Plant Cell Reports (2024) 43:65
https://doi.org/10.1007/s00299-024-03162-6

REVIEW

Microplastic contamination in the agricultural soil—mitigation strategies, heavy metals contamination, and impact on human health: a review

Muhammad Tariq[1] · Babar Iqbal[1,2] · Ismail Khan[1] · Ali Raza Khan[1] · Eun Hea Jho[3] · Abdul Salam[4] · Huan Zhou[1,5] · Xin Zhao[6] · Guanlin Li[1,2] · Daolin Du[7]

Received: 14 December 2023 / Accepted: 17 January 2024 / Published online: 10 February 2024

Abstract
Microplastic pollution has emerged as a critical global environmental issue due to its widespread distribution, persistence, and potential adverse effects on ecosystems and human health. Although research on microplastic pollution in aquatic environments has gained significant attention. However, a limited literature has summarized the impacts of microplastic pollution the agricultural land and human health. Therefore, In the current review, we have discussed how microplastic(s) affect the microorganisms by ingesting the microplastic present in the soil, alternatively affecting the belowground biotic and abiotic components, which further elucidates the negative effects on the above-ground properties of the crops. In addition, the consumption of these crops in the food chain revealed a potential risk to human health throughout the food chain. Moreover, microplastic pollution has the potential to induce a negative impact on agricultural production and food security by altering the physiochemical properties of the soil, microbial population, nutrient cycling, and plant growth and development. Therefore, we discussed in detail the potential hazards caused by microplastic contamination in the soil and through the consumption of food and water by humans in daily intake. Furthermore, further study is urgently required to comprehend how microplastic pollution negatively affects terrestrial ecosystems, particularly agroecosystems which drastically reduces the productivity of the crops. Our review highlights the urgent need for greater awareness, policy interventions, and technological solutions to address the emerging threat of microplastic pollution in soil and plant systems and mitigation strategies to overcome its potential impacts on human health. Based on existing studies, we have pointed out the research gaps and proposed different directions for future research.

Communicated by Anis Ali Shah.

✉ Babar Iqbal
babar@ujs.edu.cn

✉ Guanlin Li
liguanlin@ujs.edu.cn

✉ Daolin Du
ddl@ujs.edu.cn

1 School of Environment and Safety Engineering, School of Emergency Management, Jiangsu Province Engineering Research Centre of Green Technology and Contingency Management for Emerging Pollutants, Jiangsu University, Zhenjiang 212013, People's Republic of China

2 Jiangsu Collaborative Innovation Centre of Technology and Material of Water Treatment, Suzhou University of Science and Technology, Suzhou 215009, People's Republic of China

3 Department of Agricultural and Biological Chemistry, Chonnam National University, Gwangju 61186, Republic of Korea

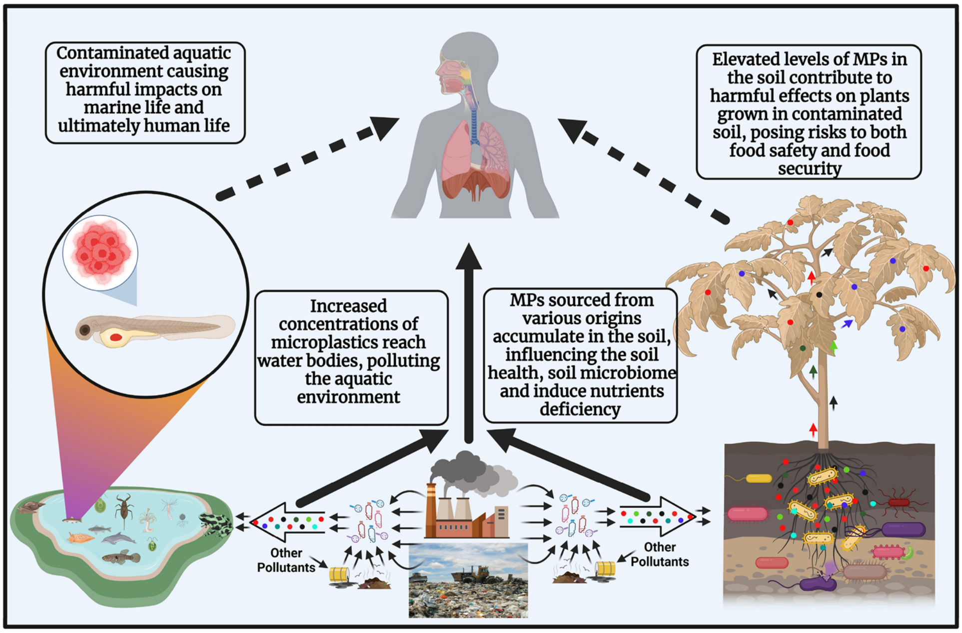
4 Key Laboratory of Natural Pesticide and Chemical Biology of the Ministry of Education, South China Agricultural University, Guangzhou 510642, People's Republic of China

5 Zhenjiang New District Environmental Monitoring Station Co. Ltd, Zhenjiang 212132, People's Republic of China

6 Department of Civil and Environmental Engineering, College of Engineering, Seoul National University, Seoul 08826, Republic of Korea

7 Jingjiang College, Institute of Environment and Ecology, School of Emergency Management, School of Environment and Safety Engineering, School of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, People's Republic of China

Graphical Abstract



Keywords Emerging contaminants · Agricultural soil health · Soil–microorganism–plant interaction · Crops · Food security

Introduction

The presence of microplastic in the environment has become a global concern, as it can negatively impact agroecosystems and human health (Iqbal et al. 2023a). However, microplastic can be ingested by marine organisms, causing physical harm, ingestion of toxic substances, and ultimately the transfer of these contaminants up the food chain (Huang et al. 2021). There is also growing evidence that humans may be exposed to microplastics through the consumption of contaminated seafood or drinking water (Torre 2020). Several studies have highlighted the increasing prevalence of microplastic in different parts of the world, including freshwater systems (Blackburn and Green 2022), urban environments (Li et al. 2021), and remote wilderness areas (Abbasi and Turner 2021). Thus, microplastic contamination in the soil affects the development and diversity of soil microorganisms, which in turn harms plant health (de Souza Machado et al. 2019). In addition, microplastic obstructs the movement of soil microbes, limits their access to nutrients, and stops them from interacting with plant roots (Wang et al. 2024). Intake of nutrients is also decreased by microplastic because they disrupt the advantageous interactions between fungi and plants (Liu et al. 2022; Bai et al. 2024). To date, there is still much to learn about the ecological and health effects of microplastics and more research is needed to develop effective management strategies regarding the soil microorganisms that drastically impact the growth and productivity of the crops (Zhang et al. 2020a; Khalid et al. 2021).

The particles whose diameter is smaller than 5 mm are regarded as microplastic that are further defined by the National Oceanic and Atmospheric Administration (NOAA) as small pieces of plastic that are no more than 5 mm long that can harm our coastal and aquatic resources (Gigault et al. 2021; NOAA 2023). These particles can come from various sources, such as due to the breakdown of larger plastic items, the shedding of microfibers from textiles during washing, and the abrasion of plastic materials in the environment (Lee et al. 2022; Iqbal et al. 2023a). Primary microplastics, such as blasting with an agent, products for personal care, and industrial cleaning agents, are consciously produced at a tiny size for their particular uses and mainly include polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Galafassi et al. 2019; Ali et al. 2024). However, Secondary microplastic arises due to the breakdown of more oversized plastic products through weathering, fragmentation, and degradation processes and originates from various sources such as textiles, rubber tires, fishing gear, and plastic packaging (Chen et al. 2024a; Zeb et al. 2024). Moreover, recent studies have identified other types of microplastic in the environmental samples, including polyethylene terephthalate (PET), polyamide (PA), and polyvinyl chloride (PVC) which conclusively impact the below and above-ground changes and thus decline the productivity of the crops and affect human health (Nava and Leoni 2021; Khan et al. 2023; Shi et al. 2023a, b).

Thus, the current review paper critically evaluates the implications of microplastic pollution on the belowground and above-ground ecosystems, its mitigation strategies, and its amplification on human health. This includes a comprehensive study of the distribution and persistence of microplastics in the environment, mitigation strategies, and the potential pathways through which they may impact soil microorganisms, soil properties, and plant growth and productivity, which subsequently affect the human body and health.

To lessen the damaging impacts of microplastic pollution on the natural world and human health, this review attempts to consolidate the existing level of knowledge on the subject, identify knowledge gaps, and suggest future research approaches. The objectives of the current study are (1) to evaluate the scope and sources of microplastic contamination in the soil ecosystems and its possible effects on the soil microorganisms, including modifications in the physical, chemical, and biological characteristics of the soil as well as the nutrient cycling and microbial population; (2) to assess how microplastic pollution affects soil microorganisms by impacting the plant growth and development, including how they are absorbed by plants, changes to their morphology and physiological characteristics, and their possible impact on crop productivity and food security; (3) study the routes through which people come into contact with microplastic in the soil, such as ingesting contaminated soil through breathing and in the food chain, and determine the possible health impacts; (4) to identify gaps in current knowledge and research needs in soil environments and their counter effect on crop growth, development, and productivity; (5) the assessment of the long-term environmental and health impacts and the development of effective mitigation strategies to reduce microplastic contamination in the soil and its effects on the crops.

Contamination of the agricultural ecosystem

Microplastics can enter agricultural ecosystems through various routes, including irrigation, fertilization, and land application of biosolids and composts (Lwanga et al. 2022). Irrigation with contaminated water sources, such as rivers and lakes, can introduce these particles into agronomic soils by contaminating the cropland (Liu et al. 2023; Iqbal et al. 2023b). Thus, microplastic can enter agricultural fields through the use of recycled water and wastewater, which are often used for irrigation in areas with water scarcity. Fertilization with sewage sludge, biosolids, and other organic amendments containing these particles can lead to their accumulation in agricultural soils (Iqbal et al. 2023b). Additionally, the use of plastic mulch film in agriculture fields may potentially contribute to microplastic contamination (Huang et al. 2020). These films are applied to soil to raise soil temperature, keep moisture in the soil, and prevent weed development (Prem et al. 2020; Tang et al. 2023a, b), but they can also break down over time, releasing microplastic into the soil where they might linger for a long period and damage the fertility and health of the soil (Yang et al. 2022). In addition, microplastic can also enter agricultural ecosystems by using composts and manure derived from animal production (Zhang et al. 2020a). These organic amendments are the carriers of microplastic that negatively impact the productivity of the crops (Porterfield et al. 2022; Iqbal et al. 2023a). Once microplastics enter agricultural ecosystems and can accumulate in soil and water, potentially leading to their ingestion by plants and soil-dwelling organisms (Tang et al. 2023a, b). It can also affect soil structure, physicochemical properties, nutrient availability, and water-holding capacity, negatively impacting crop growth and yield (Boots et al. 2019; De Souza Machado et al. 2019; Khalid et al. 2020; Liu et al. 2022).

Soil micro-organisms and feedback mechanism in the crops

Biotic components present in the soil play a critical role in the cycling of nutrient contents and keep them balanced inside the soil particles (Iqbal et al. 2023c). Thus, the soil pollutants especially microplastics and other heavy metals contamination which interact with each other in the soil can also have significant impacts on the soil microorganisms, which are crucial for maintaining soil health and ecosystem functioning (Iqbal et al. 2023b; Schmid and Schöb 2023). A thorough review of the effects of microplastic on the soil microorganisms and their roles has an impact on the abundance and activity of soil microorganisms as well as their function in soil nutrient cycling and organic matter decomposition (Sun et al. 2022; Li et al. 2023a, b, c). Relying on the microbial species and soil characteristics, different microplastics have different effects on soil microbial communities. Microorganisms may quickly adhere to and inhibit microplastic with a large surface area and significant roughness, which may hinder their evolution by forming dynamic biofilms and developing special microbial communities (Qiu et al. 2022; Zeb et al. 2024).

By changing their environment, microplastics can indirectly affect the composition and function of microbial communities (Khalid et al. 2020). They can interact with the soil matrix to create water transportation pathways that speed up soil water evaporation (Iqbal et al. 2023c). This process results in the soil surface drying up and cracking, which alters the soil's oxygen flow and alters its distribution of aerobic microbes. As a result, microplastic could also be ingested by large soil organisms like nematodes and earthworms by changing the microbial ecology (Wan et al. 2019; Rong et al. 2021). Furthermore, the diversity, evenness, and richness of soil microbial populations were all dramatically changed by polypropylene fibers (Huang et al. 2021). On the other hand, adding PE initially had little impact on the variety of soil microorganisms, but after a culture period, bacterial aggregates with distinctive community structures (Huang et al. 2022).

Thus, the potential effects of microplastic exposure revealed a greater change in the soil microbial communities and ecosystem functioning (Rong et al. 2021). Soil microbial diversity, abundance, and activity, as well as their role in soil nutrient cycling and organic matter decomposition at different levels of CO_2 affected due to microplastic contamination (Zhu et al. 2022; Buzhdygan and Petermann 2023; Li et al. 2023a). Similarly, microplastics can alter the structure and function of soil microbial communities, potentially leading to cascading effects on soil health and ecosystem functioning (Huang et al. 2022). Microplastics negatively affect the soil microbial communities in the rhizosphere of lettuce plants and significantly alter the soil microbial community, reducing the abundance and diversity of bacteria and fungi (Rong et al. 2021). Similarly, microplastics significantly reduced the diversity and abundance of microbial communities, which could impact soil nutrient cycling and plant growth of lettuce crops (Zhuang et al. 2023). Conclusively, we found that microplastics significantly altered the microbial community composition and reduced soil enzyme activities, which could impact plant growth and nutrient cycling (Fig. 1).

Overall, these reviews suggest that microplastic can have significant impacts on soil microorganisms, potentially leading to disruptions in soil nutrient cycling, organic matter decomposition, and ecosystem functioning.

Impacts on the soil properties and characteristics

The soil properties mainly include the soil structure, porosity, pH, microbial community, bulk density, and enzymatic activities, which are strongly affected by the pollutants present in the soil (Wan et al. 2019; Yu et al. 2020; Zhang et al. 2020a; Nazir et al. 2024). Thus, microplastic is considered the major pollutant nowadays, which is mainly composed of carbon contents, and negatively affects the soil properties and functioning (Yu et al. 2020). Moreover, previous researchers reported that microplastics could negatively affect soil structure, soil organic matter, soil nutrient availability, as well as microbial activities (De Souza Machado et al. 2019; Iqbal et al. 2023b; Shi et al. 2023a, b). Additionally, microplastic present in the soil adhere to the root surface through mucilage present and can penetrate through the root structure, move through the xylem inside the plant, and interfere with plant growth, including stunted root growth, changes in nutrient uptake, and alterations in the physiological properties of the plants (Li et al. 2020a; Kumar et al. 2022).

Microplastics have been discovered to have an impact on soil porosity, which can therefore affect the soil's ability to hold water and nutrients for plants, as well as the structure of

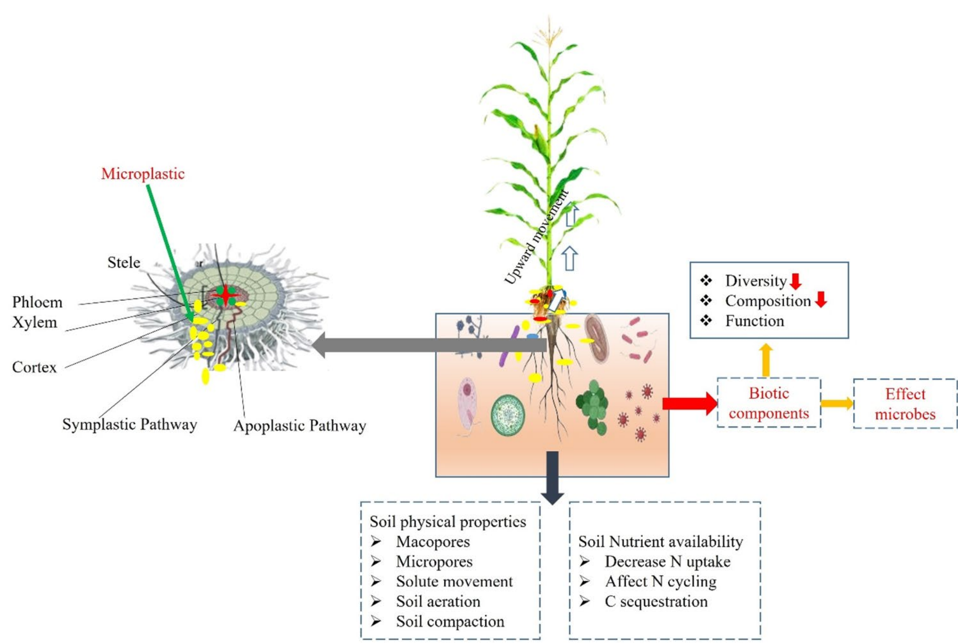


Fig. 1 Schematic diagram of microplastic contamination in the soil by penetrating the root and negatively affecting the biotic and abiotic components in the soil, especially soil microorganisms by interacting with the plant community

the soil, however, it creates soil cracks, which can increase soil porosity (Wan et al. 2019; Zhang et al. 2019; Iqbal et al. 2023a). In addition, bulk density is regarded as a significant indicator of soil health that influences the aeration of the soil, soil structure, soil compaction, and water and solute transport (Ingraffia et al. 2022; Brooker et al. 2023; Zeb et al. 2024). The hydrodynamic and agricultural ecosystem processes of soil are also connected to the bulk density of the soil, which affects crop productivity (Lu et al. 2019). Soil contamination with polyester microplastic did not significantly affect soil bulk density; however, it mainly affects the soil biogeochemical cycle and nutrient availability to the crops (Bosker et al. 2019; Zhang et al. 2019). In addition, a prior study showed that changes in soil bulk density were mainly affected due to the shape, size, and relative density of the microplastic contamination in the soil (Lozano et al. 2021; Sajjad et al. 2022; Zeb et al. 2024). As a result, the concentration of microplastic smaller than 100 µm is determined by the amount of sand, silt, and clay in the soil, all of which have a detrimental impact on the physicochemical characteristics of the soil (Liu et al. 2023). Similarly, higher silt and clay content leads to lower porosity, inhibiting the migration of microplastic into deeper soil layers, and resulting in the accumulation of microplastic in the smaller soil pores (Liu et al. 2023). Conversely, soils with higher sand content and greater porosity have lower water and fertilizer retention capacity, allowing microplastic to migrate vertically in the sandier soil layer, leading to a negative correlation between sand content and microplastic abundance (Liu et al. 2023; Ran et al. 2023). Microplastic contamination impacts the physical, chemical, and biological properties of the soil thus impacting plant growth and productivity (Lozano et al. 2021; Ali et al. 2024). Similarly, microplastic contamination in the soil negatively affects plant growth, including changes in the antioxidant enzyme activity, reactive oxygen species, and proteomics profiling by affecting the final yield of the crop (Boots et al. 2019; Li et al. 2022; Iqbal et al. 2023a, b; Iqbal et al. 2024).

Impacts on the soil nutrients availability

The nutrients are the significant growth limiting factor which mainly includes nitrogen (N), phosphorus (P), potassium (K), and other micronutrients. These nutrients are beneficial for the development and growth of crops. Thus, microplastic interacts with the soil organic matter which releases nutrients in the soil, and sometimes toxic materials are also released from the surface of microplastic which negatively affects the crops (Li et al. 2023b; Zhou et al. 2023). Moreover, microplastic influences the nutrient contents present in the soil by releasing more carbon thus strongly impacting the organic matter cycling and contents in the belowground ecosystem (Shen et al. 2023). The microplastics' interactions with nutrients, however, rely on the shape, polymer structure, degradation, additives, and concentration of the microplastic as well as their location (Lozano et al. 2021). Previous researchers found that dissolved organic P and dissolved organic N increase with PP at 7% w/w but total N, total N, and K decrease with PE at 28% w/w in soil (Yu et al. 2020). In addition to this, the concentration of NO_3-N and NO_2-N increased with the addition of microplastic by changing the N cycling irrespective of their shape and type (Chen et al. 2022). Despite this, the addition of microplastic decreased the concentration of NH_4 contents in the soil which is mainly dependent on the soil water availability (Ma et al. 2022a, b). The leachate of NO_3−N under drought conditions is higher than under non-drought conditions, but the addition of microplastic to the soil decreases the leachate of nutrients (Lozano et al. 2021). In addition, the degradation of microplastic by microbes and enzymes is determined by their internal bonds, which release greater carbon contents (Rillig 2018). Similarly, phosphates are more strongly bound to soil particles than nitrate and sulfates and therefore not affected by drought conditions in the soil (Lozano et al. 2021).

The adsorption capacity of zinc is increased by the number of microplastic particles and the rise in organic matter contents, which also improves the availability of zinc to the plants in the soils (Holden et al. 2017). Alternately, worn microplastic particles also boost soil's adsorption capabilities for its total organic carbon, calcium, copper, and chloride contents. However, they impair the desorption of heavy metals and cause them to release more of them into the soil (Holden et al. 2017; Yu et al. 2020; Iqbal et al. 2023c). As a result, the heavy metals in the soil have a stronger affinity for the worn microplastic particles, which unintentionally depletes minerals and affects the above-ground population (Yu et al. 2020).

The size of microplastic has a great influence on the adsorption of moisture contents from the soil and alternately affects the accumulation and uptake of nutrients in the plant's body which diminishes crop growth and yield (Wu et al. 2021; Iqbal et al. 2023a). The size of the microplastic plays a significant role in how the physical, chemical, and biological aspects of the soil interact with the crops, either favorably or unfavorably impacting crop yield and productivity (De Souza Machado et al. 2019; Chen et al. 2024b). Larger surface areas of smaller microplastics make them better carriers of other pollutants including heavy metals and persistent organic pollutants (Xiang et al. 2022). In addition, the cells absorbed polystyrene beads of tiny sizes, but not the larger ones, which sealed the pores in the cell wall (Jiang et al. 2019; Li et al. 2019). Furthermore, PS beads up to 0.2 mm in size penetrate cell walls and persist in cortical tissues and the vascular system, while large-sized microplastics attached to the surface of the root but were unable to penetrate the body of the plant due to the permeability of the cell wall (Jiang et al. 2019; Wu et al. 2021). Since it is widely believed that microplastic fibers and films may have more significant impacts on soil particles than microplastic beads and spheres (Wang et al. 2022). However, microplastic fibers increase the soil's capacity to retain the nutrients present in the soil and make them available to the plants for better growth and productivity (Liu et al. 2023). The accumulation and translocation of microplastic also depend on the charge on its body (Wu et al. 2021). Thus, microplastic with a positive charge can pass easily through cell membranes due to the oppositely charged characteristic of plants, and therefore it can accumulate more in plants than negatively charged particles (Sun et al. 2020).

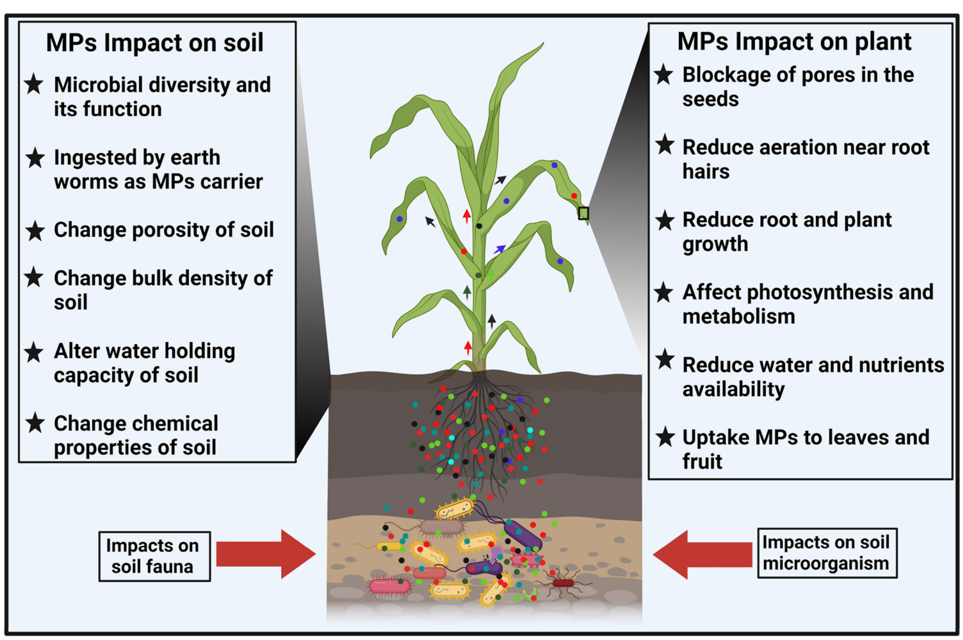
Mechanisms inside the plants

There are several mechanisms through which microplastic can penetrate plant roots and move inside the plant body. The most common way through which it enters the roots is through root root hair; there are two main pathways through which it penetrates the root hairs, (1) the apoplastic pathway, and (2) the symplastic pathway (Ruiz et al. 2020). The apoplastic pathway is the pathway that refers to the movement of water and dissolved substances outside the cells (Liu et al. 2020). The symplastic pathway involves the transport of water and dissolved substances through the cytoplasm of cells via plasmodesmata. Thus, we briefly discussed the movement of microplastic inside the soil and penetrating the root hairs which further move it through the plant body through xylem sap (Fig. 1).

Negative effect on the belowground plant parts

The plant belowground part i.e., roots play an important role in nutrient absorption, water movement inside the crop body, and interaction with various organelles to fix nitrogen and other nutrients to fulfill the needs of the crop for better productivity (Lynch et al. 2021). However, the sticking of various pollutants present in the soil to the root system negatively affected crop growth and productivity (Fig. 2). Therefore, the microplastic clings on the surface of the root due to the secretion of root mucilage, adhesive capacity, large specific surface area, and finally uptake by the roots (Wu et al. 2021). Thus, microplastic of submicron size penetrates the roots of plants and then transfers to the aboveground parts with the flow of water and nutrients (Li et al. 2020b). Endocytosis, apoplastic processes, and crack entry mode are the primary mechanisms for the absorption and accumulation of microplastics (Li et al. 2020b). Small-size microplastic-like nanobeads are internalized by cells through endocytosis which are further concentrated by the mucus layer of roots and then transported through other tissues by apoplastic mechanisms (Sun et al. 2020). However, the root cap mucilage allows the large-sized microplastic to pass through the cell wall, and the apical meristem tissues allow the microplastic to diffuse during active cell division (Li et al. 2020b). Due to its accumulation in the root system's aggregation sites, microplastic prevents nutrients and water from being absorbed by plants (Rillig et al. 2019). This is mainly due to the blocking of root surface pores reducing the ability of plants to absorb nutrients (Jiang et al. 2019). Some microplastics contain abundant C, and thus their exposure changes the carbon allocation of belowground parts of

Fig. 2 Microplastic contamination in the soil affects the soil fauna which alternatively affects the soil and plant functions



the plants (Zang et al. 2020). This change in carbon allocation may have an impact on enzyme activity, the connection between soil microbial populations and plant mycorrhiza, and ultimately the development of the plant (Wu et al. 2021).

Exposure of microplastic to plants, reduced root growth, nutrient uptake, and photosynthetic pigment content, indicating that it can have negative impacts on plant health (Yu et al. 2022). Similarly, microplastic also significantly reduces mycorrhizal colonization and has detrimental effects on the symbiotic relationship between plants and mycorrhizal fungi (Yang et al. 2021). Low concentrations of PVC, PE, and PS significantly decreased the fresh and dry weights of the belowground parts of the crops, which suggests that microplastic significantly inhibits root growth (Wang et al. 2020; Zhuang et al. 2023). Inhibition of root growth by low concentrations of PVC and PE was stronger and caused more serious mechanical damage to the root cells than that by PS, which was possibly due to the morphologies of the microplastic present in the soil (Zhuang et al. 2023). In addition, microplastic has complex indirect effects on plant growth as it alters soil microbial communities and enzyme activities, which in turn suppresses plant growth and nutrient uptake (Li et al. 2023a). Furthermore, microplastic has negative impacts on plant–microbe interactions, as the exposure changes the rhizosphere microbial communities, ultimately reducing plant growth (Ren et al. 2021). Moreover, microplastic also has a direct impact on plant growth by affecting root development and function as it reduces nutrient uptake and root exudation by altering root morphology and physiology of the plants (Liu et al. 2023; Khan et al. 2024).

Microplastic penetration, uptake, and translocation in the plants

Microplastics can enter plants through different pathways such as uptake by roots, adsorption to leaves from the outside environment, and via soil or water uptake by the plants (Liu et al. 2022). The microplastic that is absorbed in the roots of plants may go to their aerial parts, where they may subsequently assemble in the vascular system (Dong et al. 2021). Thus, microplastic first attached to the root hairs of *Arabidopsis thaliana* and then entered the root cells (Liu et al. 2022), however, microplastic can penetrate the roots of rice plants through plasmodesmata (Li et al. 2020a, b). In addition, microplastic can alter the root, make abrupt changes in the morphology and physiology of wheat plants, reduce the length and surface area of the roots, and increase the diameter of the root cells (Pignattelli et al. 2021). Moreover, PS- microplastic was taken up by the lettuce and radish plants and accumulated in their tissues, including the roots, leaves, and stem (Ma et al. 2022a, b), while PE-microplastic was observed in the roots of maize plants that translocated to the shoots of the crops (Urbina et al. 2020). In addition, microplastic altered the expression of genes involved in root development and stress responses; thereby, affecting the growth and expansion of the root system which alternately affects the physiology and final yield of the crops (Liu et al. 2022; Li et al. 2023a, b, c).

The mechanisms by which microplastic affects plant growth and development have yet to be fully understood. However, it has been suggested that microplastic may disrupt the microbial communities in the soil surrounding plant roots, leading to greater changes in nutrient availability and uptake (Kumar et al. 2022). Additionally, microplastic may directly affect plant physiology and metabolism of the crop by disrupting the cell membrane and causing oxidative stress (Wang et al. 2023). The detrimental effects of microplastic on plants have been explained by several different mechanisms. One possibility is that microplastic may physically obstruct the root hairs' passage and restrict the nutrient availability and uptake by plant roots (Huang et al. 2022; Li et al. 2023a, b, c). The exposure of crops to microplastic led to reduced photosynthetic capacity and increased oxidative stress in the maize plants. These might be due to the blockage of stomata, alternately changing the photosynthetic capacity of the crops (Sun et al. 2023).

Similarly, the atmospheric deposition of microplastic was reported to be able to accumulate on the leaves of the maize plants and resulted in a drastic change in the physiology and metabolic profiling of the crops (Zeb et al. 2021). Similarly, the cucumber plants exposed to microplastic particles led to changes in the microbiome and relative abundance of certain bacterial taxa in the root and leaf (Li et al. 2021). In addition, microplastic penetration and movement inside the plant body resulted in reduced photosynthetic efficiency and increased lipid peroxidation in the plants (Zhuang et al. 2023). Similarly, microplastic contamination in the soil, penetration inside the plant root, and movement through vascular cells led to reduced shoot and root length, as well as decreased biomass production (Liu et al. 2021; Gu et al. 2024). They also found the accumulation of microplastic in the roots and shoots of the wheat seedlings and mustard plants which revealed a greater change in the physiology and biochemical attributes concerning the carbohydrates, amino acid, and lipids metabolisms as well as leading to reduced chlorophyll content, decreased photosynthesis, and reduced biomass production in the plants (Iqbal et al. 2023a,b, 2024).

Diverse species and their response towards microplastics

Different species of plants respond differently to environmental stresses and develop specific strategies to maintain plant growth in stressful conditions. Similarly, different plant species have different penetration abilities for the uptake of nanoparticles and have different levels of sensitivity to the toxicity of microplastic (Dilnawaz et al. 2023). For instance, PS-microplastic severely hindered the root development of lettuce and corn while just marginally affecting the root growth of radish and wheat (Gong et al. 2021). Even if small-sized microplastic cannot reach the roots, they nonetheless have an impact on plant growth because they adhere to the roots, clog pores, or break cell walls, leading to oxidative stress or blocking the uptake of nutrients and water (Jiang et al. 2019; Gong et al. 2021). Similar to this, wheat and maize plants exposed to nano- and micro-PS detached the root cells' epidermis (Gong et al. 2021). In addition, PS nanoparticles were collected in the vessel walls of mung beans (*Vigna radiate*), which later moved to plant leaves (Lian et al. 2020). Therefore, microplastic is considered the source of decreasing plant photosynthesis that further affects plant growth and physiology (Chen et al. 2022; Zhao et al. 2022). Still, microplastic causes more damage to plant roots than leaves and shoots, whereas reduced oxidative stress caused by ROS is more abundant in the roots than in above-ground parts of plants (Li et al. 2023b). In addition, microplastic led to reduced photosynthetic activity, decreased chlorophyll content, reduced biomass, and growth of tomato crops (Shi et al. 2022), as well as of rice crops (Ma et al. 2022a, b). Alternatively, microplastic led to oxidative stress and DNA damage, which increased the level of reactive oxygen species and lipid peroxidation, as well as increased DNA damage in the leaves of the maize and *Vigna radiata* plants (Pehlivan and Gedik 2021; Lee et al. 2022).

Impacts of microplastics on plant productivity

The recent studies provide insight into the impacts of microplastic on plant productivity and suggest that it can have negative impacts on plant productivity through various mechanisms, including altering soil properties, reducing nutrient availability, and interfering with plant growth and development. The exposure of tomato plants to microplastic reduced the growth, root length, plant height, and fresh weight of tomato plants (Shi et al. 2023a, b). Reduced germination rates, interrupted root growth, and decreased nutrient absorption are reported as effects of microplastic on cereal crops, such as wheat and rice, leading to stunted growth and lower yield potential (Ma et al. 2022a, b; Iqbal et al. 2023b). The edible parts of vegetable crops can accumulate microplastic, causing environmental concerns and potential health problems (Bosker et al. 2019). They may lower the nutritional content and flavor of vegetables, which may affect consumer perception and market value (Cloete et al. 2021). Furthermore, consumers may experience health risks if they consume microplastic through contaminated foods (Gundogdu et al. 2022). Thus, microplastic may adversely affect fruit size, nutrient composition, and ripening processes, according to studies on fruit crops including strawberries and tomatoes (Amare and Desta 2021). Food safety and quality are also threatened by the accumulation of microplastic on fruit surfaces (Wang et al. 2022). Although there is little information on how microplastic affects crops, preliminary research indicates that these effects may be similar in terms of how they affect growth, biomass production, and reproductive success (Lozano and Rillig 2020). It is critical to look into the potential effects of microplastic pollution in natural settings since native plants are essential to ecosystem function and biodiversity preservation (Yu et al. 2021).

Impacts on the food web and penetration of human health

Nowadays it is a hot issue to discuss the effects of microplastic effects on food chains and public health. Therefore, microplastics may be absorbed and biomagnified as they go up the food chain after entering the environment and being digested by species, having an effect on both wildlife and human health (Huang et al. 2021). In addition, microplastic has adverse impacts on human health through food consumption and potential risks of ingesting, including the potentiality concerning toxicity and the accumulation of microplastic in the human body (Prata et al. 2020). The three primary routes through which microplastic and nanoplastics reach the human body are inhalation, ingestion, and skin contact (Prata et al. 2020; Rahman et al. 2021). Among the typical types of microplastic that may be breathed through the air and arise from urban dust are synthetic textiles and rubber tires. Even though microplastic and nanoplastics enter the body through all three routes, environmental exposure through inhalation, consuming food, and seafood eating poses the greatest risk of absolute exposure (Fig. 3). This is mostly caused by environmental factors such as long-term weathering of polymers, chemical polymer additive leaching, residual monomers, exposure to pollutants, and pathogenic microbial activity (Ali et al. 2024).

Ingestion is the main way that people take in microplastic particles (Lehner et al. 2019). The initial analysis revealed microplastic particles in samples of human excrement, which suggests that individuals are ingesting these particles through their food and drink. These results, along with research on digestibility absorption in environmental models, clearly show that microplastic and nanoplastics will be absorbed by people regularly (Ge et al. 2018). However, no studies have examined what happens to the micro- and nanoplastic particles once they enter the gastrointestinal tract. It would be crucial to examine the pathway of the particles through the gastrointestinal tract and determine if they pass through the gut epithelium or stay in the gut lumen. It is unlikely that microplastic may enter at the paracellular level given that the crucial holes at tight junction channels have a maximum functional size of around 1.5 nm (Alberts

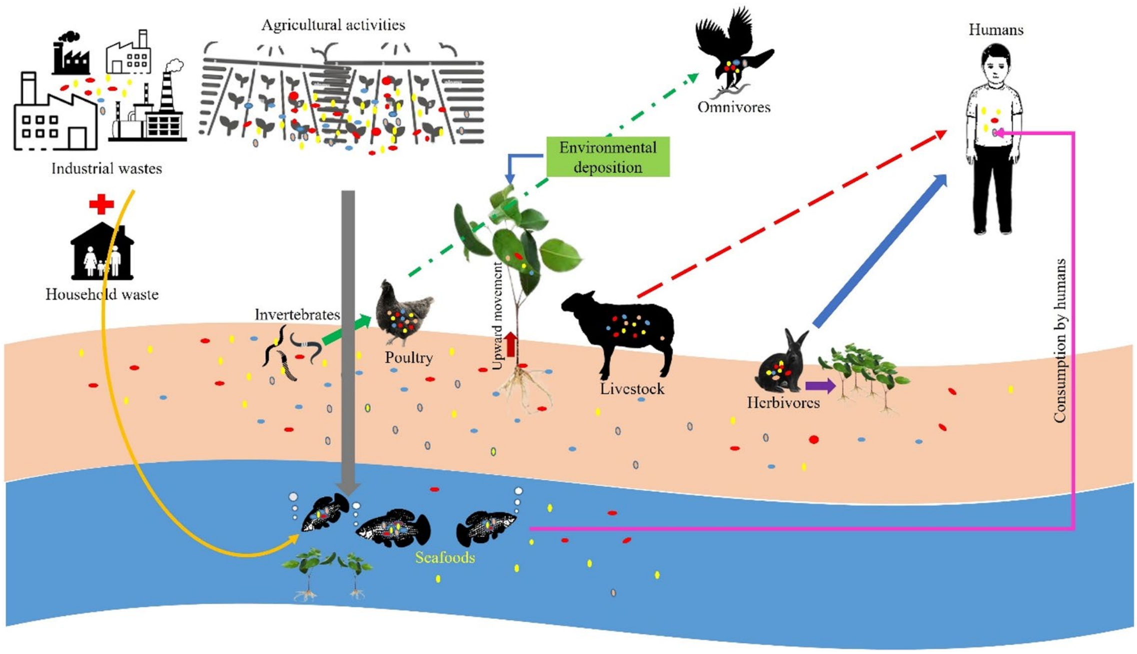


Fig. 3 The food web revealed the cycling of microplastics through bioaccumulation and biomagnification present in the aquatic, terrestrial, and agricultural land

et al. 2002). They may enter through lymphatic tissue and phagocytose or endocytose the cells in the Peyer's patches, which is particularly probable (Yi et al. 2023). Following intraperitoneal injections into mice, polymethacrylate and PS particles were observed to be phagocytosed by peritoneal macrophages (Carr et al. 2012). However, the results show that intestinal absorption in rodent models is just 0.04–0.3% (Carr et al. 2012).

The second most common route for humans to be exposed to microplastic and nanoplastics in the air is by inhalation. Indoor environments include airborne plastic particles, especially from synthetic materials, which can result in accidental inhalation or occupational exposure (Stapleton 2019). Inhaling polluted aerosols from the ocean's waves or airborne fertilizer particles from dry wastewater treatment operations might result in exposure in outdoor situations (Lehner et al. 2019). The lungs' tissue barrier is extremely thin – less than 1 μm – and their alveolar surface area is significant – about 150 m^2 (Campanale et al. 2020). This barrier is sufficiently porous to allow nanoparticles to penetrate the capillary blood system, allowing them to disperse throughout the whole human body (Lehner et al. 2019). Particle toxicity, chemical toxicity, the spread of diseases, and the introduction of parasite vectors are just a few of the negative health consequences that can arise from ingesting plastic particles, especially micro- and nanoplastics (Ohlwein et al. 2019). Particles in this size range can enter the lung deeply and either stay on the alveolar surface or go to other body parts (Stapleton 2019). Particles of plastic might harm the lungs if they are inhaled. Hydrophobicity, surface charge, surface functionalization, surrounding protein coronas, and particle size all have an impact on how well micro- and nanoplastics are absorbed and expelled from the lungs (Rist et al. 2018). In addition, the research on animal absorption rates demonstrates a connection between occupational exposures and a higher risk of lung inflammation and cancer (Prata 2018).

Another significant source through which nanoplastics penetrate the body is the health and beauty industry, particularly the body and face scrubs applied directly to the skin (Hernandez et al. 2017). Despite the lack of conclusive information about the impacts of nanocarriers, small particle size and stressed skin conditions are essential for skin penetration (Schneider et al. 2009). There is currently no research that has explicitly examined how well nanoplastics can penetrate the skin's outer layer. The skin's outermost layer, the stratum corneum, acts as a barrier to shield the skin from injury, toxins, and microbes. The stratum corneum is made up of corneocytes, and lamellae of hydrophilic lipids including cholesterol, ceramide, and long-chain free fatty acids surrounding it (Bouwstra et al. 2001). The skin may become polluted with plastic particles by contact with contaminated water or through the use of health and beauty products. Plastic particles may still enter the body through sweat ducts, skin wounds, or hair follicles even if it is predicted that absorption through the stratum corneum through contaminated water is unlikely. This is because micro- and nanoplastics are thought to be hydrophobic (Schneider et al. 2009).

Mitigation strategies to overcome microplastic contamination

Microplastic pollution is a global environmental issue with significant negative impacts on both human and environmental health. Mitigating microplastic pollution requires a multifaceted approach involving various measures ranging from source reduction to end-of-life management. Some of the points include source reduction which is one of the greatest ways to stop the contamination brought on by microplastic is to lessen the overall amount of plastic waste produced in the original environment. This might be achieved by passing laws and regulations that support the use of alternative materials, such as biodegradable plastics, or by encouraging people to utilize reusable items. To encourage their reduction, certain nations, for instance, have imposed tariffs on single-use plastics (Ali et al. 2024). Further environmentally friendly approaches that producers can embrace include decreasing packaging and creating circular designs for items (Fadeeva and Van Berkel 2021). Similarly, wastewater treatment is a major source of microplastic pollution in agricultural land. Therefore, upgrading wastewater treatment facilities with advanced treatment technologies can significantly reduce the amount of microplastic released into the environment. For example, the use of membrane filtration systems, activated carbon, and ozonation can effectively remove microplastics from wastewater (Shah et al. 2020). Additionally, consumer education about the impacts of microplastic pollution can encourage behavior change and reduce the amount of plastic waste generated. Consumer education programs can be implemented in schools, community centers, and public events. For example, the "Beat the Microbead" campaign has been successful in educating consumers about the harmful effects of microplastic in personal care products (Mitrano and Wohlleben 2020). Moreover, several innovative technologies have been developed to mitigate microplastic pollution, such as the use of magnetic nanoparticles to remove microplastic from water and the use of biodegradable plastics in packaging materials (Din et al. 2020; Goh et al. 2022). In addition, the researchers are exploring the use of enzymes and microorganisms to degrade microplastic in the environment (Zeb et al. 2024).

Government policies and regulations can play a crucial role in mitigating microplastic pollution. For example, the European Union has banned the use of microplastic in certain products, such as personal care products, and has introduced regulations to reduce plastic waste (Elliott et al. 2020). Similarly, several countries have introduced legislation to ban single-use plastics, which can significantly reduce the amount of plastic waste generated (Zeb et al. 2024). In conclusion, implementing these measures will require a collaborative effort from governments, industries, and individuals to achieve a sustainable future.

Conclusion

Microplastic pollution is a global environmental issue that poses significant risks to soil health, plant growth, and human health. Our review article highlights the current state of knowledge on the fate and effects of microplastic pollution on soil and plant systems, as well as the potential risks to human health through the food chain. The review synthesizes the latest research data and findings and identifies important research gaps and priorities for future investigation. Overall, the study shows that soil physicochemical features, microbial populations, nutrient cycling, and plant growth and development can all be profoundly impacted by microplastic contamination. Furthermore, although the entire degree of these threats is not yet known, eating food and drinking water polluted with microplastic may be harmful to human health. The review underscores the urgent need for greater awareness, policy interventions, and technological solutions to address the emerging threat of microplastic pollution in soil and plant systems and mitigate its potential impacts on human health. In summary, the review highlights the need for a comprehensive and integrated approach to address microplastic pollution, incorporating research, policy, and technological solutions, and involving interdisciplinary collaborations across multiple sectors. Only through such collective efforts can we effectively address this global environmental issue and safeguard the health of our soils, plants, and, ultimately, human populations.

Research gaps and future perspectives

- The transfer of microplastic through trophic from plants to soil fauna is mainly unexplored. Thus, microplastic can enter the plants and transfer to other living organisms such as consumers. Therefore, the health risks associated with microplastic in edible parts of crops should be investigated.
- Similarly, microplastic acts as a vector for various contaminants including heavy metals, antibiotics, pathogens, and organic pollutants in the plant-soil system. Therefore, it's the need of hour to deeply investigate the co-exposure impact of microplastic with other pollutants on the physiological, biochemical, ultrastructural, and molecular levels of different crops.
- More in-depth studies on different types of microplastics and additives according to their natural occurrence in the

soil will also help to enhance our understanding of their interactive toxicities on living organisms.

- Previous studies focused on short-term microcosm experiments. Therefore, long-term experiments at a large scale are highly recommended to fully uncover the actual effect of microplastic on edible crops. Life cycle studies are the need of hour to investigate whether microplastic can accumulate in grains of edible crops such as wheat, rice, and maize.

Authors' contributions **Muhammad Tariq**: Roles/Writing – original draft, Conceptualization, Investigation; **Babar Iqbal**: Conceptualization, Investigation, Project administration, Resources, Writing – review & editing; **Ismail Khan**: Validation; **Ali Raza Khan**: Software, Conceptualization; **Eun Hea Jho:** Resources**,** Writing – review & editing**; Abdul Salam**: Software, Conceptualization, Writing – review & editing; **Huan Zhou**: Investigation, Validation; **Xin Zhao**: Resources, Investigation, Writing – review & editing; **Guanlin Li**: Supervision, Visualization, Writing – review & editing; **Daolin Du**: Supervision, Visualization, Writing – review & editing. All authors contributed to the article and approved the submitted version.

Funding This work was supported by the Carbon Peak and Carbon Neutrality Technology Innovation Foundation of Jiangsu Province (BK20220030), the National Natural Science Foundation of China (32271587; 32350410400), the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2022R1I1A1A01055443), the Zhenjiang Municipal Policy Guidance Project of International Science and Technology Cooperation (Grant GJ2023005); the Zhenjiang Major Project of Social Development in Research and Development (Grant SH2022004), and the Senior Talent Foundation of Jiangsu University (18JDG039). This work was also supported by Zhenjiang Deweilepu Energy Environmental Protection Technology Co., Ltd. The authors wish to express their gratitude for the support. The authors also appreciated the help from Yan Shao during the writing.

Data availability Not Applicable.

Code availability Not Applicable.

Declarations

Conflicts of 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.

Ethics approval Not Applicable.

Consent to participate Not Applicable.

Consent for publication Not Applicable.

References

Abbasi S, Turner A (2021) Dry and wet deposition of microplastics in a semi-arid region (Shiraz, Iran). Sci Total Environ 786:147358

Alberts B, Johnson A, Lewis J, Raff M, Roberts K, Walter P (2002) Cell junctions. In: Molecular biology of the cell, 4th edn. Garland Science, New York

Ali N, Liu W, Zeb A, Shi R, Lian Y, Wang Q, Wang J, Li J, Zheng Z, Liu J, Yu M, Liu J (2024) Environmental fate, aging, toxicity and potential remediation strategies of microplastics in soil environment: current progress and future perspectives. Sci Total Environ 906:167785

Amare G, Desta B (2021) Coloured plastic mulches: impact on soil properties and crop productivity. Chem Biolog Technol Agri 8(1):1–9

Bai B, Chen J, Bai F, Nie Q, Jia X (2024) Corrosion effect of acid/alkali on cementitious red mud-fly ash materials containing heavy metal residues. Environ Technol Innov 33:103485. https://doi.org/10.1016/j.eti.2023.103485

Blackburn K, Green D (2022) The potential effects of microplastics on human health: what is known and what is unknown. Ambio 51(3):518–530

Boots B, Russell CW, Green DS (2019) Effects of microplastics in soil ecosystems: above and below ground. Environ Sci Technol 53(19):11496–11506

Bosker T, Bouwman LJ, Brun NR, Behrens P, Vijver MG (2019) Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *Lepidium sativum*. Chemosphere 226:774–781

Bouwstra J, Pilgram G, Gooris G, Koerten H, Ponec M (2001) New aspects of the skin barrier organization. Skin Pharmacol Physiol 14(1):52–62

Brooker RW, Hawes C, Iannetta PPM, Karley AJ, Renard D (2023) Plant diversity and ecological intensification in crop production systems. J Plant Ecol 16:rtad015

Buzhdygan OY, Petermann JS (2023) Multitrophic biodiversity enhances ecosystem functions, services and ecological intensification in agriculture. J Plant Ecol 16:rtad019

Campanale C, Massarelli C, Savino I, Locaputo V, Uricchio VF (2020) A detailed review study on potential effects of microplastics and additives of concern on human health. Int J Environ Res Public Health 17(4):1212

Carr KE, Smyth SH, McCullough MT, Morris JF, Moyes SM (2012) Morphological aspects of interactions between microparticles and mammalian cells: intestinal uptake and onward movement. Prog Histochem Cytochem 46(4):185–252

Chen G, Li Y, Liu S, Junaid M, Wang J (2022) Effects of micro (nano) plastics on higher plants and the rhizosphere environment. Sci Total Environ 807:150841

Chen H, Ye Q, Wang X, Sheng J, Yu X, Zhao S, Zou X, Zhang W, Xue G (2024a) Applying sludge hydrolysate as a carbon source for biological denitrification after composition optimization via red soil filtration. Water Res 249:120909. https://doi.org/10.1016/j.watres.2023.120909

Chen Z, Ma T, Li Z, Zhu W, Li L (2024b) Enhanced photocatalytic performance of S-scheme $CdMoO_4$/CdO nanosphere photocatalyst. J Mater Sci Technol 179:198–207. https://doi.org/10.1016/j.jmst.2023.07.029

Cloete L, Picot-Allain C, Ramasawmy B, Neetoo H, Ramful-Baboolall D, Emmambux MN (2021) Drivers and barriers for commercial uptake of edible coatings for fresh fruits and vegetables industry-a review. Food Rev Int 39:1–34

De Souza Machado AA, Lau CW, Kloas W, Bergmann J, Bachelier JB, Faltin E, Rillig MC (2019) Microplastics can change soil properties and affect plant performance. Environ Sci Tech 53(10):6044–6052

Dilnawaz F, Misra AN, Apostolova E (2023) Involvement of nanoparticles in mitigating plant's abiotic stress. Plant Stress 10:100280

Din MI, Ghaffar T, Najeeb J, Hussain Z, Khalid R, Zahid H (2020) Potential perspectives of biodegradable plastics for food

packaging application-review of properties and recent developments. Food Add Contam: Part A 37(4):665–680
Dong Y, Gao M, Qiu W, Song Z (2021) Uptake of microplastics by carrots in presence of As (III): combined toxic effects. J Hazard Mater 411:125055. https://doi.org/10.1016/j.jhazmat.2021.125055
Elliott T, Gillie H, Thomson A (2020) European Union's plastic strategy and an impact assessment of the proposed directive on tackling single-use plastics items. In: Plastic waste and recycling. Academic, Amsterdam, pp 601–633
Fadeeva Z, Van Berkel R (2021) Unlocking circular economy for prevention of marine plastic pollution: an exploration of G20 policy and initiatives. J Environ Manage 277:111457
Galafassi S, Nizzetto L, Volta P (2019) Plastic sources: a survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water. Sci Total Environ 693:133499
Ge H, Yan Y, Wu D, Huang Y, Tian F (2018) Potential role of LINC00996 in colorectal cancer: a study based on data mining and bioinformatics. OncoTargets Ther 11:4845–4855
Gigault J, El Hadri H, Nguyen B, Grassl B, Rowenczyk L, Tufenkji N, Feng S, Wiesner M (2021) Nanoplastics are neither microplastics nor engineered nanoparticles. Nat Nanotechnol 16:501–507
Goh PS, Kang HS, Ismail AF, Khor WH, Quen LK, Higgins D (2022) Nanomaterials for microplastic remediation from aquatic environment: why nano matters? Chemosphere 299:134418
Gong W, Zhang W, Jiang M, Li S, Liang G, Bu Q, Xu L, Zhu H, Lu A (2021) Species-dependent response of food crops to polystyrene nanoplastics and microplastics. Sci Total Environ 796:148750
Gu Q, Li S, Liao Z (2024) Solving nonlinear equation systems based on evolutionary multitasking with neighborhood-based speciation differential evolution. Expert Syst Appl 238:122025. https://doi.org/10.1016/j.eswa.2023.122025
Gundogdu S, Rathod N, Hassoun A, Jamroz E, Kulawik P, Gokbulut C, Özogul F (2022) The impact of nano/micro-plastics toxicity on seafood quality and human health: facts and gaps. Crit Rev Food Sci Nutr 63:6445–6463
Hernandez LM, Yousefi N, Tufenkji N (2017) Are there nanoplastics in your personal care products? Environ Sci Technol Lett 4(7):280–285
Hernández-Arenas R, Beltrán-Sanahuja A, Navarro-Quirant P, Sanz-Lazaro C (2021) The effect of sewage sludge containing microplastics on growth and fruit development of tomato plants. Environ Pollut 268:115779
Holden E, Linnerud K, Banister D (2017) The imperatives of sustainable development. Sustain Dev 25(3):213–226
Hou J, Xu X, Yu H, Xi B, Tan W (2021) Comparing the long-term responses of soil microbial structures and diversities to polyethylene microplastics in different aggregate fractions. Environ Int 149:106398
Huang Y, Liu Q, Jia W, Yan C, Wang J (2020) Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ Pollut 260:114096
Huang W, Song B, Liang J, Niu Q, Zeng G, Shen M, Zhang Y (2021) Microplastics and associated contaminants in the aquatic environment: a review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. J Hazard Mater 405:124187
Huang D, Wang X, Yin L, Chen S, Tao J, Zhou W, Xiao R (2022) Research progress of microplastics in soil-plant system: ecological effects and potential risks. Sci Total Environ 812:151487
Ingraffia R, Amato G, Iovino M, Rillig MC, Giambalvo D, Frenda AS (2022) Polyester microplastic fibers in soil increase nitrogen loss via leaching and decrease plant biomass production and N uptake. Environ Res Lett 17:113259
Iqbal B, Javed Q, Khan I, Tariq M, Ahmad N, Elansary HO, Jalal A, Li G, Du D (2023a) Influence of soil microplastic contamination and cadmium toxicity on the growth, physiology, and root growth traits of *Triticum aestivum* L. S Afr J Bot 160:369–375
Iqbal B, Li G, Alabbosh KF, Hussain H, Khan I, Tariq M, Javed Q, Naeem M, Ahmad N (2023b) Advancing environmental sustainability through microbial reprogramming in growth improvement, stress alleviation, and phytoremediation. Plant Stress 10:100283
Iqbal B, Zhao T, Yin W, Zhao X, Xie Q, Khan KY, Du D (2023c) Impacts of soil microplastics on crops: a review. Appl Soil Ecol 181:104680
Iqbal B, Zhao X, Khan KY, Javed Q, Nazar M, Khan I, Zhao X, Li G, Du D (2024) Microplastics meet invasive plants: unraveling the ecological hazards to agroecosystems. Sci Total Environ 906:167756
Jiang X, Chen H, Liao Y, Ye Z, Li M, Klobucar G (2019) Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. Environ Pollut 250:831–838. https://doi.org/10.1016/j.envpol.2019.04.055
Khalid N, Aqeel M, Noman A (2020) Microplastics could be a threat to plants in terrestrial systems directly or indirectly. Environ Pollut 267:115653
Khalid N, Aqeel M, Noman A, Hashem M, Mostafa YS, Alhaithloul HAS, Alghanem SM (2021) Linking effects of microplastics to ecological impacts in marine environments. Chemosphere 264:128541
Khan KY, Li G, Du D, Ali B, Zhang S, Zhong M, Stoffella PJ, Iqbal B, Cui X, Fu L, Guo Y (2023) Impact of polystyrene microplastics with combined contamination of norfloxacin and sulfadiazine on *Chrysanthemum coronarium* L. Environ Pollut 316:120522
Khan AR, Ulhassan Z, Li G, Lou J, Iqbal B, Salam A, Azhar W, Batool S, Zhao T, Li K, Zhang Q, Zhao X, Du D (2024) Micro/nanoplastics: critical review of their impacts on plants, interactions with other contaminants (antibiotics, heavy metals, and polycyclic aromatic hydrocarbons), and management strategies. Sci Total Environ 912:169420
Kumar R, Ivy N, Bhattacharya S, Dey A, Sharma P (2022) Coupled effects of microplastics and heavy metals on plants: uptake, bioaccumulation, and environmental health perspectives. Sci Total Environ 836:155619
Lee TY, Kim L, Kim D, An S, An YJ (2022) Microplastics from shoe sole fragments cause oxidative stress in a plant (*Vigna radiata*) and impair soil environment. J Hazard Mater 429:128306
Lehner R, Weder C, Petri-Fink A, Rothen-Rutishauser B (2019) Emergence of nanoplastic in the environment and possible impact on human health. Environ Sci Tech 53(4):1748–1765
Li Y, Li M, Li Z, Yang L, Liu X (2019) Effects of particle size and solution chemistry on Triclosan sorption on polystyrene microplastic. Chemosphere 231:308–314
Li L, Luo Y, Li R, Zhou Q, Peijnenburg WJ, Yin N, Zhang Y (2020a) Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nat Sustain 3(11):929–937
Li R, Zhu L, Yang K, Li H, Zhu YG, Cui L (2021) Impact of urbanization on antibiotic resistome in different microplastics: evidence from a large-scale whole river analysis. Environ Sci Technol 55(13):8760–8770
Li J, Yu S, Yu Y, Xu M (2022) Effects of microplastics on higher plants: a review. Bull Environ Contam Toxicol 109(2):241–265
Li G, Tang Y, Khan KY, Son Y, Jung J, Qiu X, Zhao X, Iqbal B, Stoffella PJ, Kim GJ, Du D (2023a) The toxicological effect on Pak Choi of co-exposure to degradable and non-degradable microplastics with oxytetracycline in the soil. Ecotoxicol Environ Saf 268:115707
Li Z, Li R, Li Q, Zhou J, Wang G (2020a) Physiological response of cucumber (*Cucumis sativus* L.) leaves to polystyrene nanoplastics pollution. Chemosphere 255:127041

Li G, Zhao X, Iqbal B, Zhao X, Liu J, Javed Q, Du D (2023b) The effect of soil microplastics on the *Oryza sativa* L. root growth traits under alien plant invasion. Front Ecol Evol 11:1172093

Li W, Wang C, Liu H, Wang W, Sun R, Li M, Shi Y, Zhu, D, Du W, Ma L, Fu S (2023) Fine root biomass and morphology in a temperate forest are influenced more by canopy water addition than by canopy nitrogen addition. Front Ecol Evol 11. https://doi.org/10.3389/fevo.2023.1132248

Lian J, Wu J, Xiong H, Zeb A, Yang T, Su X, Su L, Liu W (2020) Impact of polystyrene nanoplastics (PSNPs) on seed germination and seedling growth of wheat (*Triticum aestivum* L.). J Hazard Mater 385:121620

Liu Y, Tao Q, Guo X, Luo J, Li J, Liang Y, Li T (2020) Low calcium-induced delay in development of root apoplastic barriers enhances Cd uptake and accumulation in *Sedum alfredii*. Sci Total Environ 723:137810

Liu S, Wang J, Zhu J, Wang J, Wang H, Zhan X (2021) The joint toxicity of polyethylene microplastic and phenanthrene to wheat seedlings. Chemosphere 282:130967

Liu Y, Guo R, Zhang S, Sun Y, Wang F (2022) Uptake and translocation of nano/microplastics by rice seedlings: evidence from a hydroponic experiment. J Hazard Mater 421:126700

Liu Y, Xu F, Ding L, Zhang G, Bai B, Han Y, Li G (2023) Microplastics reduce nitrogen uptake in peanut plants by damaging root cells and impairing soil nitrogen cycling. J Hazard Mater 443:130384

Lozano YM, Rillig MC (2020) Effects of microplastic fibers and drought on plant communities. Environ Sci Technol 54(10):6166–6173. https://doi.org/10.1021/acs.est.0c01051

Lozano YM, Aguilar-Trigueros CA, Onandia G, Maaß S, Zhao T, Rillig MC (2021) Effects of microplastics and drought on soil ecosystem functions and multifunctionality. J Appl Ecol 58(5):988–996

Lu Y, Si B, Li H, Biswas A (2019) Elucidating controls of the variability of deep soil bulk density. Geoderma 348:146–157

Lwanga EH, Beriot N, Corradini F, Silva V, Yang X, Baartman J, Geissen V (2022) Review of microplastic sources, transport pathways and correlations with other soil stressors: a journey from agricultural sites into the environment. Chem Biol Technol Agric 9(1):1–20

Lynch JP, Strock CF, Schneider HM, Sidhu JS, Ajmera I, Galindo-Castañeda T, Klein SP, Hanlon MT (2021) Root anatomy and soil resource capture. Plant Soil 466:21–63

Ma J, Qiu Y, Zhao J, Ouyang X, Zhao Y, Weng L, Yasir AMD, Chen Y, Li Y (2022b) Effect of agricultural organic inputs on nanoplastics transport in saturated goethite-coated porous media: particle size selectivity and role of dissolved organic matter. Environ Sci Technol 56(6):3524–3534. https://doi.org/10.1021/acs.est.1c07574

Ma J, Aqeel M, Khalid N, Nazir A, Alzuaibr FM, Al-Mushhin AA, Noman A (2022) Effects of microplastics on growth and metabolism of rice (*Oryza sativa* L.). Chemosphere 307:135749

Mitrano DM, Wohlleben W (2020) Microplastic regulation should be more precise to incentivize both innovation and environmental safety. Nat Commun 11(1):5324

National Oceanic and Atmospheric Administration (2023) Microplastics. Retrieved from https://oceanservice.noaa.gov/facts/microplastics.html. Accessed 03 June 2023

Nava V, Leoni B (2021) A critical review of interactions between microplastics, microalgae and aquatic ecosystem function. Water Res 188:116476

Nazir MJ, Li G, Nazir MM, Zulfiqar F, Siddique KHM, Iqbal B, Du D (2024) Harnessing soil carbon sequestration to address climate change challenges in agriculture. Soil till Res 237:105959

Ohlwein S, Kappeler R, Kutlar JM, Künzli N, Hoffmann B (2019) Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence. Int J Pub Health 64:547–559

Pehlivan N, Gedik K (2021) Particle size-dependent biomolecular footprints of interactive microplastics in maize. Environ Pollut 277:116772

Pignattelli S, Broccoli A, Piccardo M, Felline S, Terlizzi A, Renzi M (2021) Short-term physiological and biometrical responses of *Lepidium sativum* seedlings exposed to PET-made microplastics and acid rain. Ecotoxicol Environ Saf 208:111718

Porterfield KK, Hobson SA, Neher DA, Niles MT, Roy ED (2022) Microplastics in composts, digestates and food wastes: a review. J Environ Qual 52:225–240. https://doi.org/10.1002/jeq2.20450

Prata JC (2018) Airborne microplastics: consequences to human health? Environ Pollut 234:115–126

Prata JC, da Costa JP, Lopes I, Duarte AC, Rocha-Santos T (2020) Environmental exposure to microplastics: an overview on possible human health effects. Sci Total Environ 702:134455

Prem M, Ranjan P, Seth N, Patle GT (2020) Mulching techniques to conserve the soil water and advance the crop production – a review. Curr World Environ 15:10–30

Qiu Y, Zhou S, Zhang C, Zhou Y, Qin W (2022) Soil microplastic characteristics and the effects on soil properties and biota: a systematic review and meta-analysis. Environ Pollut 313:120183

Rahman A, Sarkar A, Yadav OP, Achari G, Slobodnik J (2021) Potential human health risks due to environmental exposure to nano- and microplastics and knowledge gaps: a scoping review. Sci Total Environ 757:143872

Ran C, Bai X, Tan Q, Luo G, Cao Y, Wu L, Chen F, Li C, Lou X, Liu M, Zhang S (2023) Threat of soil formation rate to health of karst ecosystem. Sci Total Environ 887:163911. https://doi.org/10.1016/j.scitotenv.2023.163911

Ren X, Tang J, Wang L, Liu Q (2021) Microplastics in soil-plant system: effects of nano/microplastics on plant photosynthesis, rhizosphere microbes and soil properties in soil with different residues. Plant Soil 462:561–576

Rillig MC (2018) Microplastic disguising as soil carbon storage. Environ Sci Technol 52:6079–6080

Rillig MC, Lehmann A, de Souza Machado AA, Yang G (2019) Microplastic effects on plants. New Phytol 223(3):1066–1070

Rist S, Almroth BC, Hartmann NB, Karlsson TM (2018) A critical perspective on early communications concerning human health aspects of microplastics. Sci Total Environ 626:720–726

Rong L, Zhao L, Zhao L, Cheng Z, Yao Y, Yuan C, Wang L, Sun H (2021) LDPE microplastics affect soil microbial communities and nitrogen cycling. Sci Total Environ 773:145640

Ruiz S, Koebernick N, Duncan S, Fletcher DM, Scotson C, Boghi A, Marin M, Bengough AG, George TS, Brown LK, Hallett PD, Roose T (2020) Significance of root hairs at the field scale–modelling root water and phosphorus uptake under different field conditions. Plant Soil 447:281–304

Sajjad M, Huang Q, Khan S, Khan MA, Yin L, Wang J, Guo G (2022) Microplastics in the soil environment: a critical review. Environ Technol Innov 27:102408

Schmid B, Schöb C (2023) Ecological intensification of agriculture through biodiversity management: introduction. J Plant Ecol 16:rtad018

Schneider M, Stracke F, Hansen S, Schaefer UF (2009) Nanoparticles and their interactions with the dermal barrier. Dermatoendocrinol 1(4):197–206

Shah AI, Dar MUD, Bhat RA, Singh JP, Singh K, Bhat SA (2020) Prospectives and challenges of wastewater treatment technologies to combat contaminants of emerging concerns. Ecol Eng 152:105882

Shen H, Sun Y, Duan H, Ye J, Zhou A, Meng H, Gu C (2023) Effect of PVC microplastics on soil microbial community and nitrogen availability under laboratory-controlled and field-relevant temperatures. Appl Soil Ecol 184:104794

Shi R, Liu W, Lian Y, Wang X, Men S, Zeb A, Wang Q, Wang J, Li J, Zheng Z, Zhou Q, Tang J, Sun Y, Wang F, Xing B (2023a) Toxicity mechanisms of nanoplastics on crop growth, interference of phyllosphere microbes, and evidence for foliar penetration and translocation. Environ Sci Technol 58(2):1010–1021

Shi R, Liu W, Lian Y, Wang Q, Zeb A, Tang (2022) Phytotoxicity of polystyrene, polyethylene and polypropylene microplastics on tomato (*Lycopersicon esculentum* L.). J Environ Manage 317:115441

Shi R, Liu W, Lian Y, Zeb A, Wang Q (2023) Type-dependent effects of microplastics on tomato (*Lycopersicon esculentum* L.): Focus on root exudates and metabolic reprogramming. Sci Total Environ 859:160025

De Souza Machado AA, Horton AA, Davis T, Maaß S (2020) Microplastics and their effects on soil function as a life-supporting system. In: Microplastics in terrestrial environments: emerging contaminants and major challenges. Springer International Publishing, Cham, pp 199–222

Stapleton PA (2019) Toxicological considerations of nano-sized plastics. AIMS Environ Sci 6(5):367

Sun XD, Yuan XZ, Jia Y, Feng LJ, Zhu FP, Dong SS, Liu J, Kong X, Tian H, Duan JL, Ding Z, Wang SG, Xing B (2020) Differentially charged nanoplastics demonstrate distinct accumulation in *Arabidopsis thaliana*. Nat Nanotechnol 15(9):755–760. https://doi.org/10.1038/s41565-020-0707-4

Sun Y, Duan C, Cao N, Li X, Li X, Chen Y, Wang J (2022) Effects of microplastics on soil microbiome: the impacts of polymer type, shape, and concentration. Sci Total Environ 806:150516

Sun H, Shi Y, Zhao P, Long G, Li C, Wang J, He S (2023) Effects of polyethylene and biodegradable microplastics on photosynthesis, antioxidant defense systems, and arsenic accumulation in maize (*Zea mays* L.) seedlings grown in arsenic-contaminated soils. Sci Total Environ 868:161557

Tang Y, Yang G, Liu X, Qin L, Zhai W, Fodjo EK, Shen X, Wang Y, Lou X, Kong C (2023a) Rapid sample enrichment, novel derivatization, and high sensitivity for determination of 3-chloropropane-1,2-diol in soy sauce via high-performance liquid chromatography–tandem mass spectrometry. J Agric Food Chem 71(41):15388–15397. https://doi.org/10.1021/acs.jafc.3c05230

Tang Y, Li G, Iqbal B, Tariq M, Rehman A, Khan I, Du D (2023b) Soil nutrient levels regulate the effect of soil microplastics contamination on microbial element metabolism and carbon use efficiency. Ecotoxicol Environ Saf 267:115640

Torre GE (2020) Microplastics: an emerging threat to food security and human health. J Food Sci Tech 57(5):1601–1608

Urbina MA, Correa F, Aburto F, Ferrio JP (2020) Adsorption of polyethylene microbeads and physiological effects on hydroponic maize. Sci Total Environ 741:140216

Wan Y, Wu C, Xue Q, Hui X (2019) Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci Total Environ 654:576–582. https://doi.org/10.1016/j.scitotenv.2018.11.123

Wang F, Zhang X, Zhang S, Zhang S, Sun Y (2020) Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere 254:126791

Wang F, Wang Q, Adams CA, Sun Y, Zhang S (2022) Effects of microplastics on soil properties: current knowledge and future perspectives. J Hazard Mater 424:127531

Wang SC, Liu GZ, Liu FF (2023) Physiological and metabolic toxicity of polystyrene microplastics to *Dunaliella salina*. Environ Pollut 316:120544

Wang J, Liu W, Wang X, Zeb A, Wang Q, Mo F, Shi R, Liu J, Yu M, Li J, Zheng Z, Lian Y (2024) Assessing stress responses in potherb mustard (*Brassica juncea* var. multiceps) exposed to a synergy of microplastics and cadmium: insights from physiology, oxidative damage, and metabolomics. Sci Total Environ 907:167920

Wu J, Liu W, Zeb A, Lian J, Sun Y, Sun H (2021) Polystyrene microplastic interaction with *Oryza sativa*: toxicity and metabolic mechanism. Environ Sci Nano 8(12):3699–3710

Xiang Y, Jiang L, Zhou Y, Luo Z, Zhi D, Yang J, Lam SS (2022) Microplastics and environmental pollutants: key interaction and toxicology in aquatic and soil environments. J Hazard Mater 422:126843

Yang W, Cheng P, Adams CA, Zhang S, Sun Y, Yu H, Wang F (2021) Effects of microplastics on plant growth and arbuscular mycorrhizal fungal communities in a soil spiked with ZnO nanoparticles. Soil Biol Biochem 155:108179

Yang Y, Li Z, Yan C, Chadwick D, Jones DL, Liu E, He W (2022) Kinetics of microplastic generation from different types of mulch films in agricultural soil. Sci Total Environ 814:152572

Yi Q, Xu Z, Thakur A, Zhang K, Liang Q, Liu Y, Yan Y (2023) Current understanding of plant-derived exosome-like nanoparticles in regulating the inflammatory response and immune system microenvironment. Pharmacol Res 190:106733

Yu H, Fan P, Hou J, Dang Q, Cui D, Xi B, Tan W (2020) Inhibitory effect of microplastics on soil extracellular enzymatic activities by changing soil properties and direct adsorption: an investigation at the aggregate-fraction level. Environ Pollut 267:115544

Yu Y, Li J, Song Y, Zhang Z, Yu S, Xu M, Zhao Y (2022) Stimulation versus inhibition: the effect of microplastics on Pak Choi growth. Appl Soil Ecol 177:104505

Zang H, Zhou J, Marshall MR, Chadwick DR, Wen Y, Jones DL (2020) Microplastics in the agroecosystem: are they an emerging threat to the plant-soil system? Soil Boil Biochem 148:107926. https://doi.org/10.1016/j.soilbio.2020.107926

Zeb A, Liu W, Ali N, Shi R, Lian Y, Wang Q, Wang J, Li J, Zheng Z, Liu J, Yu M, Liu J (2024) Integrating metabolomics and high-throughput sequencing to investigate the effects of tire wear particles on mung bean plants and soil microbial communities. Environ Pollut 340:122872

Zhang GS, Zhang FX, Li XT (2019) Effects of polyester microfibers on soil physical properties: perception from a field and a pot experiment. Sci Total Environ 670:1–7. https://doi.org/10.1016/j.scitotenv.2019.03.149

Zhang L, Xie Y, Liu J, Zhong S, Qian Y, Gao P (2020a) An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. Environ Sci Technol 54(7):4248–4255

Zhang Y, Pu S, Lv X, Gao Y, Ge L (2020b) Global trends and prospects in microplastics research: a bibliometric analysis. J Hazard Mater 400:123110

Zhao X, Xie H, Zhao X, Zhang J, Li Z, Yin W, Yuan A, Zhou H, Manan S, Nazar M, Iqbal B, Li G, Du D (2022) Combined inhibitory effect of Canada goldenrod invasion and soil microplastics on rice growth. Int J Environ Res Pub Health 19(19):11947

Zhou J, Jia R, Brown RW, Yang Y, Zeng Z, Jones DL, Zang H (2023) The long-term uncertainty of biodegradable mulch film residues and associated microplastics pollution on plant-soil health. J Hazard Mater 442:130055

Zhu G, Liu Y, Shi P, Jia W, Zhou J, Liu Y, Ma X, Pan H, Zhang Y, Zhang Z, Sun Z, Yong L, Zhao K (2022) Stable water isotope monitoring network of different water bodies in Shiyang River basin, a typical arid river in China. Earth Syst Sci Data 14(8):3773–3789. https://doi.org/10.5194/essd-14-3773-2022

Zhuang H, Liu X, Ma H, Li R, Liu B, Lin Z, Li Z (2023) Growth and physiological–biochemical characteristics of cucumber (*Cucumis sativus* L.) in the presence of different microplastics. Arab J Geosci 16(3):194