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Review

Micro- and nanoplastics in agricultural soils: Assessing impacts and navigating mitigation

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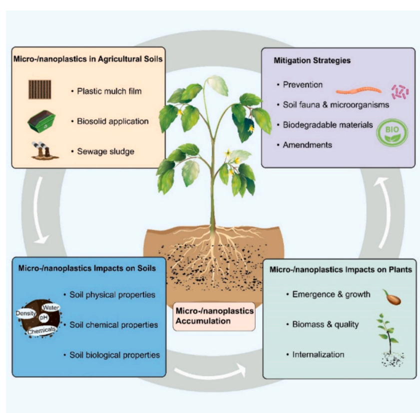
HIGHLIGHTS

- The major sources of microplastics in Australian agricultural soils are plastic film and biosolid application.
- Microplastics in agricultural soils impact physical, chemical, and biological properties of soils.
- Microplastic contamination in soils has negative potentials for plant growth and quality and sustainable agriculture.
- There are no effective and appropriate mitigation strategies to eliminate microplastics in soils.

GRAPHICAL ABSTRACT



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ABSTRACT

Micro-/nanoplastic contamination in agricultural soils raises concerns on agroecosystems and poses potential health risks. Some of agricultural soils have received significant amounts of micro-/nanoplastics (MNPs) through plastic mulch film and biosolid applications. However, a comprehensive understanding of the MNP impacts on soils and plants remains elusive. The interaction between soil particles and MNPs is an extremely complex issue due to the different properties and heterogeneity of soils and the diverse characteristics of MNPs. Moreover, MNPs are a class of relatively new anthropogenic pollutants that may negatively affect plants and food. Herein, we presented a comprehensive review of the impacts of MNPs on the properties of soil and the growth of plants.

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We also discussed different strategies for mitigating or eliminating MNP contamination. Moreover, perspectives for future research on MNP contamination in the agricultural soils are also highlighted.

1. Introduction

Annual global production of plastic materials is around 90 billion megagram (Mg) while its recycling rate is only about 9 %. Plastic production is continuously increasing due to its versatility and durability despite public awareness of environmental consequences across the world (Uddin et al., 2022). The estimated annual plastic waste is 300 million Mg globally which is 12 % (by weight) of total waste generated (Kaza et al., 2018). Plastic waste will reach 12 billion Mg by 2050 with the increasing trend in plastic production (Geyer et al., 2017). The plastic waste that was lost from or never arrived in a landfill is adverse to marine and other ecosystems (Rillig, 2018).

The estimated annual input of MNPs in Europe and North American farm regions exceeded the total accumulated load of MNPs in the global oceans (Nizzetto et al., 2016). In Australia, approximately 3.4 million Mg of plastics were consumed in 2018–2019 and 84 % ends up in landfill (Department of Climate Change, 2021). The total consumption of plastics in agriculture was 121,800 Mg in 2021 and is predicted to increase in Australia (Department of Agriculture Water and Environment, 2022). Between 2020 and 2021 in Australia, only 12.3 % of the 82,300 Mg of end-of-life plastics were recovered in the total agricultural sector (Department of Agriculture Water and Environment, 2022). This is a poor recovery rate in absolute terms which is likely to increase plastic waste and MNPs in environments. Despite the high probability of MNP pollution, there are limited studies of MNP contamination and its effect on Australian agricultural land.

Micro-/nanoplastics may have positive or negative effects on both soil properties and plant growth. Studies showed inconsistent results in the alteration of soil properties and plant growth by MNP contamination of the soil. This may be due to the complexity of the characteristics of MNPs and soils under consideration. Soils have complex and heterogeneous characteristics which limit the efficacy of different remediation methods. To date, there is no commercially viable solution to remove MNPs from the soil.

Plastic waste comprises many types of polymers in different shapes, sizes and weathering states (Browne et al., 2015). Based on size, plastic waste can be divided into different categories, including macroplastics (MaPs), microplastics (MPs) and nanoplastics (NPs). Microplastics are defined as <5.0 mm in length of any plastic-type (National Oceanic and Atmospheric Administration (NOAA), 2023). The boundary that separates MPs from NPs is not clearly defined in the literature, ranging from 100 to 1000 nm (Mitrano et al., 2021). This review considers plastic particles <5.0 mm (i.e., MNPs) since NPs are one of the constituent products of MP degradation.

Microplastic contamination of agricultural soils presents an unknown risk to food production. This review aimed to provide a comprehensive understanding of the major pathways of MNPs into Australian agricultural soils and their potential impacts on soils and plants. Potential impacts on soils and plants will not be limited in Australian studies to provide a comprehensive overview by incorporating global perspectives. Further, existing mitigation strategies to remove MNPs from soils and potential mechanisms of MNPs impacts were reviewed to deliver the synthesized outlook of MNPs in agricultural soils.

2. Sources of micro-/nanoplastics in agricultural soils

Polyethylene (PE) is the most typically used plastic-type and Polypropylene (PP) is the second in total consumption of plastic products in agriculture (Fig. 1) (Department of Agriculture Water and Environment, 2022). Representative products of PE are plastic mulch film and irrigation hoses that are widely used in the horticulture industry. Both are in

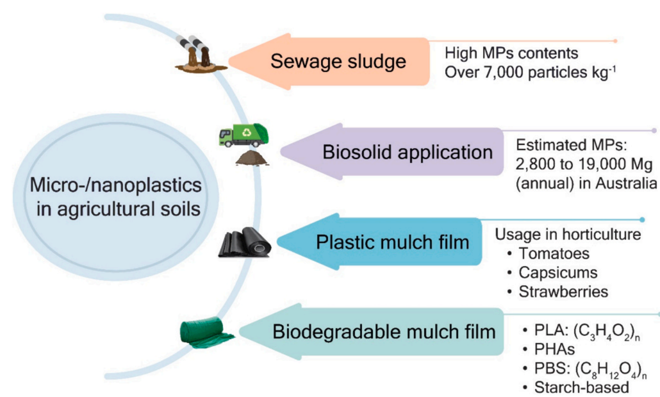

Fig. 2. Four major pathways of micro-/nanoplastics into agricultural soil. The estimated values and examples were adapted from (Ng et al., 2018; Xiangrong et al., 2018; Zhang and Liu, 2018).

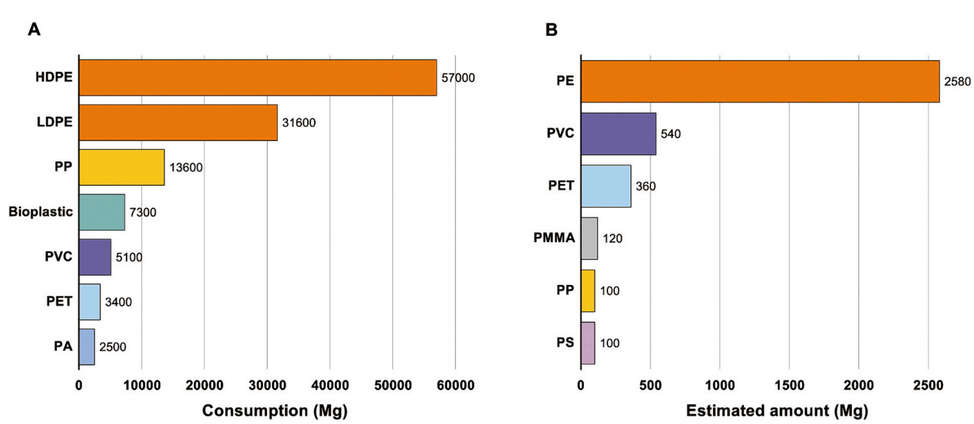

Fig. 1. **A** Total plastic product consumption in the agricultural section in Australia from 2020 to 2021 (Department of Agriculture Water and Environment, 2022). **B** Estimated micro-/nanoplastics emission in 2021 via biosolid application in Australia (Okoffo et al., 2020). Note. HDPE: high-density polyethylene, LDPE: low-density polyethylene, PA: polyamide, PE: polyethylene, PET: polyethylene terephthalate, PMMA: polymethyl methacrylate, PP: polypropylene, PS: polystyrene PVC: polyvinyl chloride.

direct contact with soils which probably generate most MNPs in soils by agricultural practices (Fig. 2).

2.1. Sewage sludge

The application of sewage sludge is considered as a major input of MNPs to agricultural land (Fig. 2) (Magnusson et al., 2016). Sewage sludge from wastewater treatment plants can contain high MNPs contents (>7000 particles kg^{-1}) or higher than general contents in subtidal zones of the ocean (15–3320 particles kg^{-1}) (Xiangrong et al., 2018; Zhang and Liu, 2018). In the case of Europe and North America, it was suggested that 50 % of sewage sludge was used either as biosolids or in direct application on agricultural land (Carr et al., 2016). Additionally, it was shown that the long-term application of sewage sludge or organic fertilizers may lead the accumulation of MNPs in the soil (Zhang and Liu, 2018).

2.2. Biosolid application

The estimated contents of MNPs in biosolids were comprised of six polymers but PE is the most abundant type (Fig. 1). It was estimated that between 2800 and 19,000 Mg of MNPs entered to Australian agroecosystem through biosolid applications (Ng et al., 2018). They also estimated that through the application of dry biosolid alone, 9 to 63 kg of MNPs (per Mg of biosolid) was applied to the Australian agroecosystem. Recent statistics showed that total biosolid production increased by over 10 % between 2015 and 2021 (310,000 to 349,000 Mg) (Australian and New Zealand Biosolids Partnership (ANZBP), 2021). Therefore, it is expected to see the applied MNPs in the Australian agroecosystem will keep increasing without mitigation strategies.

2.3. Plastic mulch film

Globally, use of plastic mulch has grown continuously since 1990s, and its production was estimated around 7.5 million Mg in 2021 (Gao et al., 2019). Plastic mulch films are generally removed after harvesting but complete removal is often not possible, leaving plastic residues behind. In 2015, the annual coverage of mulch film reached 1.45 million Mg with a covering area of roughly 18 million ha in China (Yang et al., 2020). Some studies reported that Chinese agricultural soil has a significant accumulation of plastic detritus (Huang and Hartemink, 2020). Australian horticulture farms also used PE mulch to grow tomatoes, capsicums, strawberries and other horticultural crops (Olsen and Gounder, 2001). Polyethylene has a carbon backbone that is resistant to hydrolytic and enzymatic degradation but it can be fragmented by photo-triggered or thermal-triggered oxidation (Ng et al., 2018). Therefore, microbes are unable to assimilate and mineralise PE, resulting in safe accumulation of PE MNPs in the soil.

2.4. Biodegradable polymers

Biodegradable polymer refers to the materials that can be used in limited spans before their degradation through biological activities (depolymerase) (Agarwal, 2020). There are several conventional materials to engineer biodegradable polymers: (1) using biomass or renewable resources (e.g., Polylactic acid (PLA) and Polyhydroxyalkanoates (PHAs)) to synthesize bio-based polymers and (2) petroleum-based polymers which can be utilized by microorganisms (i.e., Polybutylene succinate (PBS)) (Mekonnen et al., 2013). The global demand for biodegradable mulch film will grow to an estimated value of USD 45.24 million in 2022 and 82.82 million by 2030 (GrandViewResearch, 2022).

Soil is a complex environment. Its texture varies horizontally and vertically, temperature differs with depth, time of the day, and season, and its biochemistry such as microbial population and diversity, pH, moisture and oxygen contents also vary dynamically. These variable properties result in a highly variable degradation of plastics. Therefore, there is a high possibility that biodegradable polymers cannot be fully biodegraded and stay as small size particles in the soil due to the complexity of the soil environment. Biodegradable plastic waste is generally more prone to fragmentation thus it may produce more MNPs before mineralization (Liao and Chen, 2021; Whitacre, 2008). Further, several studies reported that biodegradable polymer MPs showed similar or even greater negative effects than conventional polymer MPs on soil fauna and plants (Ding et al., 2021; Meng et al., 2021). Therefore, more attention and further investigations are required on biodegradable-MNP contamination and its impacts during biodegradation mechanisms under different soil types and conditions.

3. Impacts of MNPs on soil properties

When the plastic residue is fragmented due to agricultural practice or degradation, it results in an abundance of MNPs in the agricultural soils. On the surface of the soil, MNPs may be moved by air and water into other environments. The discharge of MNPs from agricultural soils into the atmosphere is approximately 5 % in the western United States (Brahney et al., 2021). However, the estimation of MP discharge through runoff or water erosion has not been reported (Brandes et al., 2021). Wind or water erosion may transfer MNPs from soils, but they will be deposited again in soils or water environments. Further, agricultural practices and extreme climate events are accelerating the fragmentation of plastics in the soil. It could help the rapid degradation of MNPs but also could deposit more small sizes of MNPs, increasing internalization and tropic transfer of MNPs.

Plastic mulch film has been recognized as a beneficial technology for crop production, but large amounts of plastic mulch film residue may cause many problems in the agricultural environment (Gao et al., 2019). The reported potential concerns were the alteration of soil structure, inhibition of plant growth, secondary salinization and transportation of chemicals (Zhang et al., 2014). Compared to MaPs, the smaller sizes and increased total surface areas of MNPs exacerbate their potential to cause additional problems in the agricultural soils both on the soil physical, chemical and biological properties of soil and on the growth of higher plants (i.e., crops) (Fig. 3).

3.1. Soil physical properties

3.1.1. Bulk density

The effects of MNPs on soil bulk density and their consequential impacts are complex. Plastics generally have low density than many dominant minerals in the soil (de Souza Machado et al., 2018). It was observed that soil density was decreased by the presence of common MNPs (i.e., High-density polyethylene (HDPE), Polyether sulfone (PES), Polyethylene terephthalate (PET), Polypropylene (PP) and Polystyrene (PS)) (de Souza Machado et al., 2019). The decreased soil bulk density stimulated the increased evapotranspiration while it has positive effects on soil water holding capacity, soil aeration and root penetration. Soil bulk density correlates well with root penetration and other physical properties of soil (Dexter, 2004). Despite enhanced root penetration and growth, it is not clear that the consequential effect of MNPs in the soil is positive for total root growth. Soil organic matter and texture also influence soil bulk density. For a better understanding of MNP impacts on bulk density, an approach with combined multiple factors will be required.

3.1.2. Aggregate stability

Soil aggregate stability significantly influences the infiltration rate and soil aeration. Two studies showed inconsistent results of water-stable aggregate with the same type of MNPs (PES fibre). It was observed that water-stable aggregates significantly reduced in loamy sandy soil and increased in clayey soil (de Souza Machado et al., 2019). However, another study concluded that soil characteristics of mineral particle and the sieving process altered the aggregation with PES fibre as

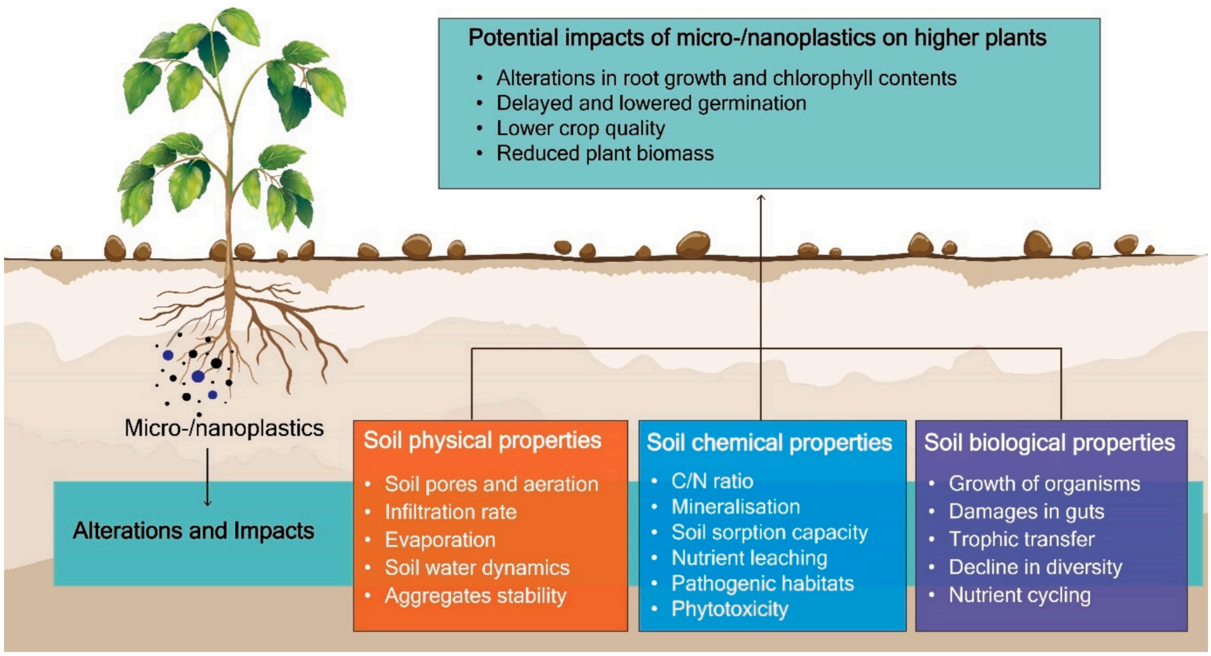

Fig. 3. Potential alterations and impacts of micro-/nanoplastics on properties of the soil based on current studies.

they had a contrast result between the laboratory and the field experiment (Zhang et al., 2019). The results demonstrated that other factors such as soil texture, clay mineralogy and organic matter are involved in the relationship between PES fibre and soil aggregate stability. When MNPs alter soil aggregation, the alteration will affect microbial activities (de Souza Machado et al., 2019). Soil microbes play a critical role in carbon cycling and storing carbon in the soil (Bhattacharyya et al., 2022). Therefore, the effects of MNPs on soil aggregate stability need to be investigated and focus on intervening mechanisms of MNPs toward soil microbial community, interaction with soil minerals and soil carbon pool alterations by age, type and concentration variations of MNPs.

3.1.3. Water holding capacity and hydraulic conductivity

Soil water properties are highly influenced by soil pores such as soil pore size and the number of pores (Bronick and Lal, 2005). When external organic particles are abundant in the soil, they significantly altered water movement within the soil, affecting soil pores (Fu et al., 2019). Macropores play a key role in the transportation of water and micropores contribute to retaining water in the soil (Abel et al., 2013). Therefore, MNP contamination possibly affects water infiltration, water-holding capacity and hydraulic conductivity of the soil by blocking soil pores.

Micro-/nanoplastics are generally hydrophobic and thus they may negatively affect water-holding capacity. Several studies reported that MNPs reduced infiltration and soil water-holding capacity (Guo et al., 2022; Jiang et al., 2017). In the case of clay textured soils, MNPs formed aggregates with soil particles and altered the original pore systems and water retention capacity. Thus, the response of soils against MNPs may vary with not only soil types but also soil texture. Saturated hydraulic conductivity also showed variable results with polymer type and soils: no changes with PES fibre (de Souza Machado et al., 2018; Zhang et al., 2019); reduction with PET and PS MPs (Shafea et al., 2023). Soil bulk density did not affect hydraulic conductivity, but soil pore alteration shifted it. Thus, soil pores may be closely associated with soil hydraulic conductivity.

Different results showed that MNP contamination in the soil may have non-monotonic effects on soil-water dynamics. The interaction between MNPs and soil particles is complicated and dependent on many factors such as the characteristics of MNPs and soil texture. Although the results are not consistent, it is evident that MNP contamination alters soil-water dynamics and may subsequently lead to reduced water availability for crops. Therefore, it is necessary to establish proper monitoring of MNP contamination and soil-water dynamic changes in soils for sustainable agricultural management and production.

3.2. Soil chemical properties

3.2.1. pH

Soil pH responses to MNP contamination also showed variable impacts (Boots et al., 2019; Wang et al., 2020a; Zhao et al., 2021). When plastics are degraded by photo-oxidation or thermo-oxidation their pH value changes depending on their release and formation of anions. In the case of HDPE, the pH value decreased under photo-oxidation conditions while the pH value increased in PVC (Bandow et al., 2017). The function between MNPs and soil pH appears that it is dependent on MP types, concentration, shape, size and ageing time. Soil pH is directly linked with agricultural productivity. The application of soil amendments such as lime is a general practice to maintain soil pH. However, the mechanisms of the soil pH alteration by MNPs are not clear and the reaction between soil amendments and MNPs has not been explored. Moreover, pH as the regulating soil chemical property for elemental speciation and nutrient availability, its change can potentially lead to increased heavy metal uptake by higher plants and reduced soil fertility. Microbes in the soil are also directly affected by pH. This may adversely affect the ecosystem functioning of the soils as soil microbes play a central role in nutrient utilization and cycling. On the other hand, biodegradable polymers (e.g., PLA) release organic acid and nutrients into soils during their degradation processes. Soil pH increased together with ammonium cation (NH_4^+) in MNPs added clay loam soil (Gao et al., 2021a). Others also confirmed that MNPs altered the carbon, nitrogen and phosphorus contents in the soil (Dong et al., 2021; Xiao et al., 2021).

Consequently, soil pH alteration by MNPs potentially causes many associated short-term or long-term issues that eventually impact soil and plant health. As soil pH is an important indicator of soil and plant health, the relationship between soil pH and MNPs should be investigated in depth to establishing appropriate managements.

3.2.2. Soil nutrient contents

The main element of plastics is carbon, is one of the most important elements in soil productivity. Polymers have high C/N ratio. Soil microbes will scavenge the soil solution to acquire sufficient nitrogen when an organic material with the high C/N ratio (i.e., over 25) is added to the soil (Brady and Weil, 2008). In the same context, several papers indicated that over 20 of the C/N ratio reduces mineral N availability and stimulates the immobilization of N (Sylvia et al., 2005). Small size of polymers such as MNPs may be recognized as organic matter by microbes. As a result, MNPs in the soil will affect the available N concentration of the soil and lead to N depletion in plants. It was highlighted that PVC and PE significantly alter the carbon pool in the soil, indicating it could negatively affect other nutrients (i.e., N and P) (Zang et al., 2020).

On the other hand, high MNP contamination leads to increased soil organic carbon (SOC) levels in soil carbon quantification. A high level of MNP addition increased organic carbon, inorganic nitrogen, and total phosphorus in the soil (Liu et al., 2017). If MNPs completely degraded relatively short time, they could be a useful source of macronutrients. However, it generally takes 12 to 32 years to completely degrade PE in moist soil (Otake et al., 1995). Considering the accumulation volume of MNPs in soils, it is hard to conclude that MNPs only have a positive effect on soil nutrient deposition. In a recent study, MNPs disrupted the measurement of precise SOC level and thus results cannot ensure the bioavailable carbon source in the soil (Kim et al., 2021). Consequently, inaccurate SOC quantification could impact soil nutrient management practices and crop production (Rillig, 2018).

The sorption capacity of the soil decreased after 10 % of PE was added to the soil (Hüffer et al., 2019). Soil sorption capacity affects the natural retention ability of soil which makes the soil a shield of groundwater from organic contaminants leaching. Leaching is a serious concern in water pollution but also in the degradation of soil which leads to a deficiency of nutrients and thus declined production. The existing study focused on soil sorption capacity changes with only LDPE powder (Hüffer et al., 2019). A further study is required to address the impacts of MNPs on agricultural soil leaching under the conditions of various types, sizes, shapes and concentrations of MNPs.

3.2.3. Carrier of chemicals

There are many additives, such as colourants, fillers, reinforcements and functional additives, to process the plastics so that they have the desired characteristics (de Souza Machado et al., 2020). Many studies emphasized that MNPs can release or leach the additives into ground water, which has a high potential for bioaccumulation and trophic transfer within the food web (Wu et al., 2016). Further, MNPs have been confirmed as a carrier of harmful chemicals in the water environment: carrier of antibiotics (Li et al., 2018) and metals (Wang et al., 2020b).

The vector effect of MNPs in the agricultural soil is more concerning due to direct and repeated application of chemicals (i.e., pesticides). Plastic residues accumulated pesticides in soils and influenced the soil habitat (Ramos et al., 2015). Glyphosate is one of the most common herbicides in the Australia and New Zealand cropping system (Thompson and Chauhan, 2022). In a study, MNPs (i.e., PP powder) could not adsorb or interact with glyphosate due to the hydrophilic characteristic of glyphosate (Yang et al., 2018). However, the interaction between glyphosate and MNPs (i.e., PP powder) decreased dissolved organic carbon and phosphorus (Liu et al., 2019). Previous studies only used PP powder to analyse the interaction with glyphosate. However, other MP types (i.e., PE) and chemicals should be investigated since plastic mulch film and irrigation hoses have direct contact with chemicals and soils. Moreover, MNPs from actual polymer products need to be investigated since there are discrepancies between pure polymer powders and MNPs such as the roughness of the surface, shapes, brittleness, specific areas of surface and the surface composition by ageing. The vector effect of MNPs would increase over time unless they are removed from soils or degraded completely. Besides, they may stay in the soil with chemicals which increases the mobility and stability of chemicals. There is also the opportunity that MNPs can be pathogenic habitats as it was discovered in the water environment. All these results and findings demonstrate they are likely to add risks to soil biota, crops and even human health.

3.2.4. Heavy metals and MNPs in the soil

Micro-/nanoplastics and heavy metals have overlapped characteristics as they are recalcitrant to degradation, persist for long periods and accumulated in the soil as contaminants. Micro-/nanoplastics may act as a vector for heavy metals in the soil and also promote the uptake of heavy metals by plants.

The positive correlation between the number of MNP particles and the content of cadmium (Cd) was reported in an industry site soil test (Zhou et al., 2019). Moreover, MNPs affect the Cd adsorption or desorption capacity of the soil which likely impacts plant health and growth since Cd in the soil is readily available to uptake by plants. Some studies reported that MNPs in the soils enhance the mobility of Cd by decreasing the adsorption capacity of the soil, thereby inducing synergetic impacts of Cd and MNPs to the agroecosystem (Huang et al., 2023). Therefore, investigation of the relationship between Cd and MNPs is required to evaluate potential risks in agricultural soils.

The interaction between heavy metals and the surface of MNPs depends on the morphology of MNPs (i.e., physical absorption), electrostatic attraction and organic-bound forms (Kumar et al., 2022). When MNPs are generated by mechanical abrasion and degradation processes, their morphologies become rougher and fragile by ageing. Thus, the adsorption capacity of MNPs in the soil is presumably to increase over time with increased opportunity of carrying heavy metals. Even though there is no synergetic negative effect between heavy metals and MNPs, both are contaminants and thus will produce some consequences in crop production and agroecosystem sustainability. The coupled effects of MNPs and heavy metals should be investigated under various perspectives of soil functions with aged MNPs.

3.2.5. Soil enzyme activities

Soil enzymes play major roles in regulating the soil ecosystem such as nutrient cycling, transformation of organic matters and detoxification of pesticides (Sinsabaugh et al., 2008). The proportion of carbon, nitrogen and phosphorus of soil enzymes is often used as an indicator of microbial biomass and activities (Cleveland and Liptzin, 2007). The relationship between soil enzymes and microbial activity also affects the degradation of chemicals applied in the soil (Hüffer and Hofmann, 2016). Therefore, accumulated chemicals with MNPs may change the soil enzymes as well as soil microbial activities, ultimately soil may have a reduction in function in the nutrient cycling.

However, the effects of soil enzyme alteration may be negative or positive. If MNPs increased organic C, N and P in the soil, it can be positive for plant growth but also accelerate nutrient (i.e., N) leaching. Phthalate (PAEs) content was the main reason to alter the enzyme and microbial activity in the soil with PVC MNPs (Zhu et al., 2022). PAEs are widespread in agricultural soils through plastic mulch film and well-known contaminants as they inhibit soil enzyme activities (He et al., 2015; Wang et al., 2016) In the study of the half-life of herbicides in a MNPs-contaminated soil, it was discovered that MNPs delayed the degradation of herbicides and reduce the enzyme activities in the soil. In horticultural practice, plastic mulch film is installed after spraying pesticide in soils to reduce further applications. As plastic mulch film and pesticide contact directly, plastic mulch film probably absorbs chemicals on their surfaces. Under this type of practice, it is probable that MNPs inhibit soil enzyme activities and negatively impact soil health. Further, soil toxicity by pesticides may increase due to decreased soil enzyme activities.

3.3. Soil biological properties

3.3.1. Soil fauna

Soil fauna contribute to the transportation and distribution of MNPs in the soil. Various soil fauna have been investigated to examine the effects of MNPs on their growth, survival and reactions: earthworms (Huerta Lwanga et al., 2016; Wang et al., 2019); collembolan (Zhu et al., 2018b); springtail (Zhu et al., 2018a); nematode (Kim and An, 2019); isopod (Kokalj et al., 2018); snail (Song et al., 2019). The studies showed that earthworms can directly ingest MNPs while their experiments were not under uniform conditions: different species of earthworms, type of MNPs and MNP concentration (Huerta Lwanga et al., 2016; Wang et al., 2019).

Agricultural soils are human-impacted soils and likely have more chances of being exposed to plastic products. Some agricultural practices such as plastic mulch film and biosolid applications increase MNP contamination in agricultural soils (Ng et al., 2018). Under these particular practices, MNP impacts on soil fauna are a concerning issue. Earthworms are often used as bioindicators to show soil health and fertility. If their survival and fitness are endangered by MNPs, it may impact soil structure and even higher plants. Other soil fauna under MP contamination also showed similar results. In summary, a high concentration of MNPs can increase the mortality of soil fauna as well as interfere with growth and induce oxidative stress. Studies claimed that 1 % of MP concentration in the soil is insignificant to earthworms but the concentration of MNPs is not uniform in all soil layers and it could be excessively high at close to the surface of soils (Rodriguez-Seijo et al., 2017; Wang et al., 2019).

3.3.2. Soil microorganisms

Soil microorganisms and their activities are involved with almost every soil property directly and indirectly. They also have been considered important bioindicators to reflect soil health and quality. Soil microbial biomass and activities tend to decrease under soil contaminations such as heavy metals and organic pollutants (Gong et al., 2021). It was also observed that MNPs impacts soil microbial biomass and activities (Ng et al., 2021). On the other hand, some studies found abundant Actinobacteria on the surface of PE MNPs (Huang et al., 2021; Huang et al., 2019; Ya et al., 2022). Another study noted that MNPs stimulated certain soil microorganisms which are tolerant to MNPs (Gao et al., 2021a).

However, the threshold value in the resistant ability of soil microbial against external stresses varies from species which means MNP contamination in the soil may lead to an alteration in soil microorganism diversity. High concentration of MNPs in soils increased CO_2 emission and decreased nutrient use efficiency which potentially affects plant growth and productivity (Gao et al., 2021a; Zhang et al., 2022). Most of the studies included LDPE MNPs in experiments and found alterations in microbial activities and emissions with higher contamination levels. However, heterogeneous characteristics of MNP contaminations and soil properties may contribute to different results (Ya et al., 2022). One study observed even opposite effects of MNPs on CO_2 and NO_2 emission depending on soil types (Yu et al., 2021). Soil microorganisms are the main component in the decomposition of organic matter, influencing nutrient cycles (Martínez-García et al., 2018). Nutrient cycling and emissions can also affect plant growth and crop productivity. Thus, the impact of MNPs on soil microorganisms is a critical issue and requires more investigation with different soil characteristics such as soil organic matter and soil pH.

4. Impacts of MNPs on higher plants

The alterations of soil properties by MNPs may impact higher plants. The alterations and problems in soils by MNP contamination are concerning issues but also MNP impacts on vascular plants cannot be ignored as they are vital in ecological balance and nutrient cycling. There are several concerns on the impacts of MNPs on plants which need to be investigated and addressed: (a) Can plants uptake, translocate and accumulate MNPs in their internal parts? (b) How do MNPs impact growth and reproduction of plants? (c) Can MNPs move from soils to food chain through trophic transfer? (d) What are the components of MNPs that make them toxic or harmful to plants? (e) Will MNPs contribute to accelerating the negative effects on plants together with another abiotic stress condition? Currently, many studies have observed adverse impacts of MNPs on higher plants (see Table S1).

4.1. Internalization of MNPs by plants

Microplastics (i.e., 1.51 μm in carrot and 2.52 μm in lettuce) even have been found in various vegetables and fruits in supermarkets (Conti et al., 2020). Nano-sized MNPs may enter the internal part of plants through roots and leaves from the air, water and soil (Table 1). In a foliar study, they also noted strong evidence of stomata pathway and translocation from leaves to roots while they used relatively bigger size and lower concentration of PS NPs (93.6 nm, 0.1 and 1 mg L^{-1}) (Lian et al., 2021). We need more studies to support the penetration of MNPs into the internal part of the vascular plant. However, MNPs could pass the stomata on the leaves since the size of stomata varies on plant species, their guard cell length and environmental pressures (Lawson and Blatt, 2014).

Several studies reported that MNPs in submicrometer (i.e., 50 to 700 nm) can penetrate into root, confirming that the roots can adhere, uptake, accumulate and translocate NPs from surrounding environments such as water and soil (Giorgetti et al., 2020; Li et al., 2019; Sun et al., 2020). Besides, PS beads in 2–5 μm were observed in the root of lettuce and wheat under hydroponic culture (Li et al., 2020a). Thus, there is a strong possibility that MNPs can enter the body of plants via surrounding environments (Gao et al., 2021b; Lian et al., 2021; Sun et al., 2021) (Fig. 4). Although plastic particles have higher mobility and are well distributed in hydroponic culture than in soil culture, MNPs can penetrate the root. Under stress conditions, roots tend to expand their length or the total area (Nibau et al., 2008). However, their extension is likely to happen in lateral finer roots, which means MNP contamination leads to more lateral root growth (de Souza Machado et al., 2019). Increased lateral roots would have a more additional opened site at later root emergence and thus increased probability of MNPs entering into the body of plants. Generally, the lateral roots grow horizontally in soil where the concentration of MNPs may be high by fragmentation of plastic mulch film or biosolid application (Osmont et al., 2007). Root system and depth might be critical factors in the internalization of MNPs from soils. Many vegetables and some grains have shallow root depths, exposing a high risk of internalization of MNPs (Jiang et al., 2017).

After MNPs entered the root, they moved to shoots and leaves while some MNPs may be trapped in the root cap mucilage. It was observed that MNPs were located in the vascular system and the cortex tissue of the roots, indicating that their pathway is via the apoplastic transport system (Li et al., 2019). Recent studies also confirmed the accumulation of MNPs in the xylem (Li et al., 2023a). Therefore, MNPs may translocate from roots to shoots and leaves through the water transport system of plants. In the soil culture, increased temperature and higher transpiration rate can accelerate the internalization of MNPs in shoots and leaves. The internalization of MNPs is a concerning issue especially for vegetables and fruits since almost all parts of them are edible.

4.2. Potential mechanism of MNPs' impact on plants

4.2.1. Oxidative stress response

The balanced reactive oxygen species (ROS) levels play a key role since they are involved in the regulation of the transition between cellular proliferation and differentiation (Tsukagoshi et al., 2010). High levels of ROS can cause DNA damage and incorrect timing of programmed cell death which are significant threats to plant health (Xie

Table 1
Reported internalization of micro-/nanoplastics in plants.

Exposure environments	Plant	Type of MNPs	Size (μm)	Location	Detection device	Ref.
Soil	Thale cress (*Arabidopsis thaliana*)	PS	0.04	Root tips	TEM LCSM	(Sun et al., 2020)
Hydroponics Sand matrices Sandy soil	Wheat (*Triticum aestivum*) Lettuce (*Lactuca sativa*)	PS PMMA	0.2 2.0	Root Stem Leaf	SEM With fluorescence labelling	(Li et al., 2020a)
Agar growth media	Thale cress (*Arabidopsis thaliana*) Wheat (*Triticum aestivum*)	PS	0.04 1	Root tips	LCSM	(Taylor et al., 2020)
Hydroponics	Faba bean (*Vicia faba*)	PS	0.1 5	Root	LCSM	(Jiang et al., 2019)
Hydroponics	Maize (*Zea mays* L.)	PS	0.2 2.0	Root	LCSM SEM	(Li et al., 2023a)
Hydroponics	Lettuces (*Lactuca sativa* L.)	PS	0.2	Root Stem Leaf	LCSM	(Li et al., 2019)
Hydroponics	Wheat (*Triticum aestivum* L.)	PS	0.2	Root Shoot	Hyperspectral-enhanced-dark field microscopy SEM	(Li et al., 2023b)
Hydroponics	Cucumber (*Cucumis sativus*)	PS	0.1	Root Stem Leaf	SEM	(Li et al., 2021)
Foliar spray	Lettuces (*Lactuca sativa* L.)	PS	0.0936	Leaf Stem Root	TEM SEM	(Lian et al., 2021)
Foliar spray	Maize (*Zea mays* L.)	$PS-NH_2$ PS-COOH	0.022 0.024	Leaf Stem Root	Micro-photoluminescence-spectra SEM	(Sun et al., 2021)

Note. SEM: scanning electron microscopy, TEM: transmission electron microscopy, LCSM: laser scanning confocal microscopy.

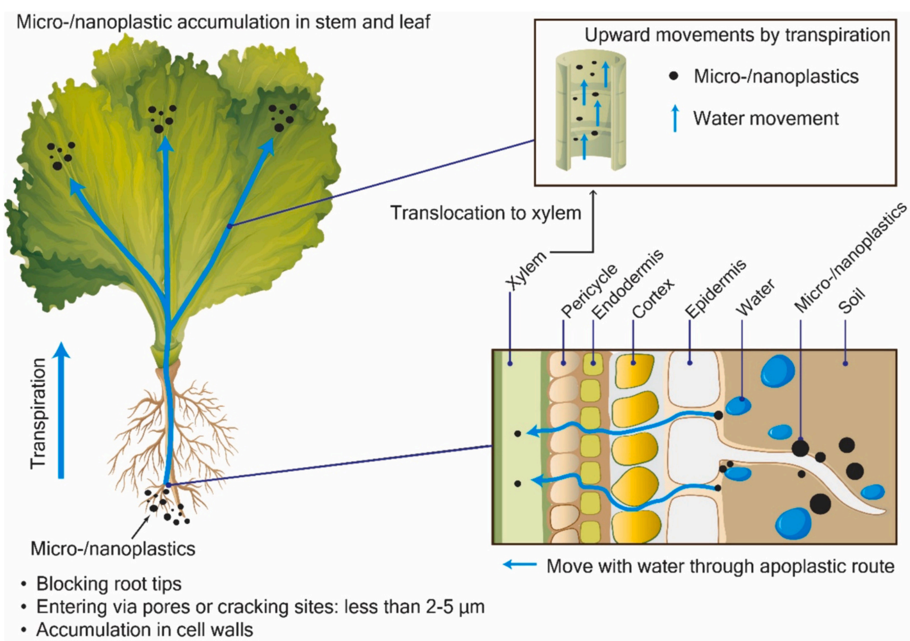

Fig. 4. The potential internalization route of micro-/nanoplastics in plants. Micro-/nanoplastics enter through tips or cracking sites on roots. They were moved from apoplastic route to xylem by water movement (transpiration) in plant system.

et al., 2014). Among the stress factors, organic pollutants have been recognized to be adsorbed by MNPs in a water environment (Costigan et al., 2022). Though MNPs are not considered organic pollutants, they can carry or adsorb organic pollutants and thus plants may have oxidative stress responses under MNP contamination (Fig. 5). Especially, MNPs in agricultural soils are expected to have more toxicity consequences due to the application of pesticides.

Possibly, blocking external parts of roots by MNPs inhibited the growth of primary roots and uptake of nutrients and drove plants to have more lateral roots. Several studies observed increased activities of a range of antioxidant enzymes and antioxidants that were generated by plants to scavenge ROS and protect them from oxidative damage by MNPs. They found that superoxide dismutase (SOD), catalase (CAT) and/or peroxidases (POD) activities increased regardless crop species (i.e., wheat, fava bean, rice and maize) (Fajardo et al., 2022; Jiang et al., 2019; Liao et al., 2019; Zhou et al., 2021). Similar trend was observed with NPs, but the particle size was a key factor to determine the stress response of plants (Li et al., 2020b).

It may be categorized into three different situations by the size of particles: no penetration of MNPs into the cell wall thus increasing ROS response in root tips by blocking root pores; penetration and accumulation of MNPs in the plant thus decreasing or no ROS response at root tip and increasing ROS response at root tissue; MNPs maybe internalized and be degraded by plants thus first increasing response at root tissue

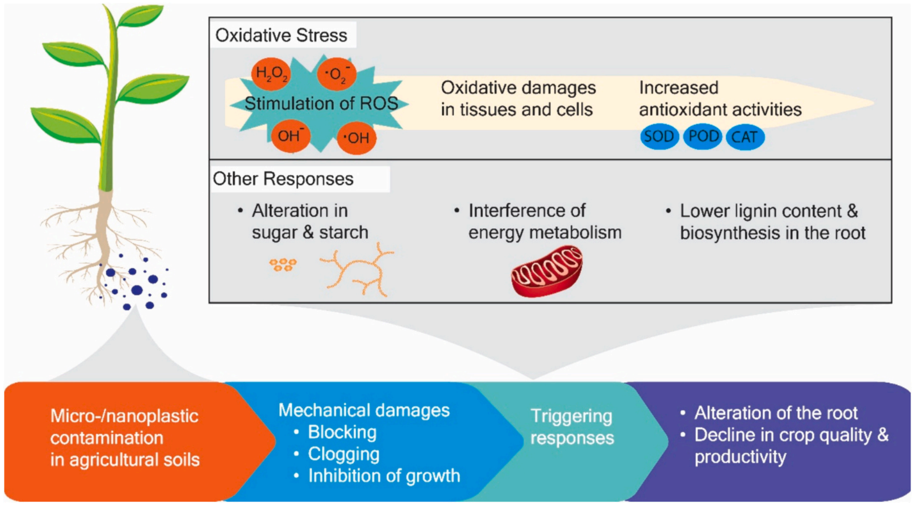

Fig. 5. Possible response mechanisms of plant caused by micro-/nanoplastics in soil. The oxidative response and the molecular response were triggered by micro-/nanoplastics in soil. Ultimately, two different responses deliver negative outcomes in root structure and crop quality and productivity.

and then decreasing response at root tissue. However, these are only speculations based on possible situations and observed ROS responses against pollutants. The internalized size can be diverse with particle shapes of MNPs or crop species since crops have different pore sizes and structures of the cell wall (Jiang et al., 2018). Most of the literature used PS beads to test the responses of plants against MNPs. Fragmented MNPs may have a greater negative effect on plant cells than smooth spherical shapes. However, the nonspherical shape of MNPs (size <1 μm) is hard to obtain due to technical challenges (Jakubowicz et al., 2021).

4.2.2. Other responses of plants

It has been reported that MPs (i.e., PS and HDPE) decreased the chlorophyll and starch contents but increased leaf soluble sugar concentration of the Chinese cabbage (Yang et al., 2021). The same tendencies were observed in rice roots under PS NPs: decreased starch contents and increased soluble sugar contents (Zhou et al., 2021). Starch is the main carbon source in carbon metabolism which provides energy for growth or biosynthesis. Decreased starch may be explained by two possible mechanisms: (1) MNPs inhibited the upstream metabolite for the starch synthesis pathway and thus starch in the grain breaks down to glucose to maintain its energy source; (2) MNPs regulated gene related to the decomposition of starch which led to the accumulation of sucrose and inhibition of glucose production (Wu et al., 2022). Sugars play a role in signalling to regulation of plant responses to stresses to enhance stress tolerance (Julius et al., 2017).

Based on the alteration of starch and sugar levels by MNPs, it is presumed that MNPs may have a relationship energy metabolism in plants (Fig. 5). Polystyrene MNPs inhibited the tricarboxylic acid cycle and disrupted fatty acid contents by down-regulating fatty acid metabolism (Wu et al., 2022). Similarly, toxicity in MNPs and arsenic synergistically induced declining of obtained energy by rice and a redistribution of energy from growth to defence (Xu et al., 2023). The major alterations included the downregulation of carbohydrate metabolism through photosynthesis, amino acid and fatty acid synthesis, and activation in defence-related pathways such as glutathione metabolism, diterpenoid biosynthesis and phenylpropanoid biosynthesis. Thus, there is a potential mechanism that plants may use more energy to defend themselves against the stress from MNPs rather than grow.

Moreover, another study investigated on the alteration of nitrogen metabolism and related genes by MNPs. They also observed transcriptomic alteration by MNPs' impacts on rice growth such as interference of nitrogen metabolism of the rice and inhibition of photosynthesis in the leaf and phenylpropanoid biosynthesis in rice root, indicating that inhibited phenylpropanoid biosynthesis may lead to the decline in the lignin content of the root (Yang and Gao, 2022). Similar results were observed with promoted activities of laccases and decreased microtubule conduction which may eventually alter the root structure (Zhou et al., 2021). It still requires more studies to test whether root growth or biomass is decreased by MNPs in the soil. However, the alteration of lignin content and composition is a clear evidence of stress response of plants (Moura et al., 2010). The alteration of root structure during the early stage of growth has a high potential to affect the production or quality of crops. Thus, MNP contamination may play as another novel stress factor that ultimately impacts crop yield and quality in agricultural productions.

4.3. Effects of MNPs in agriculture

4.3.1. Effects on germination

Planting practice depends on their farm system and crop species. Some grains may directly be planted into soil as seeds and thus they germinate in the soil. No significant negative effect was observed in *Z. mays* germination under MNP contamination in soils (Fajardo et al., 2022). However, lowered germination of the same genotype *Z. mays* was reported in MNP contaminated *vitro* tissue culture (Martín et al., 2023). The difference in results may be explained by the complexity of the soil matrix and the mitigation effect of soils. Moreover, hydroponic cultures and vitro tissue cultures offer a stronger mobility and uniform dispersion of MNPs in media than soil cultures (Liao et al., 2019). The reported mechanism of MNP effect on germination was delayed germination by blocking the seed coat though the total germination rate was not affected by MNPs (Bosker et al., 2019). The size of MNPs may be a key factor in physical impacts on the surface of seeds. In addition, another study indicated that aged MNPs displayed a less impact on germination thus organic pollutants on MNPs surface induced oxidative stress and adverse impacts on germination and plants (Pflugmacher et al., 2021). Thus, chemicals carried by MNPs such as organic pollutants are another major factor of MNPs' impact in germination.

4.3.2. Effects on roots

The phytotoxicity of MNPs was investigated under various approaches. Early studies suggested the potential translocation of MNPs within parts of the plant (Liebezeit and Liebezeit, 2015). According to a study on nanoparticle adsorption, agricultural plants can take up the nanoparticles by various pathways such as root and foliar application (Su et al., 2019). Thus, certain sizes of MNPs in the soil also have a strong potential to be absorbed by the pores of root cells. PS beads with a size of 0.2 μm were found in the root and leaves of a lettuce plant, confirming strong possibility of adherence, uptake, accumulation and translocation of MNPs by plants (Li et al., 2019).

The root may have stress when the concentration of MNPs is high enough to stick on the surface of the root and disturb absorbing water and nutrients. Regarding the hydrophobicity of MNPs, the root would have trouble absorbing the water in soil. Several studies observed increased root length or biomass under MNP treatment as plants tend to extend their root system under stressful conditions (Meng et al., 2021). However, the empirical evidence of the interaction between root and MNPs is not enough to fully understand the alteration of root activities by MNPs and the mechanism of MNP absorption by roots in soil.

4.3.3. Effects on crop yield and quality

The potential damages of MNPs on crop health and yield are the threats to farm production and crop quality. Lei & Engeseth demonstrated impacts of PE-MNPs on lettuce, including specific lettuce quality traits (Lei and Engeseth, 2022). They observed consistent results with abiotic stress impacts on lettuce such as decreased chlorophyll contents which leads to inhibition of photosynthesis and reduced biomass. They also found that the firmness (lignin content) of lettuce increased, and shelf life was shortened as weight loss and colour change of lettuce were accelerated by PE MNPs.

Chlorophyll contents can be used as the parameter of plant biomass and photosynthesis but cannot entirely represent growth of plants. Moreover, increasing chlorophyll contents under stress is one of the tolerant strategies of plants (Khayatnezhad et al., 2011). Lignin accumulation has been reported in the abiotic stress response of plant or defence mechanism of plants as lignin increased firmness of plants (Song et al., 2021). The mechanism for shortened shelf life by PE MNPs is unclear but it may be also associated with oxidative damage in cellular molecules which are related to the storability of plants. Despite there is a high possibility of nutrient changes in crops due to inhibition of nutrient and water uptake by MNPs, there is no study on MNPs' impacts on crop nutrient quality.

4.4. Human health risks

Concerns are growing about the significance of MNPs to human health yet their effects on human health still lack of comprehensive information and evidence. Micro-/nanoplastics can enter the human body through the pathways in the diet and the environment (Fig. 6) (Vethaak and Legler, 2021). The major pathways of MNPs are ingestion and inhalation which are related to air, water and food (Kelly and Fussell, 2020). The atmospheric pathways of MNPs are direct inhalation and dust settling on food. According to existing studies, the principal type of MNPs differed from location and the dominant shape of MNPs was fibre and fragment. The atmospheric deposition rate was between 575 and 1008 particles m^{-2} day^{-1} in central London (Wright et al., 2020). In a dense urban site in Paris, the average atmospheric fallout of MNPs was between 14 and 206 particles m^{-2} day^{-1} (Dris et al., 2016). As well as outdoor air, MNPs are existing in the indoor air (Gaston et al., 2020). In an Australian indoor MNPs study, they observed that MNP concentration in a childcare site was 2.25 ± 0.38 particles m^{-3}, in an office was 1.20 ± 0.14 particles m^{-3}, in a school was 1.03 ± 0.40 particles m^{-3} and inside a vehicle was 0.20 ± 0.14 particles m^{-3} (Perera et al., 2023).

Micro-/nanoplastics also have been reported in drinking water (i.e., tap water and bottled water). The concentration of MNPs is varied by origin of water, manufactured place, and analysis methods but generally, bottled water has higher concentrations of MNPs than tap water. The reported concentration of MNPs in tap water was between 0 and 628 particles L^{-1} while bottle water was between 0 and 4889 particles L^{-1} (Danopoulos et al., 2020). In an Australian bottled water study, it was noted that the concentration of MNPs ranged from 0 to 80 particles L^{-1} and annual consumption of MNPs by bottled water was expected around 400 particles $year^{-1}$ (Samandra et al., 2022).

Seafood is not the only pathway of MNP ingestion via oral intaking. Micro-/nanoplastics have been reported in sugar, sea salt, honey, milk, beer and other beverages (Diaz-Basantes et al., 2020; Iñiguez et al., 2017; Li et al., 2022b). However, the quantification methods of MNP consumption via food is challenging since there is a lack of analytical methods in various food matrices and also alteration of MNPs contents by processing and cooking (Kwon et al., 2020). One study investigated the concentration of MNPs in store-bought rice in Australia, reporting 30 to 40 mg kg^{-1}. They mentioned that MNP concentration lowered after washing and cooking which reflects MNPs may be originated from industrial processing, not from rice itself (Dessì et al., 2021). There is no study on the total concentration of MNPs in the plants though some studies reported strong evidence of soil and water pollution by MNPs (World Health Organization, 2022). In the case of vegetables, people may intake MNPs through vegetables such as lettuce in a salad which can uptake MNPs from soils or waters (Li et al., 2020a).

The potential bioaccumulation of MNPs in the human body has various mechanisms such as particle, chemical and microbial effects. The toxicity of MNPs depends on the type, size, shape, hydrophobicity and surface charge. Chemicals are a serious concern as they have infamous impacts on human health and even reproduction: incorporated

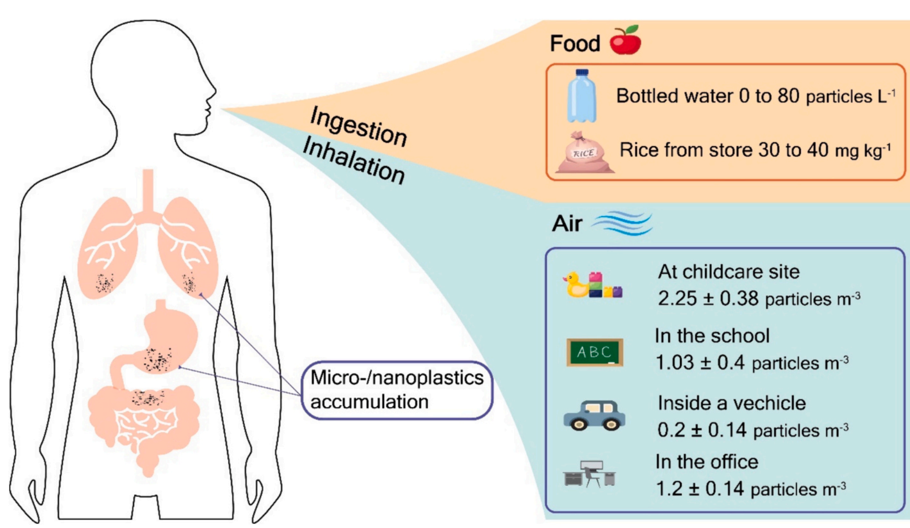

Fig. 6. The estimated amount of micro-/nanoplastics in air, food and water from Australian studies (Data adapted from (Dessì et al., 2021; Perera et al., 2023; Samandra et al., 2022)).

additives and plasticizers; absorbed materials from surrounding environments; adsorbed heavy metals (Lithner et al., 2011).

Epidemiological data shows the adverse effects of synthetic fibre (i.e., nylon) and plastic dust (i.e., PVC and polyurethane) by inhalation such as macrophages, frustrated phagocytosis, decreased lung function and lung cancer (Lilis et al., 1976; Soutar et al., 1980). Several studies found that PS MNPs adversely affected the digestive, hepatic, renal, thyroid, cardiac and reproductive systems of rodents (Carr et al., 2012; Driscoll et al., 2000). However, most studies used the homogenous shape of PS MNPs which is not comparable to reality (World Health Organization, 2022). Additionally, MNPs are often mixed with other chemicals such as persistent organic pollutants (e.g., dioxins and polycyclic aromatic hydrocarbons), and heavy metals. It was noted that gastric solution leached organic compounds on the surface of MNPs which can affect the digestive system (Li et al., 2022a). It is still inconclusive whether MNPs can affect the gastrointestinal tract or other organs due to limited studies. Nonetheless, the potential harmful impacts of MNPs should be monitored and continually investigated for accurate characterizing and quantifying in human health risks assessment.

5. Challenges in removal of MNPs in soils

There are no effective removal methods for MNPs in the natural environment (Yin et al., 2021). Separation of MNPs in soils is a significant challenge due to the complex soil matrix, nearly random patterns of MNP accumulation in soils and a lack of comprehensive understanding of MNPs in the soil (Wang et al., 2020c). Moreover, removal strategies are required to be uncontroversial to soil health, including soil organisms. Soil organisms can eliminate MNPs in soils, but their efficiency and sustainability are questionable. Biodegradable materials may have negative impacts on soils and plants while their performance and cost are still behind conventional plastic materials. As a single strategy is not effective, a combination of different strategies can be an optimal solution to remove MNPs in soil (Fig. 7).

5.1. Prevention

One of the strategies is filtration using a membrane bioreactor and rapid sand filtration with up to 98.3 % MNP removal efficiency (Bayo et al., 2020). These technologies are particularly designed for wastewater facilities and cannot apply to MNPs in soils. However, they can help to reduce MNPs in the biosolid and sewage sludge, decreasing MNP application into agricultural land. Electrocoagulation is another technology to remove MNPs in wastewater facilities, improving filtration efficiency through existing systems (Shen et al., 2022). This technique is useful for water and air since those environments can focus only on removal. In a soil environment, coagulation and removal processes are nearly impossible due to MNPs attached to soil particles and the surface of roots.

On the other hand, some approaches to MP removal in a water environment may be applied to the soil. One study noted that giant clams can remove MNPs by ingestion and adhesion with an efficiency of over 60 % from the water column (Arossa et al., 2019). It may have undefined side effects on giant clams but this concept of bioremediation with non-edible food can apply to MNP removal in soils.

5.2. Degradation by soil fauna

Plastic degradation has been investigated with various terrestrial invertebrates such as earthworms, waxworms and mealworms. Waxworms can chew and eat PE films and their gut can degrade PE (Yang et al., 2014). It was also found that mealworms can degrade PS or Styrofoam in their gut (Yang et al., 2015). The mealworm gut can degrade even mixed plastics (i.e., PE and PS) (Brandon et al., 2018). Thus, a bioremediation method may be promising to remove MNPs in the soil. However, there are differences in environmental conditions and purposes of application between plastic degradation in the specific environment and removal of MNPs in the soil. Moreover, waxworms and mealworms are not well adapted to the soil environment as they are relatively sensitive to moisture and temperature (Yong et al., 2022).

Earthworms are strong candidates in engineering soil structure, nutrient cycling and pollution remediation (Peng et al., 2020). Yet some studies indicated that MNPs negatively affected the survival and fitness of earthworms (Cao et al., 2022; Huerta Lwanga et al., 2016). One recent study reported that earthworms improved soil properties and promoted microbial activities in MNPs (i.e., PE and PVC) contaminated soils (Li et al., 2023c). They found MNPs in earthworm casts which indirectly confirms the ingestion and degradation of MNPs in the soil though they

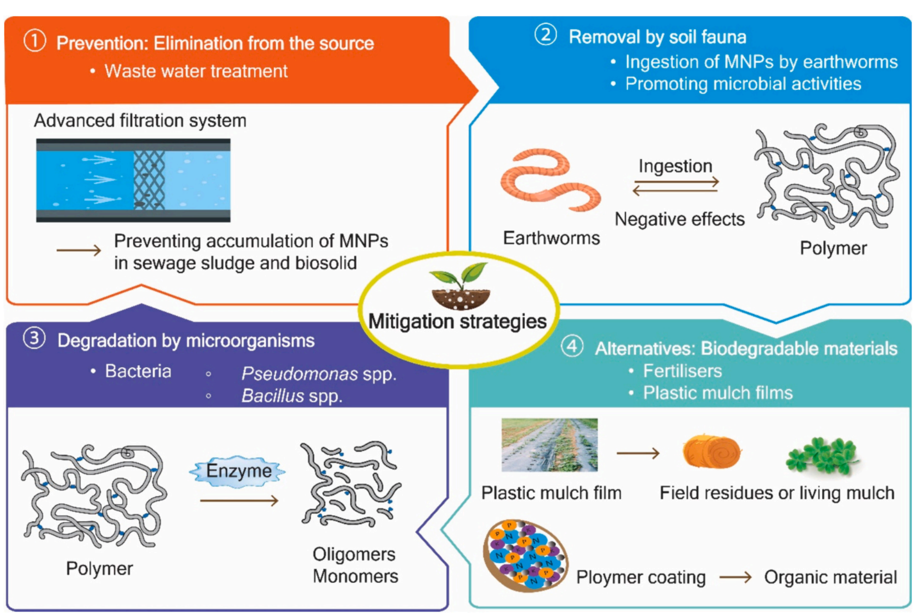

Fig. 7. Potential mitigation strategies to remove MNPs in soil based on current studies. Replacing to bio-degradable materials is applicable in fertilizer and mulch film. Degradation by microorganisms and removal by soil fauna are ecofriendly approaches to degrade or remove MNPs in the soil. Elimination from sources is related to wastewater facilities, a preventing strategy of MNPs before entering soils.

did not report the concentration of MNP alteration by earthworms. Bioremediation of MNPs in the soil by earthworm may be a promising strategy yet it still needs to be examined in many perspectives. The removal efficiency of MNPs would be a priority criterion in this bioremediation strategy. The improved removal rate may be expected under cooperation with another soil fauna for the comprehensive degradation of MNPs. Further, sustainable bioremediation requires a healthy earthworm life cycle and precise investigation under realistic conditions such as actual sizes, doses and types of MNPs in the field and field scale investigation.

5.3. Degradation by microorganisms

Degradation of plastics by microbes has been studied with many species and types of plastic since several species of microorganisms can consume paraffin as their carbon source (Kale et al., 2015). Bacteria in the gut of soil fauna can produce enzymes to degrade plastics. In LDPE and HDPE degradation, *Pseudomonas* spp. and *Bacillus* spp. were reported to be the most studied bacteria species, showing in high efficiency (Muhonja et al., 2018). Fungi species such as *Aspergillus* spp. and *Fusarium* spp. also have been reported to give relatively high efficiency in PE degrading (Das and Kumar, 2014).

Gram-positive bacteria from earthworm's guts were reported to degrade PE MNPs in the soil within 4 weeks: 60 % of reduction in weight of PE MNPs in the soil (Lwanga et al., 2018). The reduction in weight does not necessarily reflect the removal rate of MNPs. It is debatable that increased smaller-sized MNPs have a positive effect on fast degradation while smaller-sized MNPs have a more adverse effect on soils and plants. Nanoparticles and several volatile compounds along with the size reduction of MNPs were observed. Nanoplastics are necessary constituents in the degradation of MNPs as well as several volatile compounds (Kyaw et al., 2012). The effect of NPs and volatile compounds during microbial degradation of MNPs stays largely unexplored yet they may have negative impacts on soil organisms and plants. The mitigation strategy by soil microorganisms requires a relatively long period and optimum conditions such as soil moisture and soil temperature. Moreover, Gram-positive bacteria may have a negative influence on plants (Francis et al., 2010). Several bacteria strains were investigated while there was no fungal strain study in the biodegradation of MNPs in the soil (Yuan et al., 2020). Mitigation strategy by soil microorganisms requires a relatively long period and optimum conditions such as soil moisture and soil temperature. Those optimum conditions may conflict with crop growth conditions. Moreover, selected bacteria may have a negative influence on plants. Thus, mitigation of MNPs in agricultural soil requires a more investigation into the microbes-soil-plant relationship. Actual field conditions should also be included for the feasibility and measurement of the actual capacity of MNP removal and stability of microorganisms.

5.4. Replacing with alternatives

For agricultural soils, a replacing strategy can be applied to fertilizers, plastic mulch film, packaging, and small utilities. Replacing with alternatives not only means changing materials, but also suggests modifying processes in agricultural practices. Plastic mulch film is one of the niche applications which requires specific standards for biodegrading as they are often left in soils (Dominish et al., 2023). Plastic mulch film can be replaced by living mulch (e.g., white clover) (Deguchi et al., 2017); agricultural waste mulch (e.g., straw) (Akhtar et al., 2018); biodegradable-bioplastics (Xiong et al., 2018).

The ideal biodegradable-bioplastics would have satisfied the performance with a strength and durability, controlled biodegradable period and complete biodegradation into the carbon cycle. However, there are still issues as compared to conventional plastic films such as tensile strength, flexibility and faster degradation under natural conditions. Moreover, biodegradable-bioplastics may release more MNPs during their biodegradation processes. Additionally, those secondary MNPs mostly ranged between 1 and 50 μm which is the size of MNP internalization (i.e., < 2 μm) (Li et al., 2020a). Several studies reported the negative effects of biodegradable bioplastics. In the lettuce and tomato study, extracts of bioplastic (i.e., Mater-Bi) inhibited the growth of lettuce root and tomato plants with increased proline contents (Serrano-Ruíz et al., 2018).

The negative impacts of biodegradable bioplastics are still inconclusive due to a lack of evidence. Besides, biodegradable bioplastics alter the communities of soil microorganisms which may affect biodegrading capacity of soil environment. For a sustainable agroecosystem, biodegradable bioplastic needs innovative technology with eco-friendly materials which can substitute additives and plasticizers. The potential risk of forming more MNPs may be solved by adopting other strategies such as consumption by earthworms or non-edible plants since fragmentation is an unavoidable process in biodegrading.

5.5. Additional strategies

Photocatalytic degradation is the process that degrades plastic particles through catalytic reactions until they become CO_2 and H_2O (Zhao et al., 2007; Uheida et al., 2021). This strategy is still evolving toward utilizing green materials such as extrapallial fluid of fresh blue mussels (Ariza-Tarazona et al., 2019). However, MNPs in soils have critical conditions to apply photocatalytic degradation: effective sunshine cannot reach inside the soil layers; MNPs are protected by soil particles from lights; application of chemicals may cause another issue in the soil. It needs additional physical processes for photocatalytic reactions while the physical technique may especially be inefficient for MNPs in the soil.

The ferromagnetic-biochar (i.e., Fe_3O_4-biochar) layer prevented over 90 % of the percolation of MNPs by water and 74 % of ferromagnetic-biochar was recovered by a magnet (Tong et al., 2020). Ferromagnetic-biochar also contributes to the separation of metals on the surface of MNPs and in the soils (Ye et al., 2020). However, the installation of ferromagnet-biochar is a challenge in MNPs-contaminated soil. Further, field conditions may cause different results regarding the interaction between ferromagnetic-biochar and the clay content, soil organisms. Biochar was reported to promote the growth of microbes such as *Pseudomonas* spp. as the most effective bacteria to biodegrade PE (Qi et al., 2021). Thus, the combined mitigation strategy of soil microorganisms and soil amendment may have great potential to eliminate MNPs in the soil.

6. Conclusion

The presence of MNPs in soil threatens soil environments as well as plants. Accumulation of MNPs in soil will keep increasing as the degradation of plastics is an extremely slow process. MNPs in the soil causes alterations in soil properties. Despite considerable studies of MNPs' impact on soils, there is still a lack of understanding and clear conclusions due to the complexity of soil environments. Moreover, contrasted results on MNP impact on plant growth may make it difficult to predict the consequences of MNPs in the soil-plant environment. Considering the high potential for negative impacts of MNPs on plants and the food web, particular attention is required to MNPs in agricultural soils. However, there are no efficient and distinguished strategies to eliminate MNPs from soils and more reliable investigations on MNPs in the soil are required for comprehensive understanding and development of MNPs-free soil system.

7. Future perspectives

This paper highlights the current knowledge on alterations of soil properties by MNPs, potential impacts of MNPs on higher plants and existing mitigation strategies to remove MNPs from soils. The following research directions are recommended for future in-depth-study on MNPs in soil:

1) The sustainability of biodegradable plastic MNPs is an urgent issue that needs to be investigated. Micro-/nanoplastics in the biosolid can be removed during the wastewater treatment processes. Considerable efforts have been dedicated to wastewater treatment technologies to remove MNPs yet more efforts are needed to develop highly efficient and cost-effective technologies to apply for the removal of MNPs in soil systems.
2) The interaction between MNPs and soil aggregates stability is one of the priorities that to be comprehensively investigated which is related to soil carbon pool alteration and soil microbial community. As water is an important factor in agricultural production, monitoring of MNP concentration and changes in soil-water dynamics is another priority for sustainable agricultural management and production.
3) Micro-/nanoplastics have been considered a stress factor in soil-plant systems, but the synergetic consequences of MNPs and abiotic stresses have not been studied well. Some of the direct factors such as soil pH and soil nutrient contents were investigated yet empirical evidence is not enough to conclude.
4) Soil leaching is a serious issue in agricultural production and surrounding environments and extreme climate events such as flooding have accelerated soil-leaching issues. More studies are required to address the impacts of MNPs on agricultural soil leaching under the improved characterizations of MNPs which reflects real field situations.
5) More studies are required to comprehensive understanding of MNP adsorption by plants. Particularly, underground growing crops such as potatoes and carrots are concerning as they would have more opportunities to contact MNPs.
6) The effect of MNPs on crop yield and productivity is most likely negative but it is still controversial. In fact, many studies only used PS MNPs (pellet products) in the experiment which may not represent genuine field circumstances. Thus, studies should consider their targeting field conditions including types, sizes, doses, shapes and exposure time of MNPs.
7) Pesticides may interact with MNPs, yet studies could not prove any absorbance or interactions between them and MNPs. The interaction between glyphosate and MNPs should be studied with more types of MNPs including aged MNPs (i.e., smaller size and rougher surface). Additionally, MNPs in soil may contribute to the stabilization of applied chemicals in the soil.
8) A combination of different approaches to removing MNPs in soils (e.g., soil organisms and sustainable amendment) may have the potential to eliminate and degrade MNPs. However, all previous studies were conducted under laboratory conditions. Thus, a field scale study is required to evaluate the actual capacity of alleviating MNP contamination in soil.
9) The plastic mulch film is beneficial in many ways such as water, weed and temperature control in horticulture production. These benefits are limiting the adoption of alternative practices in improving water quality (i.e., fewer MNPs in water) in the long term. Therefore, the economic and the environmental assessments of MNPs from the plastic mulch film are required to evaluate actual benefits or impacts on the agroecosystem.

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CRediT authorship contribution statement

Yoonjung Seo: Writing – original draft, Visualization, Conceptualization. **Zhezhe Zhou:** Writing – original draft, Methodology. **Yunru Lai:** Writing – review & editing, Supervision, Conceptualization. **Guangnan Chen:** Writing – review & editing, Supervision, Conceptualization. **Keith Pembleton:** Writing – review & editing. **Shaobin Wang:** Writing – review & editing, Investigation. **Ji-zheng He:** Writing – review & editing. **Pingan Song:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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