the content of soil organic matter (SOM) and ultimately affecting the normal agricultural crop productions (Kim et al., 2021; Meng et al., 2022). However, regarding mitigation of MPs/NPs pollution, biodegradation of soil plastic particles can be an effective way to alleviate the intensity of contamination in terrestrial lands (Sun et al., 2022). In the case of direct implementation, the exogenous application of melatonin in crops reduced both uptake and translocation of NPs by crop roots and shoots respectively, which boosted the tolerance of plants towards MPs/NPs toxicity (Li et al., 2021a, b, c, d).

To date, most of the review articles are concerned with the distribution and toxic potential of MPs/NPs from the aquatic ecosystem to the human food web (Huang et al., 2021). Thus, an urgent demand to autopsy the potential adverse effects of MPs/NPs on crop production is inevitable. For example, Zhou et al., (2021a, b, c) mentioned the impact of MPs in agroecosystems. Yin et al. (2021) considered the effect of MPs/NPs in vascular plants. Recently, Okeke et al. (2022) reviewed the effect of MPs on the food chain. The effect of MPs on the growth of plants was reviewed by Yadav et al. (2022). However, the analysis is still superficial, and explanations of the root reasons (antagonistic effect of MPs/NPs in plants) responsible for the malfunctioning of the food web are insufficient. More specifically, several potential issues including the entrance of plastic particles followed by the weakening of plant defense mechanisms, the factors related to MPs/NPs and plants that determine the toxicity, and how they interfere with food quality and quantity are needed to analyze critically. As the research on the aforementioned issues is in its early stage, thus, very little information can be found on how to mitigate the adverse effect of MPs/NPs in plants. Therefore, to the best of our knowledge, for the first time, this article critically analyzed the imminent concern of MPs/NPs toxicity in plant/crop production regarding food security and food safety, with special consideration of basic food and nutrition providing grain crops, vegetables, and fruits. In addition, this review also represents an in-depth study to unearth the potential risk with probable quantification of MPs/NPs ingested by humans, especially through basic food suppliers and potential remediation methods to minimize the intensity of such noxious pollution from agroecosystems.

Routes of MPs/NPs accumulation and translocation in plants

MPs/NPs may accumulate in plants through two pathways: root uptake and foliar uptake (Sun et al., 2021). Though MPs are too large to pass through the physical barriers of intact plant tissue (Li et al., 2020a), they are easily absorbed on the surface of plant roots and seeds. MPs, for example, have been discovered to accumulate in the pores and roots of garden cress (*Lepidium sativum*) (Bosker et al., 2019) and broad bean (*Vicia faba*) (Jiang et al., 2019). Furthermore, MPs are not capable of penetrating cell walls but can block the pores of cell walls or connections between cells, resulting in a reduction in water and nutrient transport into plant cells. In contrast, it is possible that NPs, like nanoparticles, can pass through plant cell walls (Fig. 1). Previously, studies claimed that a large number of nanosized plastics were likely to enter root tips via the epidermis or rhizodermis via intercellular wall pathways, which is a lignified epidermis

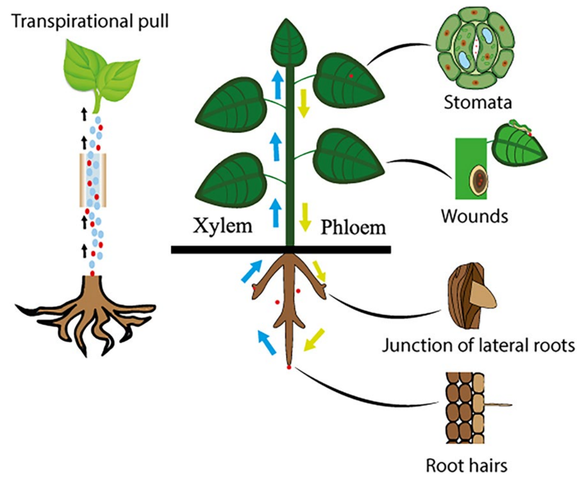

Fig. 1 Routes of MPs/NPs accumulation and translocation into plants

route (Zhang et al., 2019). Thus, the roots and other organs (nutrient uptake) of vascular plants are highly susceptible to NPs intake (Sun et al., 2021). After passing through the plant cell wall, these nanosized particles move towards the endodermis via osmotic pressure and capillary action, a process known as the apoplastic pathway (Deng et al., 2014). In an experiment, Dong et al. (2021a, b) exposed that PS-based NPs (50–150 nm in size) are more likely to enter carrot roots and then translocate to the plant's leaves. Similarly, Sun et al. (2020a, b) later claimed that PS-based NPs could be taken up by *Arabidopsis thaliana* roots and eventually migrate to the aboveground parts. Moreover, NPs can enter through the junction of lateral roots. Evidence of PS microbead uptake in both wheat and lettuce plants is observed from the site of lateral root emergence to the stele through the crack-entry mode (Li et al., 2020a). The study provided an outline of the internalization of both polymethylmethacrylate (PMMA) and polystyrene (PS) from the apical root zone, crossing epidermal layers where the region of the Casparian strip is not developed fully. Thus, PS particles diffused through apoplastic spaces towards the xylem vessel and were transported from the roots to the shoots.

Moreover, NPs may follow a simplistic route in which these particles interact with membrane proteins, ion channels, and aquaporins and engage in ion transportation and internalization via endocytosis (Tripathi et al., 2017). For example, aquaporins in rice roots facilitate the uptake of NPs (Zhou et al., 2021a, b, c). In terms of endocytosis, one study found that NPs (PS beads) could enter into tobacco cells via clathrin-independent endocytosis (Bandmann et al., 2012). Another study recently discovered that rice roots can absorb PS-based NPs (100 nm) via endocytosis (Wu et al., 2021). Thus, once NPs enter plant roots, they can translocate to various organs, and the intensity of such translocation is determined by the transpiration stream. Similar findings were found in Li et al.'s study (Li et al., 2020a), where a higher rate of transpiration (main pulling force) aided in the uptake of plastic particles, which were then responsible for transporting them from roots to shoots.

Furthermore, the stomatal pathway is another potential route for plant leaves to absorb nanoparticles (Lv et al., 2019). Engineered nanoparticles, for example, can be absorbed through the stoma and then transported to various parts of the plant via apoplastic routes (Zhao et al., 2017). Similarly, a recent study emphasized the interaction of plants and airborne NPs (Lian et al., 2021a). In this experiment, lettuce (*Lactuca sativa L.*) plants were exposed to PS-based NPs for a set of times through foliar application. Then, microscopic analysis revealed that PS-NPs were absorbed into the leaves via stomatal opening and then migrated to the roots via the vascular bundle (Lv et al., 2019). They then examined the lettuce foliar surface and discovered a massive accumulation of PS-based NPs around the leaf stomata. In addition, recently the findings of a study clearly illustrated that the presence of PS (0.2 μm) mostly restrained the xylem and cortex tissue of lettuce and wheat roots and also in the leaves (Luo et al., 2022). The above-discussed observations depict that once NPs enter into the vascular bundle of roots, they can readily transfer along the vascular cylinder following the nutrient and water transporter xylem to the shoot and leaves (Fig. 1). On the other hand, the advent of NPs via leaf stomata reveals that these tiny particles can pass through another transporter, namely phloem which performs sugar and amino acid transportation from leaf to other plant parts. In addition, NPs may bind with membrane proteins of the cell and can internalize into the cells. Particularly, aquaporin's are advocated as a transporter of NPs inside the plant cells (Zhou et al. 2021a). Further research is mandatory to diagnose the in-depth knowledge about various NPs transporters through the plant body with a complete understanding of the cellular mechanisms involved there.

Furthermore, wounds in plant tissues caused by mechanical injury, disease-pest infestation, and environmental stresses may provide additional pathways for MPs/NPs to enter the plant body. PS-NPs, for example, were discovered in damaged leaf cells (Lian et al., 2021a, b). Such plastic particle entry may interfere with normal wound healing processes and impede signaling. As a result, the MPs/NPs may cause physical blockage, disconnecting cells and ultimately weakening signal transmission. In this regard, it is worth noting that MPs/NPs can also obstruct the micropyle of crop seeds (such as beans), preventing water and nutrient uptake and thus reducing seed germination. Among all of these routes, the adsorption and uptake of MPs/NPs via root tips are the most responsible for plant toxicity. Plants growing in MPs/NPs-contaminated soil or irrigated with wastewater pose a risk due to the negative effect of these plastic particles on plant growth and development. Furthermore, there is a greater risk of airborne deposition of MPs/NPs on various plant parts in urban and industrial areas.

Factors affecting phytotoxicity

The contamination of MPs/NPs in crop fields is determined by several factors related to different plastic polymers (Fig. 2). Plastic particles with various physical and chemical properties of different polymers are successively fragmented into different sizes by biological and physicochemical actions (Weithmann et al., 2018). The size of the plastic particles determines their transfer to plants. According to Li et al. (2019), available MPs in soil environments of various sizes can be taken up by plant roots and translocation streams, and alterations in plant chemical composition occur. Furthermore, Bosker et al. (2019) demonstrated that MPs/NPs can reduce the germination rate, while another study on beans revealed the availability of PS-based NPs in the roots of such species. Furthermore, MPs and NPs were found to adsorb via vascular plant roots (*Spirodela polyrhiza*), but no internalized plastic particles were found in this study (Dovidat et al., 2020). As a result, smaller plastic particles have a higher chance of being internalized into plant tissues. MPs, in particular, cannot be absorbed into plants like NPs, so they are likely to accumulate on plant roots and germinating seed surfaces, obstructing water and nutrient uptake or rupturing cell-to-cell connections.

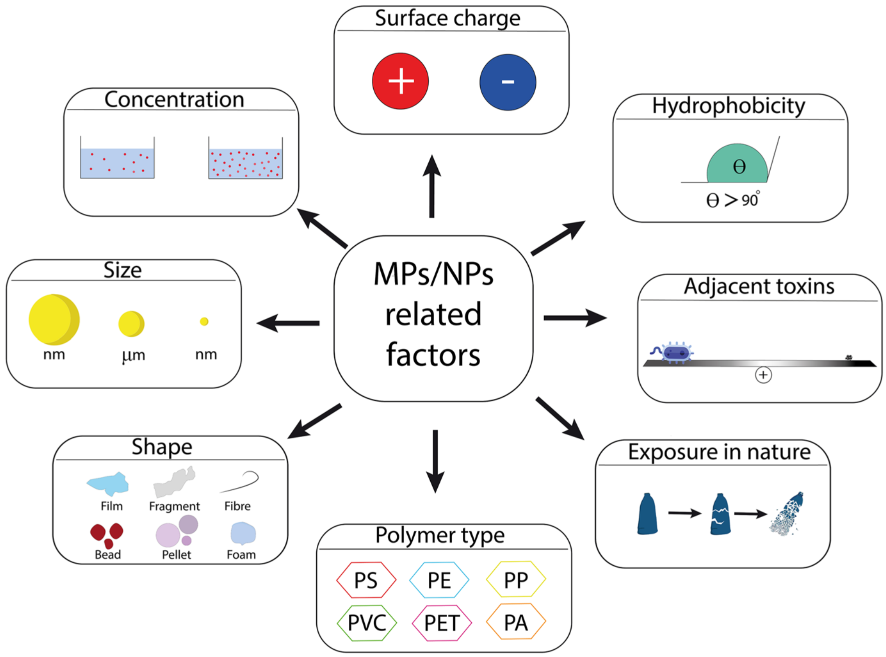

Fig. 2 MPs/NPs-related factors affecting toxicity

Plastic particles with different shapes like beads, films, fragments, and fibers have been observed to change the structure, texture, and bulk density of soil (Rillig et al., 2019). Such changes in soil structure may have an impact on the available microorganisms, soil fertility, and the rate of nutrient mineralization. Furthermore, plastic films in the soil structure form water channels, resulting in a higher rate of water evaporation (Vallespir Lowery & Ursell, 2019; Wan et al., 2019). Several studies on different plants, in addition to soil, revealed the uptake and translocation of PS microbeads into different plant parts, reducing photosynthetic activities and slowing plant growth. Aside from the morphological characteristics of plastic particles, the polymeric composition of plastic particles is an important factor. Such as, in an experiment, polystyrene (PS)-MPs and polyethylene (PE)-MPs are found to be more toxic to antioxidant enzymes in tomato plants than polypropylene (PP)-MPs (Shi et al., 2022). Thus, plastics with varying polymer compositions may have varying effects on plant growth. Polyvinyl chloride-based MPs, for example, inhibit *Lepidium sativum* germination and growth when compared to polypropylene and polyethylene-based MPs (Pignattelli et al., 2020).

The effects of MPs/NPs in plants can vary based on MP exposure concentrations. To support this claim, Li and co-researchers (Li et al., 2020a, b, c, d, e, f, g) investigated the toxicological effects of MPs at various concentrations in lettuce (*Lactuca sativa* L.). Similarly, another study on lettuce demanded that elevated MP concentrations are responsible for reducing the plant's height, weight, leaf number, and root length (Gao et al., 2019). Furthermore, Boots et al. (2019) discovered that the gradual introduction of MPs into perennial ryegrass (*Lolium perenne*) harms plant development. Furthermore, the surface charge of MPs/NPs is an important factor in determining their uptake in plants. For example, positively charged nanoparticles are more likely to attract negatively charged cell membranes, resulting in the rapid uptake of charged or neutral nanoparticles (Kettler et al., 2014). Furthermore, (Sun et al., 2020a) discovered that both positively and negatively charged PS-based MPs accumulate in Arabidopsis roots, introducing more reactive oxygen species and suppressing seedling growth. According to the zeta potential of MPs/NPs, they are naturally neutral in charge, but they can have positive or negative surface charges due to adhered metals, organic chemicals, or other toxic additives. As a result, the surface charge of MPs/NPs is an important regulator in controlling their pattern of interaction with plants, soil, or aquatic systems.

Furthermore, MPs/NPs are hydrophobic, have a lower density, and have a larger surface area. These properties enable them to adhere to plant roots or seed surfaces, inhibiting water absorption and respiration and, as a result, reducing root and bud growth (Liu et al., 2019). For example, (Sun et al., 2020b) demonstrated that positively charged and hydrophobic PS-based NPs can be absorbed by plant roots and inhibit their growth. Furthermore, the surface hydrophobicity and higher surface-to-volume ratio of MPs/NPs may serve as vectors for various contaminants, such as antibiotics, pesticides, heavy metals, and herbicides, in plants (Lian et al., 2020a). Concerning the hydrophobicity of MPs/NPs, Xia and co-researchers (Xia et al., 2020) demanded that surfactants can convert hydrophobic MPs into hydrophilic MPs, increasing the adsorption capacity of available pollutants by up to tenfold. The above-mentioned phenomena are governed by a strong electrostatic attraction mechanism between charged MPs and plastic particles (Liu et al., 2020a, b; Zhang et al., 2018).

Aside from surface charge, the age of MPs in the environment and their interaction with various organic/inorganic contaminants such as heavy metals, dichlorodiphenyltrichloroethane, and polycyclic aromatic hydrocarbons have been observed (Hüffer et al., 2018; Liu et al., 2019). The aged plastic polymers in the environment increase the possibility of higher levels of degradation, resulting in an increased surface area to adsorb pollutants. The micro-environment of a plastic particle (i.e., the immediate small-scaled area) has been identified as ecological (eco) corona which is categorized by adsorption of multifarious organic molecules extracellularly, thus leading to the formation of an organic surface corona (layer) and which affecting the behavior plastic particles and interaction MPs/NPs with soil organisms and other soil constituents (Nasser & Lynch, 2016).The ecocorona can influence considerably the size and shape, as well as surface constituents and also the mobility and degradation of plastic particles in the environment (Rillig et al., 2017). Moreover, this ecocorona may be hard or soft which is dependent on the affinity of the adsorbed molecules, and it can stimulate the pollutant transfer through the soil profile with their various binding affinity to the surfaces of plastics. However, the fate of MPs/NPs in the soil mainly relies on ecocorona properties, which may affect the interaction of plastic particles with soil components like organic matter, clay minerals, and also soil organisms (like earthworms) which can feed plastic particles (Lwanga et al., 2017). For example, NPs (less than 50 nm in size) can pass through the prokaryotic and eukaryotic cells/tissues with absorption of pathogens, which multiply the potential toxicity of MPs/NPs along with the biohazardous potential of pathogenic microbes. Indeed, NPs below a size of 50 nm pass through eukaryotic and prokaryotic cell membranes with the absorbance of pathogenic microbes, thus increasing the biohazard potential of pathogens (Nasser & Lynch, 2016). It is an alarming fact that the more the ages of MPs/NPs in the environment will exert more changes in the ecocorona of MPs/NPs which may create different levels of toxicity to soil and crop plants.

The impact of MPs/NPs on plant toxicity is profoundly influenced by a variety of crop production-related factors (Fig. 3). The effect of MPs/NPs on seed germination and plant growth varies depending on the species. For instance, PS-based MPs reduced the germination capacity of dicotyledon *Lepidium sativum* (cress) (Bosker et al., 2019). Similarly, a reduction in seed germination is also observed in perennial ryegrass (*Lolium perenne*) (Boots et al., 2019). In contrast, Lian et al. (2020b) observed the opposite effect of MPs/NPs on seed germination and stated in previous experiments that PS-based NPs significantly assisted wheat seedling growth rather than inhibited seed germination. Moreover, the phytotoxicity of PE-based MPs on food crops such as mung bean (*Vigna radiata*) and soybean (*Glycine max*) has been experimented where soybean crops are more affected than mung beans (Wang et al., 2021a, b, c). Furthermore, a reduction in biomass was observed in different studies with different crops such as maize (*Zea mays* L.) (Wang et al., 2020a, b), wheat (*Triticum aestivum*) (Qi et al., 2018), and onion (*Allium fistulosum*) (de Souza Machado et al., 2018).

The negative impact of MPs/NPs on seed germination begins during the plant life cycle. The likelihood of seed germination and growth, as well as its economic and ecological significance, are critical factors in plant species propagation. Plants are highly vulnerable to disease, injury, and water/environmental stress during the germination stage, making it the most critical stage of the plant life cycle (Tuğ & Yaprak, 2019). However, seed germination and root growth are important factors to consider when assessing the direct effect of MPs/NPs on plants. Several studies have shown that MPs/NPs harm the seed germination rate and speed. A study with different concentrations of PS-based NPs was recently found to impair rice germination and seedling growth (Spanò

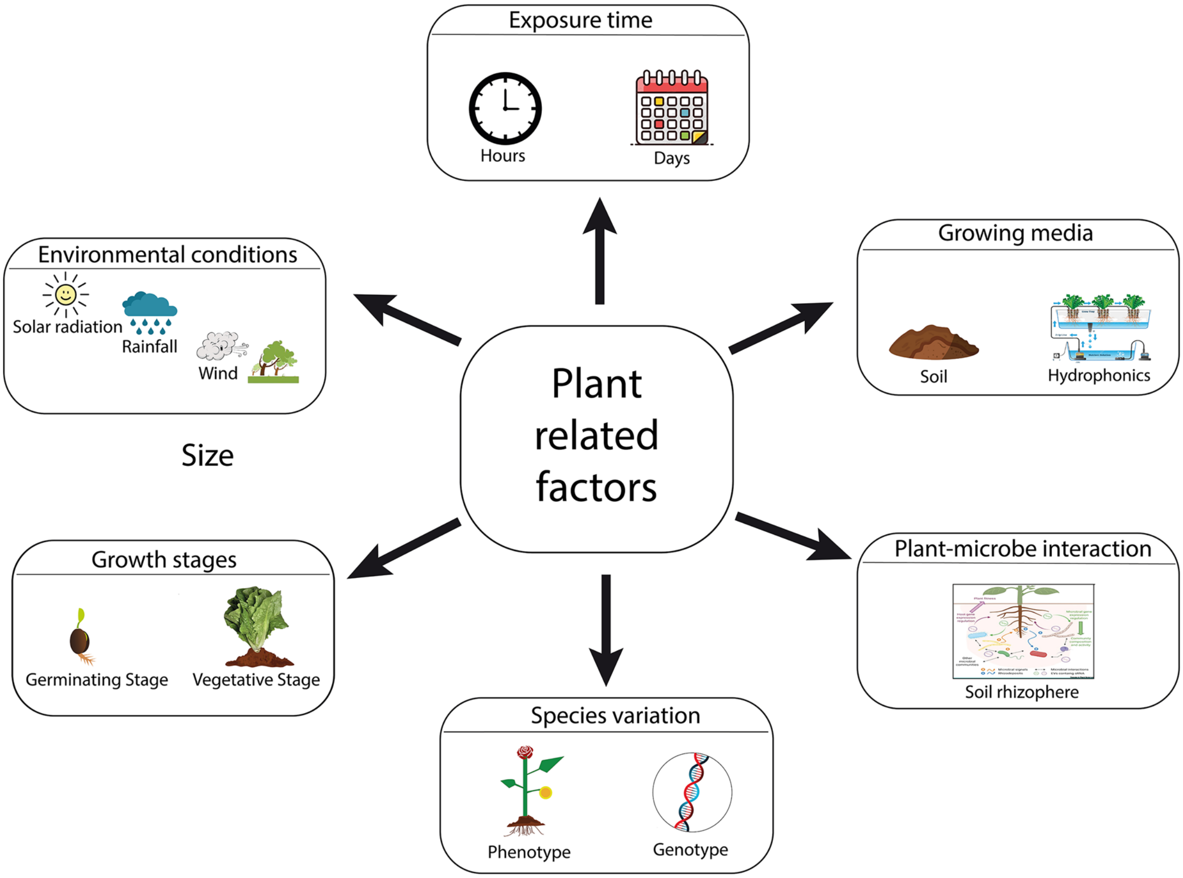

Fig. 3 Plant-related factors and MPs/NPs toxicity to plants

et al., 2022). The result shows that PS-based NPs can be easily absorbed and migrate to the aboveground parts of rice seedlings during the early stages of plant development. The negative impact of NPs not only on the physiology and cell biology of rice seedlings but also on the alteration of reactive oxygen species (ROS) diffusion at the cellular level was observed (Zhou et al., 2021a, b, c). Another study on rice found that high concentrations of PS-based MPs significantly inhibited the germination percentage, germination index, and germination vigor of rice seeds when compared to low concentrations of PS (Zhang et al., 2021a, b). Another study found that PE-based MPs can reduce the vigor index, germination energy, and germination index of soybean (Wang et al., 2021a, b, c). Potential causes, in this case, include the presence of MPs in the seed coat, which inhibited water absorption capacity, blocked available pores, and ultimately slowed seed germination (Bosker et al., 2019).

Polymeric MPs/NPs also have varying degrees of impact on seed germination. Pignatelli (2020) investigated the acute and chronic toxicity of four types of MPs on *Lepidium sativum*, including polyethylene (PE), polyvinylchloride (PVC), polypropylene (PP), and a mixture of PE and PVC. They also proposed an order of the previously mentioned polymers based on their negative impact on seed germination, such as PVC > PE > PP. In another experiment, Lian et al. (2020a) inspected the negative effect of PS-based NPs on seed germination and wheat growth (*Triticum aestivum* L.). Another study on perennial ryegrass was conducted in comparison to high-density PE and fibers from the clothing industry (Boots et al., 2019). When compared to the control sample, very few seeds germinated in response to fiber exposure. Onion seeds (*Allium cepa*) were also tested against polylactic acid (PLA)-treated compost and found a lower rate of seed germination as well as inhibition of the cell division rate compared to the control (Souza et al., 2020).

MPs/NPs, in particular, can easily accumulate in the testa as well as the surface of the pores, lowering plant water uptake. Furthermore, plastic particles disrupt the natural development of root hairs, limiting water and nutrient uptake and, as a result, affecting physiological performance. Furthermore, root growth is dependent on plant carbohydrates, and poor root growth limits photosynthesis and leaf expansion and disrupts the nitrogen cycle. Thus, from the standpoint of ecology and agriculture, this phenomenon is responsible for yield losses, as well as decreased seed germination and stress in crop production (Pflugmacher et al., 2020). In terms of plant growth, exposure to MPs/NPs for varying lengths of time may affect the degree of change in plants at various stages of development. Enyoh et al. (2020) investigated the quantitative phytochemical analysis of juvenile lime trees (*Citrus aurantium*) grown on plastic-loaded clayey soils in 2020. They discovered a variation in phytochemical content in different parts of the juvenile tree, with the negative effect primarily observed on root biomass rather than aerial biomass. Mateos-Cárdenas et al. (2019) demonstrated in another study that PE-based MPs can be easily adsorbed to the surfaces of duckweed species (*Lemna minor*). Furthermore, the experiment revealed that as the time duration increased, so did the amount of adsorbed MPs in fresh and dried *Lemna minor* colonies. The reason for this is that prolonged exposure to MPs/NPs may alter the physicochemical properties of plastic particles, resulting in increased adsorption and toxicity.

In general, hydroponically grown plants have higher growth rates as well as higher transpiration rates, which provide a strong driving force to maintain the apoplastic translocation of PS-based microbeads (Li et al., 2020a, b, c, d, e, f, g). Similarly, Sun et al. (2020a, b) discovered that *Arabidopsis thaliana* takes up significantly more negatively charged PS-based plastic particles than positively charged particles. The author emphasized that the higher aggregation of such positively charged plastic particles is mostly supported by the growth medium (half-strength Murashige and Skoog solution) and root exudates in response to this attribute. Thus, a comparison of solid culture and hydroponic culture revealed that the apoplastic barrier of the depressed root would aid in the transportation of plastic beads through the root's tip. In this regard, caution should be exercised when supplying water for hydroponic crop cultivation. Because of the scarcity of cultivable land and other stresses on crop production in the field, hydroponic agriculture in a controlled environment is gaining popularity. These crops are directly used in the production of fresh vegetables for human consumption as well as cattle feed. Growing crops in untreated/contaminated water may aid in the rapid uptake of NPs by plants.

Plant growth stages may have a greater impact on MPs/NPs toxicity. Because the greatest number of MPs was counted during the 72-h incubation period, the number of adsorbed MPs was later slightly reduced (Mateos-Cárdenas et al., 2019). Similarly, Goss et al. (2018) supported the previous statement by identifying a higher amount of MPs on the blades of seagrass (*Thalassia testudinum*) in its early stage and a slight decrease with plant growth. This decrease may have occurred as a result of plants' rapid cell division as well as their growth. Furthermore, when MPs adhere to the seed micropyle or pores, they can cause physical blockage of water and nutrient uptake, ultimately slowing seed germination. A mature plant, on the other hand, has strong root structures; if a physical blockage occurs in one location, the plant's other location may become active in terms of water and nutrient uptake.

Environmental factors such as solar radiation, temperature, rainfall, and wind, in addition to plastic and plant-related factors, may influence the impact of MPs/NPs pollution. Rainwater can wash plastic particles from one place to another, facilitating the rapid dispersal of plastic particles. Similarly, wind may play an important role in transporting tiny plastic particles from urban or industrial areas to crop-growing farms, even in remote rural areas. Natural disasters such as floods, storms, and even soil erosion can disperse these plastic particles, leading to an increase in MPs/NPs-mediated pollution. As a result, the crop growing season must also be considered in the case of MPs/NPs toxicity to plants. When the light intensity is high, plants naturally increase their transpiration rate to absorb water and related nutrients. According to previous research, transpiration pull is an important factor in increasing the uptake of NPs from the soil as well as plant nutrients. Furthermore, the weathering process can exacerbate the breakdown of larger plastics into MPs/NPs. The increase of soil MPs/NPs causes crack formation which leads more soil water to evaporate and prolongs the drought period. As a result, it may amplify the impact of climate change on crop production. Similarly, various agricultural practices, such as tillage or other biological activities, may cause mechanical aberration of MPs into NPs, facilitating their movement into deeper soil layers or even into groundwater and causing pollution. To address all of these issues, research must be conducted as soon as possible. According to previous research, MPs are present in the roots, leaves, and stems of major food-producing cereals, pulses, and oil seed crops (Table 1), as well as vegetables and fruits (Table 2). The adsorption of MPs on germinating seeds is extremely detrimental to crop production if this situation persists. MPs, in particular, adhere to seeds and plant roots, resulting in reduced water absorption and the development of the radicals and plumules of emerging seedlings. The uptake and distribution of scaled-down NPs in plants reveal that NPs enter the plant via nutrient transportation pathways. Furthermore, reductions in plant biomass may be caused by a variety of factors, including changes in soil physical properties (such as soil structure and water holding capacity), changes in chemical properties (such as soil pH, nutrient availability, and soil enzymes), and variations in the distribution and activities of soil biota, which are thought to be the soil bioengineers. MPs/NPs may be adsorbed to soil particles and adhere to soil biota. Most importantly, the charges of MPs/NPs are highly dependent on the dispersal media, resulting in a disruption in the triple association of soil, plant roots, and soil microorganisms in the rhizosphere interphase. Collectively, all these factors are supposed to determine the toxicity level of MPs/NPs pollution in plants.

Plant responses to MPs/NPs toxicity

MPs/NPs contamination in agricultural land had a direct impact on plant growth and development (Fig. 4), resulting in a decrease in plant biomass and making plants more susceptible to other stresses (Fig. 5). Furthermore, the transfer of MPs/NPs from primary producers to consumers via trophic transfer causes serious health problems in humans (Fig. 6). As a result, the first level of toxic effects begins with plant properties.

Morphological

MPs/NPs can interfere with plant growth through morphological alterations in plants. For example, exposure to MPs/NPs of varying sizes altered root morphology in corn (Zhang et al., 2022a, b, c, d). Because of the presence of MPs/NPs, plant growth parameters such as fresh and dry weights of leaves, roots, and the number of leaves are gradually decreasing (Gao et al., 2019). Furthermore, PS-NPs are discovered to be distributed across the intercellular and intracellular spaces of the rice root (Zhou et al., 2021a, b, c) where aquaporins in rice roots may facilitate the entry of NPs. Accumulation and distribution NPs have revealed that they can move across cells via the liquid phase of endocytosis and vascular systems within the plant body (Chae & An, 2020; Lian et al., 2020a, b). Thus, the accumulation of these particles by roots impairs water and nutrient movement, which negatively reflects plant root-shoot growth (Wu et al., 2020). Short-term PS-NP exposure caused complete or partial detachment of the root epidermis in wheat and corn, indicating cell membrane damage. Furthermore, root activity indicates plant functions that have a strong influence on plant metabolism and absorption, root growth, and overall development of aboveground parts. For example, the presence of PS and PTFE reduced rice root activity while also significantly reducing the transpiration pull (Dong et al., 2020). Furthermore, when PS-NP were applied to the plant's foliage, they significantly reduced the dry weight, height, and leaf area of lettuce compared to the control (Lian et al., 2021a, b). Furthermore, laser confocal scanning microscopy confirmed the accumulation of PS-NPs in the root of the broad bean (*Vicia faba*) which blocked the connections between cells or cell wall pores of plant nutrient transportation (Jiang et al., 2019). However, sharp edges of plastic fragments may create physical damage on plant roots or sometimes fibers may tie the roots tightly, which may cause shrinkage of roots in that particular part.

Physiological

In terms of physiology, various studies have shown that exposure to MPs/NPs can impair the formation of chlorophyll in shoots or leaves, ultimately inhibiting plant photosynthesis (Gao et al., 2019; Dong et al., 2020; Li et al., 2020a, b, c, d, e, f, g). On the other hand, the effects of MPs/NPs on plant photosynthesis can be identified by analyzing photosynthetic pigments (Gao et al., 2021a, b; Huang et al., 2019a, b).

Table 1 Impacts of MPs/NPs on cereals

Crop name	Polymer type	Concentration per Liter	Size µm	Exposure duration Days	Growing media	Effect	References
Rice (*Oryza sativa*)	PS	7×10^{11} to 7×10^{13} particles	0.08 to 1.0	14 to 40	Hydroponic	Metabolic processes and plant growth	Liu et al. (2022)
	PS	0.1 to 10 mg	0.1 to 1.0	14	Hydroponic	Root length, nutrient uptake, and oxidative stress	Wu et al. (2021)
	PS	0.1, 10, 1000 mg	0.20	14	Hydroponic	Antioxidant enzyme activity, gene expression	Zhang et al. (2021a, b)
	PS-NPs	10, 50, 100 mg	0.02	16	Hydroponic	Root length, metabolism (inhibit the biosynthesis of jasmonic acid and lignin)	Zhou et al. (2021a, b, c)
	PS-MPs	50 and 250 mg	8.5–30.7	21 and 142	Both homophonic and soil	Metabolic systems and biomass	Wu et al. (2020)
	PS and PTFE	0.04, 0.1, or 0.2 g	10	17	Hydroponic	Rice biomass, chlorophyll content, and oxidative burst	Dong et al. (2020)
Wheat (*Triticum aestivum*)	PS-NP	0, 0.01, 0.1, and 1.0, 10 mg	0.10	21 0	Hydroponic	Phytohormone signal transduction pathways, carbon metabolism, and plant biomass	Lian et al. (2022)
	PHBV	10% (W/W)	0.087 – 0.006	25	Soil	Amino acid metabolic and biosynthetic processes, plant hormone signal transduction, and plant-pathogen interaction as well as metal ion transport pathways	Zhou et al. (2021a, b, c)

Table 1 (continued)

Crop name	Polymer type	Concentration per Liter	Size µm	Exposure duration Days	Growing media	Effect	References
	PE-MPs	0.5%, 1%, 2%, 5%, 8% w/w	200–250	15	Soil	Photosynthetic system of leaves and antioxidant system in wheat roots	Liu et al. (2021)
	PS	100 mg	0.50	8	Hydroponic	Root length	Zong et al. (2021)
	PS and PMM-NPs	-	0.2, 2.0	20	Soil and hydroponic	Submicrometer and micrometer-sized MPs uptake into plants	Li et al. (2020a)
	PS microbead	0.5, 5.0, 50 mg	0.2, 2, 7	10	-	PS microbeads uptaken by roots	Li et al. (2020b)
	PS-NPs	0.01, 0.1, 1.0, 10	-	14 and 21	Hoagland solution	Micronutrients contents and root-to-shoot biomass ratio	Lian et al. (2020a, b)
	PS-NPs	10 mg	0.10	21	Hoagland solution	Antioxidant enzyme activities	Lian et al. (2020a, b)
	PS-NPs and MPs	0.029	0.04–1.0	5	Agar media	Root surface	Taylor et al. (2020)
	PE and biodegradable plastics	1% (w/w)	50, 50, 500, 1000	2 and 4	Soil	Above-ground and below-ground plant parts during both vegetative and reproductive growth	Qi et al. (2018)
Maize (*Zea mays*)	PE	0.030–0.045 g/kg	150–180	60	Soil	Photosynthesis and antioxidant systems	Fu et al. (2022)
	PS-NPs and PS-MPs	1 and 10 mg	0.10–5.0	7	Hydroponic	The dry weight of root, root length, root/shoot ratio, and induced oxidative stress	Gong et al. (2021)

Table 1 (continued)

Crop name	Polymer type	Concentration per Liter	Size µm	Exposure duration Days	Growing media	Effect	References
	PS-NPs	50 mg	0.10–0.50	15	Hydroponic	Metabolic imbalance, root microstructure	Zhang et al. (2022a, b, c, d)
	PCF-MPs	0.01%, 0.1%, and 1% w/w	-	30	Soil	Shoot biomass, plant water status, and cell membrane permeability	Lian et al. (2021a, b)
	PP, PET, PVC, PS, PE	0.02 g (w/w)	75–150 and 150–212	21	Soil	Biochemical imbalance, cell membrane, photosynthetic pigments, photosynthetic capacity, and xenobiotic stress	Pehlivan and Gedik (2021)
	PS both (+) and (−) charge	1.0 g	0.022–0.024	28	Soil	The phenotype of seedlings and plant growth	Sun et al. (2021)
	PE (micro beads)	0.0125 and 100 mg	3	10 and 15	Hydroponic	Water and nutrient uptake, plant growth	Urbina et al. (2020)
	PE, PLA	0.1, 1, 10% w/w	100–154	30	Soil	Plant growth and high Cd accumulation in plant tissues	Wang et al. (2020a, b)
Barley (*Hordeum vulgare*)	PS	2000 g	5.64 ± 0.07	14	Hydroponic	Photosynthesis and reactive oxygen species burst in mitochondria	Chen et al. (2022)
	PS	2000 g	5.64 ± 0.07	14	Hoagland solution	Activities of cell wall peroxidases in roots and carbohydrate and ROS metabolism enzymes in leaves	Li et al. (2021a, b, c, d)

Table 1 (continued)

Crop name	Polymer type	Concentration per Liter	Size µm	Exposure duration Days	Growing media	Effect	References
Oat (*Avena sativa*)	PEIs	100, 250, 500, 750, and 1000 mg/kg	-	6	Soil	Length of roots	Rychter et al. (2019)
Mung bean (*Vigna radiata*)	MPs	-	57–229	30	Soil	Water and oxidation stress and hindered growth in plants	Lee et al. (2022)
	PE-MPs	0, 10, 50, 100, 200, and 500 mg	6.5–13.0	7	Aqueous suspension	Germination energy and germination index	Wang et al. (2021a, b, c)
	PS-NPs	10 or 100 mg/kg	-	10–14	Soil	Physiology of the plant and root growth	Chae and An (2020)
Soybean (*Glycine max*)	PS	10 mg/kg	0.10–100.0	30	Soil	Higher genotoxic and oxidative damage to soybean roots	Xu et al. (2021)
	LDPE and Bio	0%, 0.1%, 0.5% and 1% (w/w)	50–200	60–120	Soil	Germination viability of soybean seeds	Li et al. (2021a, b, c, d)
	PE-MPs	0, 10, 50, 100, 200, and 500	6.5–13	7	Aqueous suspension	Germination index and vigor index of soybean	Wang et al. (2021a, b, c)
Mustard (*Brassica campestris* L.)	PMMA-MPs, NPs	0, 0.01, 0.1, 1, 5, and 10 g	10–0.10	4	Solution (petri dish)	Germination index	Dong et al. (2022)
Rape (*Brassica napus* L.)	MPs	0.001%, 0.01%, 0.1% w/w	-	-	Soil	Metabolism and bioaccumulation of heavy metals	Jia et al. (2022)

PS polystyrene, *PE* polyethylene, *PP* polypropylene, *PVC* polyvinylchloride, *PLA* polylactic acid, *HDPE* high-density polyethylene, *PMMA* polymethylmethacrylate, *PEIs* polyethylenimines, *PET* polyethylene terephthalate, *PCF* polymer-coated fertilizer, *PHBV* poly (3-hydroxybutyrate-co-3-hydroxyvalerate)

Table 2 Impacts of MPs/NPs on fruits and vegetables

Crops name	**Polymer type**	**Concentration** mgL^{-1}	**Size** µm	**Exposure duration** days	**Growing media**	**Effect**	**References**
Lettuce (*Lactuca sativa*)	PS MFs	0.1 and 0.2	190–310	9	Soil	Plant shoot length, photosynthesis and chlorophyll content, and reduction of amino acids	Zeb et al. (2022)
	PS	0.1–1	0.093	21	Soil	Total antioxidant capacity, reduction in micronutrients and essential amino acids, decrease in nutritional quality	Lian et al. (2021a, b)
	PE	0.1, 1, and 10	> 500	45	Soil	Plant biomass	Wang et al. (2021a, b, 2021c)
	PS	1, 2, 4, and 10, 20	0.1–5	7	Hydroponic	Cell walls to distortion and deformation, oxidative bursts in carrot tissue, and destroy the tertiary structure of pectin methyl esterase and causes carrots to lose their crispness	Dong et al. (2021a, b)
	PE	0.25, 0.5, 1	23	14 and 28	Hydroponic	Soluble protein and sugar content in lettuce leaves, led to the expansion of endoplasmic reticulum vesicles and cell rupture	Gao et al. (2021a)
	PS	0.25, 0.5, 1	0.1–1.0	28	Hydroponic	Cell membrane and wall damaged, reducing lettuce biomass	Gao et al. (2021b)
	PVC	0.5, 1, and 2 (w/w)	18–250	21	Soil	Reduce the capacity of electron transfer, absorption	Li et al. (2020a, b, c, d, e, f, g)

Table 2 (continued)

Crops name	**Polymer type**	**Concentration** mgL^{-1}	**Size** µm	**Exposure duration** days	**Growing media**	**Effect**	**References**
	PS	50	200–1000	14	Soil and hydroponic	Absorption and transportation from root to shoot	Li et al. (2020b)
	PE	0.25, 0.5, 1.0	23	14 and 18	Hydroponic	Growth parameters, photosynthetic rate, stomatal conductance, transient transpiration rate, fluorescence parameters, chlorophyll content of leaves, and activity of Rubisco	Gao et al. (2019)
Cucumber (*Cucumis sativus* L.)	PS-NPs	10	0.1–0.7	14 and 65	Hydroponic	Levels of Mg, Ca, and Fe in cucumber fruits significantly decreased	Lian et al. (2021a, b)
	PS-NPs	50	0.1–0.7	21 and 65	Hydroponic	Physiological indexes, biochemical metabolism of cucumber and total biomass, chlorophyll a, chlorophyll b, soluble sugar, carotenoid, and proline content on cleaves	Li et al. (2020a, b, c, d, e, f, g)
Common bean (*Phaseolus vulgaris*)	LDPE-MPs and Bio-MPs	0.5, 1.0, 1.5, 2.0, 2.5 w/w dry soil weight	53–1000	14	Soil	Chlorophyll content, leaf area and fruit biomass	Meng et al. (2021)
Broad bean (*Vicia faba*)	PS	10, 50, 100	5.0–0.1	48	Hydroponic	Higher genotoxic and oxidative damage, and the biomass and catalase (CAT) enzymes activity	Jiang et al. (2019)

Table 2 (continued)

Crops name	Polymer type	Concentration mgL^{-1}	Size µm	Exposure duration days	Growing media	Effect	References
Onion (*Allium cepa* L.)	PS-NPs	0.01, 0.1, and 1.0	0.05	72	Distill water	Indicated cytotoxicity (reduction of the mitotic index) and genotoxicity (induction of cytogenetic anomalies and micronuclei)	Giorgetti et al. (2020)
	PS	25, 50, 100, 200, and 400	0.1	3	Distill water	Root length, mitotic index, induced chromosomal and nuclear aberrations	Maity et al. (2020)
Spring Onion (*Allium festulous*)	PE, PET, PP, PS	0.2–2.0 w/w	8–500	1.5	Soil	Plant biomass, tissue elemental composition, root traits	de Souza Machado et al. (2019)
Chinese cabbage (*Brassica chinensis* L.)	HDPE, GPPS	2.5, 5, 10, and 20	25–850	30	Soil	Soluble sugar concentration and the concentration of leaf chlorophyll	Yang et al. (2021)
Carrot (*Daucus carota*)	PS	10 and 20	0.1–5.0	7	Hydroponic	Distortion and deformation of cell walls, induced oxidative bursts, carrot quality	Dong et al. (2021a, b)
Radish (*Raphanus sativus*)	PEIs	100, 250, 500, 750, and 1000	-	6	Soil	Root length	Rychter et al. (2019)
Garden cress (*Lepidium sativum*)	PP, PE, PVC	0.02 (w/w)	120–5000	21	Soil	Germination	Pignattell et al. (2020)
Tomato (*Lycopersicon esculentum Mill.*)	PET, PVC	1.29–1.40 and 1.30–1.58	> 1.2	109	Soil	Fruit production	Hernández-Arenaset al. (2021)
Lime (*Citrus aurantium*)	LDPE, PP and PS	1 w/w	5000	2, 4, 6, and 8	Soil	Plant biomass and plant phytochemical	Enyoh et al. (2020)
	LDPE, PP, PS	1 w/w	5000	270	Soil	Vegetative growth	Verla et al. (2020)

PS polystyrene, *PE* polyethylene, *PP* polypropylene, *PVC* polyvinylchloride, *PLA* polylactic acid, *PEIs* polyethylenimines, *PET* polyethylene terephthalate, *HDPE* high-density polyethylene, *GPPS* general purpose polystyrene, *LDPE* low-density polyethylene

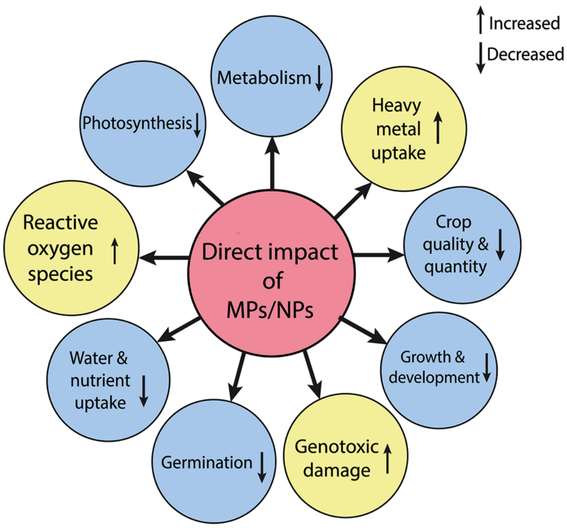

Fig. 4 Direct impact of MPs/NPs on plants

Studies on different crops have revealed a decrease in photosynthesis activities due to MPs/NPs exposure (Tables 1 and 2), for example, when PS-based NPs were exposed to corn (*Zea mays*) (Zhang et al., 2022a, b, c, d) where the chlorophyll content of the plants decreased, indicating that NPs interfered with overall plant health. Furthermore, MPs/NPs influence cucumber mineral elements and alter biochemical or physiological metabolism and mineral contents and act as electron transporters or enzyme activators (Li, Li et al., 2020a, b, c, d, e, f, g; Lian et al., 2021a, b). PS-NPs also influenced the content of photosynthetic pigments in lettuce (Lian et al., 2021a, b; Yu et al., 2020). Similar effects of NPs exposure were observed in Chinese cabbage (*Brassica rapa* L.) and Arabidopsis plants (Sun et al., 2020a, b; Zhang et al., 2022a, b, c, d). Additionally, the presence of MPs/NPs on the leaf surface may impede photosynthesis activities (due to obstruction of the pore of leaf stomata) as well as other cellular activities in plants.

Biochemical

MPs/NPs' exposure in crop plants causes biochemical imbalances. For instance, PS-NPs altered biochemical metabolism in cucumber plants (Li et al., 2020a, b, c, d, e, f, g). MPs/NPs contamination can induce oxidative stress in plants, which is reflected in the accumulation of reactive oxygen species (ROS) in plant tissues (Chen et al., 2022; Pehlivan & Gedik, 2021). Thus, for maintaining normal homeostatic conditions, the plant antioxidant system is activated to remove ROS and thus survive under adverse conditions (Judy et al., 2019). Generally, oxidative burst occurs in plants when the production of ROS exceeds the level of the antioxidant defense system (Wang et al., 2021a, b, c). Thus, to build up resistance in the

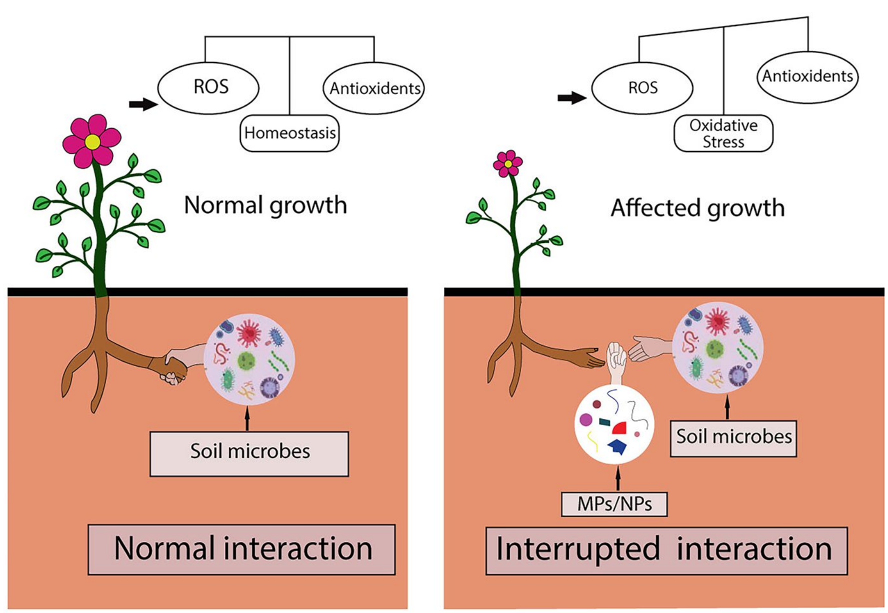

Fig. 5 Disturbance of MPs/NPs in the plants and soil microbes interaction

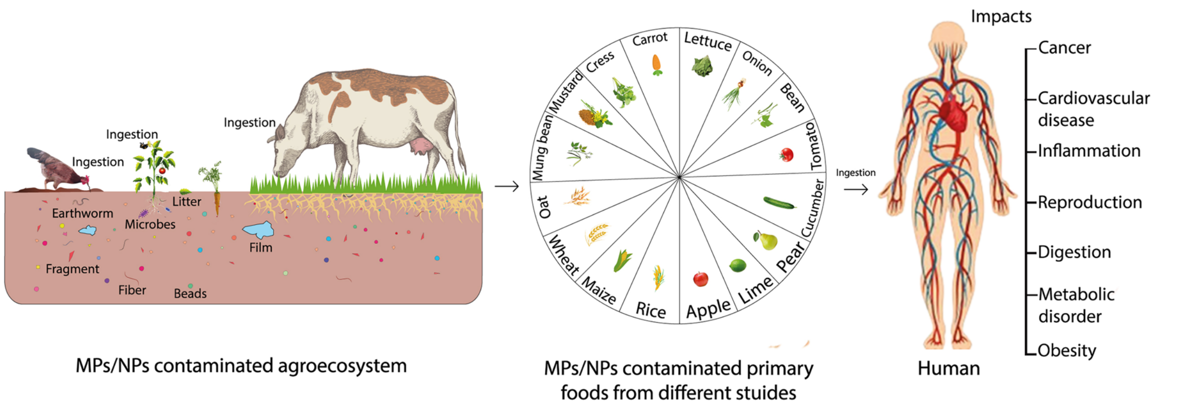

Fig. 6 MPs/NPs toxicity from primary producers to ultimate consumers

plant body, they produce several beneficial elements such as enzymatic and nonenzymatic antioxidants accordingly (Ogbe et al., 2020). Results from various studies demonstrate that MPs/NPs contamination causes oxidative burst in various crops (Tables 1 and 2). However, for detoxifying ROS, plants produce different antioxidative enzymes, such as SOD (superoxide dismutase), CAT (catalase), POD (peroxidase), APX (ascorbate peroxidase), and various nonenzymatic antioxidants (Wang et al., 2010). The results from several studies reveal that polymers such as PS, PE, PP, PVC, and PTEF are responsible for altering the production of such enzymes at different levels, resulting in imbalances in maintaining homeostasis in crops (Liu et al., 2021; Pehlivan & Gedik, 2021; Santamaría et al., 2018; Wu et al., 2021). It ultimately produces metabolic disorders which induce stresses on plants, reflect the death of plant tissues, and decrease overall crop yield.

Metabolic

MPs/NPs, similar to physiology and morphology, have an impact on the metabolic pathways of terrestrial plants. Plant nutrient uptake capacity, energy production, biosynthesis, and antioxidant defense systems can all be affected by changes in metabolic pathways (Li et al., 2020a, b, c, d, e, f, g; Wu et al., 2020; Zhou et al., 2021a, b, c). Recently, Zhou et al., (2021a, b, c) revealed the impact of MPs/NPs on rice root carbon content, specifically inhibition of root carbon metabolism. Furthermore, plastics inhibited the biosynthesis of jasmonic acid and lignin in rice roots. As a result, these flaws reduce the plant's ability to defend itself against stress and impair the formation of the plant's cell wall (Wang et al., 2022a, b). Another study exposed hydroponically grown rice to PS-based MPs/NPs and discovered a rapid change in secondary metabolites, while saccharides, lipids, organic acids, amino acids, glycosides, amines, and polyol compounds gradually decreased (Wu et al., 2020). In another study, the metabolites of lettuce leaves changed dramatically when exposed to polyester microfibers (Zeb et al., 2022).

Moreover, interference of MPs/NPs in metabolism may induce further problems related to phytohormones in plants. Phytohormones play crucial roles in combating various stresses in plants and assist in regulating the growth and development of crops. For instance, jasmonic acid (JA) is produced in plants by the oxidation of α-linolenic acid, which regulates the growth of roots and the senescence of leaves. However, a study reported that exposure of NPs in rice seedlings significantly decreased the JA content in roots (Zhou et al., 2021a, b, c). Moreover, PS-NPs altered hormone transduction signaling pathways (such as metabolism of α-linolenic acid and biosynthesis of carotenoids) in plants (Lian et al., 2022; Sun et al., 2021). Thus, the alteration of plant metabolism due to MPs/NPs exposure in plants is a great concern because it may reflect a reduction in both crop yield and quality.

Genetic

MPs/NPs can address cytogenotoxicity and genotoxicity in plant cells via chromosomal and nuclear aberrations (Giorgetti et al., 2020; Maity et al., 2020). Internalization of NPs into plant cells has been shown to alter gene expression, regulating root development and nutrient transport in rice (Zhou et al., 2021a, b, c). Another study exposed PS-based NPs to broad beans and discovered a decrease in the mitotic index and an increase in micronucleus frequency in root cells (Jiang et al., 2019). Furthermore, Maity et al. (2020) claimed that PS-based MPs can cause morphotoxicity, oxidative stress, and cytogenotoxicity and affect onion (*Allium cepa*) gene expression (Maity et al., 2020). Similarly, Giorgetti et al. (2020) investigated PS-based NPs exposure against onion and concluded that genotoxicity (induction of cytogenetic anomalies and micronuclei), as well as cytotoxicity (reduction of mitotic index), occurred even at the lowest NPs dose. The following are some possible explanations for structural demolition and genetic anomalies in plant cells in response to MPs/NPs exposure: (a) the production of excessive ROS, which causes oxidative damage to plant cells and genetic processes, and (b) the alteration of gene expression (cdc2), which results in the irregular evolution of the plant cell cycle (Giorgetti et al., 2020; Maity et al., 2020; Wu et al., 2020). As a result of MPs/NPs exposure, plant growth is reduced, possibly due to evidence of excessive ROS production, chromosomal and nuclear abnormalities, and decreased cdc2 expression.

Interruption of MPs/NPs on plant-microbial interaction in the soil rhizosphere

The rhizosphere is a narrow vibrant zone in the soil matrix providing a suitable interface for interactions between plant roots and microorganisms compared to bulk soil (Mueller et al., 2019). The rhizosphere is a hotspot of microbial diversity in soil. MPs/NPs are influencing soil physicochemical properties and can potentially disturb microbial diversity (bacteria, archaea, fungi, and protists) and the plant-soil microbial interfaces (de Souza Machado et al., 2019). Thus, a series of alterations trigger imbalance in the interactions of plants and soil microorganisms and hamper normal plant growth and development (Fig. 5). The presence of MPs/NPs in terrestrial environments causes alteration in physical and chemical assets of soil which affects the plant performances through changes in their root systems (Rillig et al., 2019). For instance, De Souza Machado et al. studied the probable effects of MPs/NPs in a soil–plant model. The result reveals that MPs of different concentrations affect soil aggregation, bulk density, and soil rhizosphere significantly (De Souza Machado et al., 2019). Thus the changes in soil composition and structure may affect soil fertility with the reduction of microbial communities (Qi et al., 2020). Moreover, microorganisms like bacteria and fungus increase the bioavailability of nutrients in the soil through fixation of nitrogen and mobilization of major nutrients (N, P, K) to plants during remediate soil structure by improving soil stability and aggregation (Rashid et al., 2016). In addition, the catalyzing effect of enzymes in biochemical reactions plays a vital role in nutrient recycling. MPs/NPs are observed to affect soil enzymes like glucosidase, urease adversely (Yang et al., 2018). However, the ingestion and accumulation of MPs/NPs in the intestine of soil organisms (Schöpfer et al., 2020) may happen which may be responsible for decreased activity of gut microorganisms (Kim et al., 2019). Moreover, MPs/NPs can disturb the metabolism of energy (Kim et al., 2019), increase oxidative stress (Song et al., 2019), and decrease the reproduction and the body length of soil fauna (Kim and An et al., 2019). Judy et al. observed that MPs reduced respiration rate and increased the mortality in the microbial communities of soil dwellers (Judy et al., 2019). Besides, the adsorption of other contaminants like heavy metals on MPs/NPs amplifies the risks further (Hüffer et al., 2019). All these facts can cause harm to the normal growth and function of microbes in the soil ecosystem. As a result, the aforementioned variations in the soil ecosystem affect biogeochemical cycles related to nutrient recycling resulting in plant growth and development (Lecomte et al., 2018). In general, regarding plant–microbe association, root exudates play a significant role in facilitating interactions between nearby plants and surrounding microorganisms (Jain et al., 2020). Moreover, toxic substances are already present in the plastic particles (during manufacturing) before arrival in the soil or adsorbed from the environment onto their surface (ecocorona). These impurities can be transported to the soil along with MPs/NPs, affecting symbiotic relationship between roots of plants and their symbionts resulting in negative effects on plant growth (Rillig et al., 2019).

MPs/NPs contamination in plant-soil systems exerts a series of deviations from normal situation. Regarding soil microbes, the findings from a recent study reveals that PS-NPs of different sizes in bacteria *Escherichia coli* induce oxidative stress through ROS generation and augment resistant capacity against antibiotics (Ning et al., 2022). This result suggests that production of ROS is the key mechanism to increase resistance mutations in bacteria towards environmental stress. Specifically, NPs can penetrate through cell membranes and destroy cellular functions (Fig. 5). The internalization of positively charged NPs produced more cell stress with initiation of high levels of ROS (Dai et al., 2022). Thus, uptake and accumulation of NPs into tissues causes fluctuations in REDOX homeostasis and causes cell death in severe cases (Muhammad et al., 2021). Generally, antioxidant defense mechanisms activate to scavenge the produced ROS to maintain homeostasis conditions in cells (Judy et al., 2019). Oxidative damage occurs in tissues when the level of ROS exceeds the level of antioxidant enzymes in organisms' cells. This mechanism is well described in the biochemical responses of plants to MPs/NPs toxicity. A recent study on rice demonstrated that MPs/NPs can disrupt amino acid metabolism and impair the synthesis of leucine, valine, glutamate, citrulline, and threonine (Wu et al., 2020). Amino acids and their derivatives play important roles in plants, including protein synthesis, response to nutrient deficiencies and stresses, and overall plant growth and development. As a result, a decrease in amino acid content can impede various biological activities within plant cells, specifically signal transduction and plant defense mechanisms in response to various stresses. Amino acids with antioxidant properties play an important role in accepting free radicals and protecting plants from a variety of abiotic stresses (Pidatala et al., 2016). In another experiment, the transcriptome analysis reveals that PS-NPs induced gene expression that regulates antioxidant enzymatic activities in rice roots (Wang et al., 2022a, b). Here, it has been demonstrated that the partly decline in xenobiotic toxicity in rice is triggered via external sources through regulation of the biosynthesis process of phenylpropene and the mechanism involved in the cell detoxification process.

Weakening of plant defense mechanisms

Carriers of heavy metals and pathogens

Exposure to MP/NP plants has direct negative effects on crop production. Apart from that, MPs/NPs contamination in soil and plants enhances the chances of heavy metal and pathogen intrusion, resulting in the weakening of plant defense mechanisms against various stresses during crop production. For example, MPs/NPs have been shown to increase the abundance of pathogenic microorganisms in arable soil ecosystems (Zhu et al., 2022). MPs/NPs can transport organic and inorganic toxins from their surroundings. As a result, the chemicals emitted by such pollutants may be toxic to soil-oriented organisms and plants (Wang et al., 2020a, b). Organic chemicals have a stronger attraction to MPs in soil because both compounds are hydrophobic. The results from a recent study showed that exposure to six different polymers, PS, PE, PLA, PA, PHB (polyhydroxybutyrate), and PBS (polybutylene succinate), in Zn-Pd-contaminated soil caused changes in soil enzymatic activities, pH, nutrient availability, and microbial activities (Feng et al., 2022). Thus, MPs/NPs contaminated with organic and inorganic compounds may harm the growth of earthworms as well as other soil biota. Significant concentrations of various heavy metals have also been observed on the surface of MPs/NPs in various habitats (Zhou et al., 2019). For example, the combined treatment of MPs/NPs (PS and PTFE) and the heavy metal As III (Arsenic) has been observed to inhibit growth and biomass accumulation in rice seedlings by reducing root activities and photosynthesis particularly Rubisco activity (Dong et al., 2020). In another study, Wang et al., (2020a, b) revealed that cadmium-spiked PE in maize has a phytotoxic effect and that the simultaneous presence of MPs and Cd has the potential to alter plant performance and root symbiosis and pose a higher risk to soil biodiversity and agroecosystems.

MPs/NPs with fragmented surfaces are more likely to transport pathogens and toxic substances into the soil (Qian et al., 2018). More specifically, the presence of plastic trash is highly conducive to the colonization of various pathogens, such as *Bacillus cereus*, *Pseudomonas*, *Stenotrophomonas maltophilia*, and *Escherichia coli*, in MPs biofilms (Parthasarathy et al., 2019). The presence of MPs/NPs also interferes with the dissipation of antibiotics and bacterial resistance genes. Soil MPs/NPs can absorb more hydrophobic antibiotics, as well as antibiotic resistance genes (Lu et al., 2020; Yan et al., 2020a, b). As a result of these explanations, it is clear that available MPs in the environment serve as hotspots for gene transfer between different pathogens. Furthermore, sharp-edged MPs cause more damage to plant root cells than blunt-edged MPs (Kalčíková et al., 2017). Due to their light weight, MPs/NPs can transmit pathogens and insects from one crop field to another.

MPs/NPs generated problems related to mucilage

Root cap cells primarily assist the regulation of root growth and protect the root's stem cell niche. To protect plants from pathogenic infections, this root cap naturally secretes large amounts of mucilage (hydrated polysaccharide) (Driouich et al., 2021). Furthermore, viscous mucilage not only lubricates root tips for easy penetration into the soil but also promotes nutrient uptake by plants and improves soil quality by improving aeration and water infiltration. Furthermore, mucilage has been shown to improve the phytoremediation capacity of contaminated soil (Sun et al., 2015). However, the presence of MPs/NPs jeopardizes the presence of such beneficial elements secreted by plant roots. Li et al. discovered that PS-based microbeads were trapped extracellularly in wheat root cap mucilage (Li et al., 2020a, b, c, d, e, f, g). As a result, such trapping can impair the plant's defense mechanism against pathogenic activities. Even washing before the experiment could not remove the available PS microbeads from the root surface, demonstrating the strong bonding between the root surface and the microbeads. The negatively charged microbeads interact with similarly charged root surfaces and mucilage, though the opposite phenomenon is supposed to occur (Driouich et al., 2013). Due to the higher hydrophobicity of the root cell wall and PS beads, another study proposed that the presence of mucilage dominates hydrophobic interactions between PS microbeads and the root surface (Li et al., 2020g. This phenomenon can be explained by the fact that electrostatic interactions or specific bond formation between the charged soil surface and charged solute species can be classified as specific or nonspecific (Zhou & Pang, 2018). Furthermore, in nonspecific interactions, the chemical bonding between the soil surface and solution ions balances the charged soil particles via electrostatic interactions (Zenteno et al., 2013).

In a study, Urbina et al. (2020) demonstrated that PE-based MPs were adsorbed on the root surface and formed complexes with root mucilage. The author also identified a feathery white coat covering the roots of plants as a result of the interaction between root mucilage and MPs. Microfibers have been shown in studies to reduce soil aggregation by preventing macroaggregates from combining with microaggregates (Lozano et al., 2021; Zhang & Liu, 2018). Soil biota, on the other hand, may increase soil aggregation by forming mucilage with extracellular compounds and binding the particles. However, the availability of microfibers may even weaken the stability of soil aggregates by impairing the normal function of soil biota (de Souza Machado et al., 2019; Lehmann et al., 2019; Liang et al., 2019). Moreover, root cap cells emit mucilage along with other exudates as the first line of plant defense to combat mechanical stress, contaminants, and the aggregation of soil particles (Schwab et al., 2016). Based on previous research, it is hypothesized that MPs/NPs disrupt mucilage (an important root exudate) by forming strong physical and ionic bonds, affecting normal plant root anchorage to soil and making plants more susceptible to both biotic and abiotic stresses. Furthermore, because mucilage is a soil-binding agent, the disruption of MPs/NPs may impair soil aggregation formation or nutrient binding to soil particles.

Crop quality

Due to the widespread dispersal of MPs/NPs, it is unavoidable to investigate the potential environmental threats that may impede crop yield and nutritional quality. The impact of MPs/NPs from agroecosystem on the human food web is a potential threat (Fig. 6). In a recent study, for example, reduction of both plant biomass and nutritional quality of lettuce were observed with PS-NP exposure (Lian et al., 2021a, b). In particular, the levels of six essential amino acids, leucine (30.1%), isoleucine (20.7%), valine (10.7%), lysine (22.2%), threonine (8.7%), and tryptophan, were significantly lower in PS-NP-treated lettuce plants than in controls (36.9%). Furthermore, the levels of semi- and nonessential amino acids, such as serin, proline, tyrosine, arginine, aspartate, ornithine, and asparagine, were lower than those in the control groups. Furthermore, previous research has found that exposing PS-NP to wheat roots can affect mineral uptake and distribution (Li et al., 2020a; Lian et al., 2020a, b). Moreover, the results from a combination of both laboratory and field experiments revealed that MPs/NPs exposure causes a decline in 26 organic acids and 12 amino acids in rice plants (Wu et al., 2020). As essential minerals are critical for plant growth as well as human dietary mineral intake, MPs/NPs contamination in plants disrupts plant growth in a variety of ways. In another study, the absorption of PS-NPs (0.2 μm) in wheat and lettuce roots and subsequent transport to the shoot harmed plant vigor via cell membrane modification and changes in intracellular metabolic activities (Luo et al., 2020), resulting in a decrease in crop yield. Adjacent toxic materials with MPs/NPs must be considered. For example, common plasticizers (such as phthalates) have been shown to end up in wheat crop grains, posing a potential threat to human health (Shi et al., 2019). Again, in terms of nutritional needs in humans, for example, 8–18 mg Fe (Iron) is recommended as RDI (Recommended Daily Intake), but the reduction in Fe content in lettuce may reduce 0.3 mg Fe intake in humans per day (Lian et al., 2021a, b). Furthermore, the strong adherence of MPs/NPs to root crops reduces crop aesthetic value. Thus, the presence of MPs/NPs in major cereals, vegetables, and fruits not only reduces crop yield but also quality, which, when combined with other hazardous materials, may exacerbate the global problem of hidden hunger.

Quantification of MPs/NPs pollution

According to the studies mentioned above, it can be established that plants can trap a significant amount of MPs/NPs. Studies on two different vascular plants, *Camellia japonica* and *Pittosporum tobira*, for example, revealed the adhesion of MPs on their surfaces; the leaves of those plants hold a significant number of MPs ranging from 0.07 to 0.19 items/cm^2. Various surveys conducted in 11 countries estimated that the plant leaves absorbed approximately 0.13 trillion MPs (Chen et al., 2020; Liu et al., 2020a, b). It is a matter of concern that MPs/NPs can even be found in supermarket edible fruits (Conti et al., 2020). The World Health Organization recommends that each person consume 400 g of vegetables and fruits in a single day (Organization, 2019). As a result, a significant amount of MPs/NPs may be consumed by humans daily through fruits and vegetables (Fig. 6). This statement is supported by the fact that approximately 200,000 plant species are edible worldwide (Pironon et al., 2019). As MPs/NPs contaminate the environment, those plants become contaminated with MPs/NPs, exposing humans to them through daily intake. As a result of the rapid growth of the population and economy, the consumption of MPs/NPs is gradually increasing with the consumption of contaminated plant products.

Estimation of ingested MPs/NPs via dietary intake by humans is largely dependent on the extent of MPs/NPs exposure and food habits of a specific region. As a result, the estimated rate will differ significantly across the globe (De-la-Torre, 2020). For example, an Australian consumes approximately 1 g of plastic particles from rice (stored in plastic bags) per year based on per capita rice consumption (Dessì et al., 2021). However, the quantity will be two to three times higher for people who eat rice as their main diet two to three times per day, such as the people of Bangladesh. According to the findings of several studies, an average estimation of MPs/NPs intake through various foods such as single-serve rice (13 mg), a cup (Plastic) of tea (0.016 mg), drinking water (1-L bottle) (0.657 mg), and seafood per serve (0.7–3 mg) has been reported (Dessì et al., 2021; Hernandez et al., 2019; Ribeiro et al., 2020; Zuccarello et al., 2019). Conti and colleagues quantified the number of plastic particles with average sizes ranging from 1.51 to 2.52 μm on various fruits and vegetables, including broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), carrot (*Daucus carota*), apple (*Malus Domestica*), and pear (*Pyrus communis*). Furthermore, the yearly ingestion rate of MPs/NPs through table salt has been estimated to be 37 and 100 particles, respectively, for each person in Europe and only in China (Karami et al., 2017) (Yang et al., 2015). These data also show that Asia (51%) is the most polluted region, followed by North America (18%) and Europe (17%) (Geyer, 2020).

Moreover, the current pandemic (COVID-19) is also hastening MPs/NPs pollution into the environment via personal protective equipment and related medical wastes. One of the recent studies revealed that face masks are responsible for releasing the countless amount (ten thousand) of needle-like micro/nanofibers into the environment due to mechanical aberration (Wu, Li et al. 2022). These microfibers are prone to penetrate the biological membrane and result in tissue and organ dysfunctions in plants (Oliveira et al., 2018; Liu et al., 2019; Wu et al., 2020), followed by the biomagnification of MPs/NPs from the plant to the human intestine through the food chain (Li et al., 2020). Furthermore, textile and clothing industries are also becoming potential hubs of MPs/NPs due to the rapid utilization of synthetic polymers, including polyester and polyamide (Mathalon and Hill 2014; Remy et al., 2015; Carney-Almroth et al., 2018). Countries with large textile industries are at higher risk of MPs/NPs toxicity. For example, the economy of Bangladesh has been dominated by textile/garment industries and MPs/NPs toxicity in soil and plants are massive. Because, research has enumerated that in Bangladesh, 34.9 trillion fiber-based MPs were discharged into the aquatic environment in the fiscal year of 2021 (Dey and Jamal 2021). Nevertheless, in 2016, an organization called ESDO (environment and social development association) investigated the extent of MPs/NPs pollution in three major Bangladesh cities: Dhaka, Sylhet, and Chittagong. According to the study, various cosmetic products (such as face wash, detergent, and toothpaste) are a potential source of MPs/NPs (especially microbeads). The study also quantified MPs pollution, such as 8000 billion microbeads released into three cities' water bodies each month. More specifically, in Dhaka, Chittagong, and Sylhet, approximately 7000 billion, 1000 billion, and 200 billion microbeads are released into the aquatic environment, respectively. As a result, it is easy to estimate that surface water in Bangladesh is becoming a potential hub of MPs/NPs, and irrigation with such contaminated water exposes crops to pernicious MPs/NPs pollution**.** Aside from cosmetics, the garment industry is also responsible for MP pollution (Carney-Almroth et al., 2018). In 2016, 65 million tons of plastic waste from textile fibers were generated (Henry et al., 2019), and these waste microfibers are eventually discharged either in terrestrial ecosystems via landfilling or in aquatic environments via wastewater (Bouwmeester et al., 2015). Thus, along with land filling by massive amounts of plastic polymers, there is an enormous chance of MPs/NPs entry into crop lands through irrigation. As a result, immediate action must be taken against MPs/NPs (microfibers and microbeads) for the sake of the environment, and with that goal in mind, this study also considered the critical analysis of possible remediation. In addition, the impact of MPs/NPs pollution in Sundarbans, Bangladesh (the largest mangrove forest in the world), is also massive, with potential threats to the mangrove ecosystem (Adyel and Macreadie 2021). According to research, the cumulative flows of the Meghna, Ganges, and Brahmaputra Rivers introduce 3 billion MPs into the Bay of Bengal each day (Napper et al., 2021). In a single fiscal year, 1.7 × 108 tons of plastics/ha are transported to the Sundarbans, primarily from upstream rivers of the Bay of Bengal (Lebreton et al., 2017). Even increased tourist (~250,000 persons) activities in Sundarbans contribute to huge MPs pollution each year (Adyel and Macreadie 2021; Mahmood et al., 2021). MPs/NPs have already been found in various aquatic creatures in the Indian territory's Bay of Bengal (Goswami et al., 2020). Moreover, in mangrove ecosystems, the sediments and roots with special features (such as density and thickness) are suitable for trapping plastic particles (Duan et al. 2021). Therefore, interdisciplinary investigations regarding the properties of MPs/NPs in places with different trophic levels around the world are needed.

Impact on human health

Exposure of humans to MPs/NPs primarily occurs through ingestion and inhalation (Revel et al., 2018). Aside from inhalation, the majority of contamination in the human body occurs through drinking water and taking foods, resulting in a variety of health effects (Fig. 6). Furthermore, it covers a wide range of MPs/NPs-contaminated primary producers that ensure our major food and nutritional needs, such as cereals, pulses, oilseed crops, vegetables, and fruits, which ultimately transfer from farm to our dining table, resulting in exposure of MPs/NPs to humans (Fig. 6). According to a recent study, ingestion is the most common way for humans to be exposed to MPs/NPs (Lehner et al., 2019). Inhalation of airborne MPs/NPs occurs most commonly through synthetic garment/textile fibers, rubber tires, and dust (Prata, 2018). According to a recent report from IQAir (Swiss Air Quality Technology Company), Bangladesh will have the worst air quality in 2021, up from the second worst in 2020. Furthermore, the waste generated by COVID-19, as well as the existing air pollution, amplifies the negative impact of the situation. In this regard, it has been

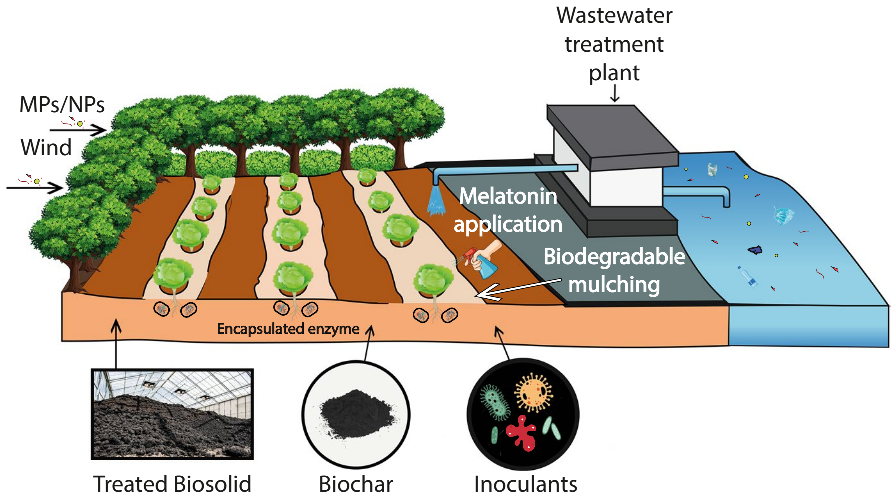

Fig. 7 Remediation of MPs/NPs pollution from crop fields

demonstrated that, aside from the intake of MPs/NPs from directly plastic-contaminated foods, the deposition of airborne MPs/NPs in our meals significantly increases the toxicity level and is an alarming threat for the people of Bangladesh (Catarino et al., 2018).

Following MPs/NPs ingestion, potential translocation and subsequent absorption occur through the digestive system (Whelan et al., 2011). For example, ingested plastic particles (150 m) could translocate to the circulatory system from the fish gut cavity at a rate of 0.3% (Barboza et al., 2018). Plastic particles were detected and quantified in human blood for the first time (Leslie et al., 2022). Here, polymers such as PS, PP, and PET are encountered. Furthermore, two different studies have shown that PS beads of 50, 80, and 240 nm, as well as microsized PP, are permeable to the human placenta (Ragusa et al., 2021; Wick et al., 2010). PS-NPs (44 nm) internalized into human cells inhibited cell viability, altered gene expression, and caused morphological aberration and inflammation (Nadanaciva et al., 2011). During an in vitro study, PS particles with diameters of 202 and 535 nm caused inflammation in human lung cells (Hu & Palić, 2020). In another study, nanoparticles (21 nm and 48 nm in size) were applied to myocardial cells (Ye et al., 2010). Thus, the presence of MPs/NPs in the bloodstream and cardiac cells may cause blockage and interfere with normal circulation, resulting in heart disease in humans. Furthermore, MPs/NPs accumulation in the gut and liver caused inflammatory effects, increased lipid buildup in the liver, and increased catalase and superoxide dismutase enzymes, indicating oxidative stress (Lu et al., 2016). Because of the large surface area and persistent nature of MPs/NPs in human tissues, they can cause oxidative stress and subsequent cytotoxicity with chronic inflammation, potentially increasing the risk of cancer (Prata et al., 2020). Surprisingly, MPs/NPs absorption may alter the diversity and function of gut microbes, resulting in metabolic dysfunction in humans. This may increase the risk of obesity, diabetes, and other chronic liver diseases (Weiss & Hennet 2017). MPs/NPs have been shown in studies to harm gut homeostasis, male reproduction, and F1 progeny (O'Neill & Lawler, 2021). Furthermore, additives (phthalates, BPA) or plasticizers associated with MPs/NPs are linked to sexual abnormalities, cardiovascular disease, hormonal imbalances, obesity, cancer, and birth defects in humans (Dey et al., 2021; Gómez & Gallart-Ayala, 2018; Koelmans et al., 2014). As vectors, MPs/NPs have the potential to transmit diseases. However, human studies are limited, and more research into these infamous problems is needed.

Remediation

In regard to MPs/NPs remediation or solution to this pollution in agricultural land, the first question is from where the problem is approaching. The overall outlook for MPs/NPs remediation in crop fields is depicted here (Fig. 7). Plastic mulch materials contribute significantly to MPs/NPs pollution. Organic mulching materials instead of plastic ones such as crop residues, tree leaves, rice straws, husks, wood dust, and water hyacinths are encouraged in conservation agriculture because they decompose easily (Mancinelli et al., 2015), though these materials can be difficult to handle at times and can be problematic for large area coverage. Despite their low cost and ease of use, plastic mulches cause many MPs/NPs problems in the soil environment. As a result, switching from plastic mulches to organic and biodegradable materials may be a promising technique for reducing the risks of MPs/NPs pollution to maintain sustainability. For example, a completely biodegradable polymer and natural fiber based on starch could be a potential way to reduce the massive plastic waste in crop fields (Tan et al., 2016). Natural polymers can also be used to replace plastic polymer-coated fertilizers. The global use of plastic mulch in agriculture (beginning in 2018) is expected to reach 59% by 2026 (Sintim et al., 2020). Biodegradable films degrade in the soil for varying lengths of time depending on the climatic conditions that can be related to the degradation rate of compost is observed to be faster than that of soil (Sintim et al., 2020). Similarly, depending on the materials and temperature of pyrolysis, biochar application in MPs/NPs-polluted soil can improve soil quality (Palansooriya et al., 2022). Furthermore, wastewater is being used at random in agricultural fields all over the world, particularly in developing countries. As a result, irrigation should be applied after wastewater treatment to reduce MPs/NPs contamination in crop fields (Hamzah et al., 2021). The use of wastewater for crop production poses a health risk and degrades environmental quality.

The use of biosolids is another way for MPs/NPs to enter the soil. Organic solids include sewage sludge, cattle manure, kitchen waste, and agricultural byproducts (Peng & Pivato, 2019), all of which contain high levels of MPs/NPs, heavy metals, and other organic pollutants. As a result, such materials should be treated for two reasons before application to farmland. The primary goal is to reduce MPs/NPs, and the secondary goal is to reduce the number of heavy metals or other hazardous materials. Recently, researchers have concentrated on the development of technologies to treat biosolids sustainably. For example, hyperthermophilic composting (HTC) is more effective than other conventional solid waste treatment methods in terms of reducing MPs/NPs and heavy metal pollution (Chen et al., 2021; Huang et al., 2019a, b). Chen et al. (2021) used HTC technology on a large scale (200 t) of sewage sludge to remove MPs/NPs and obtained the highest percentage of removal. The study found that several bacteria, including Bacillus, Geobacillus, and Thermus, have thermophilic properties that aid in biodegradation. The findings point to a promising method for removing plastic particles from the natural environment. Furthermore, phytoremediation using plants and their associated microorganisms can be used to clean up polluted soils and wastewater. As a result, the discovery of suitable microorganisms to accelerate biodegradation via enzymatic depolymerization has recently emerged via biocatalysis to reduce the number of MPs/NPs discarded in the environment. As a result, engineered enzymes can be used to degrade MPs/NPs in situ (Zurier & Goddard, 2021). Moreover, engineered plants can be introduced through genetic modification to enhance abiotic stress tolerance in plants (Jochum et al., 2019).For example, the biosynthesis of osmoprotectants like GB (glycine betaine) governed by the gene BADH (betaine aldehyde dehydrogenase) and the introduction of such genes can enhance the tolerance capacity of different plant species against various abiotic stresses (Niazian et al., 2021). Therefore, with proper identification, isolation and finally introduction of tolerance genes through plant genetic engineering may be employed to develop desired crop species growing in MPs/NPs-contaminated soil. Moreover, plants that can absorb more MPs/NPs can be identified so that they can be used as trap crops.

Several bacteria, fungi, and algae have been discovered to be capable of degrading plastic particles in soil (Dey et al., 2021). In this regard, beneficial microorganisms can be discovered and introduced into MPs/NPs-polluted soil. Furthermore, enzymatic degradation of plastic particles may be important. For example, studies have shown that the bacterial stain 201-F6 (*Ideonella sakaiensis*) secreted enzymes such as MHETase and PETase, which hydrolyze PET to eco-friendly monomers (Yoshida et al., 2016). Again, heavy metal and hydrocarbon contamination of water and soil is successfully remedied by using encapsulated silica (Camenzuli et al., 2017). As a result, it is possible to speculate that encapsulated enzyme treatment may be promising for MPs/NPs remediation from the soil. Thus, PETase and MHETase enzymes can be extracted from *Ideonella sakaiensis* (201-F6 species or other species with similar properties) cultured in a controlled environment. These enzymes would then be encapsulated in a biodegradable lignin shell. The use of such encapsulated enzymes, particularly near/around seeds during sowing or even near the plant root zone, may create a new era of MPs/NPs remediation from soil. As a result, the enzymes will be released from the capsule near the germinating seeds that may protect them from the adhering of MPs/NPs. Furthermore, these will help to degrade MPs/NPs that have attached to plant roots.

Furthermore, some recent studies indicate a new era of escape from these notorious problems. Exogenous melatonin application may be a promising method for managing MPs/NPs pollution in plants and soil. Melatonin helps plants cope with abiotic stresses to a large extent. For example, it has recently been discovered that exogenous melatonin application in wheat reduces root uptake and subsequent translocation to the shoot of NPs with the regulation of gene expression in aquaporins through upregulation both in roots and leaves (Li et al., 2021a, b, c, d). Melatonin induced ROS scavenging to improve redox homeostasis and increased plant tolerance to MPs/NPs toxicity. With all of the precautions in place, using exogenous melatonin in plants may be a promising technique for achieving sustainability in crop production in MPs/NPs-contaminated soil.

The frequency of MPs/NPs pollution by air deposition is high in urban and suburban areas, particularly along roads and in industrial areas. As a result, a series of trees of varying heights should be planted in industrial areas or along roadsides. These will serve as a windbreak as well as an air screening. As a result, air deposition of MPs/NPs and other pollutants to crop plants may be reduced. After a certain time, the border trees can be used to make furniture as well as fuel. Furthermore, the increased number of trees will help to mitigate the effects of climate change. Essentially, such an establishment will provide an opportunity to increase farm income. Moreover, these trees could be a breeding ground for disease-causing pests, lowering the rate of pest infestation in the main crop.

Conclusions

The accumulation and translocation of MPs/NPs into plants add a new dimension of concern with the existing problems. MPs/NPs inhibit seed germination and crop growth in addition to transporting a variety of toxic substances, heavy metals, and pathogens into agroecosystems; more specifically germination and seedling stages are more vulnerable than mature plants. Even, the species variation of plants with different genetic make-up also determines the toxic level in plants. For example, rice plants are more susceptible to MPs/NPs toxicity than wheat. Therefore, it is alarming for rice-producing countries as compared to wheat-producing countries. Environmental conditions such as temperature and humidity have an impact on the transpiration pull within the plant that ultimately influences the uptake of MPs or NPs in plants. Crops grown hydroponically are more susceptible to MPs/NPs toxicity. Thus, it is a matter of concern that with the increase of global population and limitation of cultivable land, more emphasis is being given on hydroponic growing media. In this case, MPs/NPs free water should be ensured to run the process safely. Even the shape of the MPs/NPs has an impact on the plant toxicity, as microbeads are more harmful to plants compared to other shapes. On the contrary, microfibers are harmful to soil. Moreover, various MP and NP polymers with different properties may form a diverse range of ecocorona in the soil, and make the situation worse.

Future perspectives

In fine, action should be taken by the local authority, researchers, and politicians to define a threshold level of MPs/NPs pollution in the soil and plants that would ensure policy-makers taking appropriate actions on reducing MPs/NPs pollution in the terrestrial ecosystem. Further research is also needed to get in-depth knowledge on NPs transportation through the plant body with the complete understanding of the cellular mechanisms involved there. Moreover, trap crops can be planted on the roadsides to absorb micro/nanoplastic particles (plastic loving plants) on a greater scale.

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Declarations

Ethical approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors. The authors approved the manuscript, and there are no ethical issues to declare.

Consent to participate The authors have agreed on the manuscript, and there are no issues to disclose.

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