https://doi.org/10.17221/180/2025-PSE

Effects of microplastics on farmland soils and plants: a review

Minhua Zhang[1], Weiguan Li[2], Qingkui Li[3], Aneela Younas[1], Muhammad Shaaban[1], Yuyang Li[1], Jing Liu[1], Yanfang Wang[1], Zhanqiang Ma[1], Zhaoyong Shi[1], Hongtao Shen[4], Ling Liu[1]**

[1]College of Agriculture, Henan University of Science and Technology, Luoyang, P.R. China
[2]Henan Provincial Tobacco Corporation, Zhengzhou, P.R. China
[3]China Tobacco Henan Import and Export Limited Company, Zhengzhou, P.R. China
[4]Technology Centre, China Tobacco Henan Industrial Limited Company, Zhengzhou, P.R. China
**Corresponding authors: shtluoyang@126.com, liuling1978@haust.edu.cn*

Citation: Zhang M.H., Li W.G., Li Q.K., Younas A., Shaaban M., Li Y.Y., Liu J., Wang Y.F., Ma Z.Q., Shi Z.Y., Shen H.T., Liu L. (2025): Effects of microplastics on farmland soils and plants: a review. Plant Soil Environ., 71: 829–848.

Abstract: Microplastics (MPs) are plastic particles smaller than 5 mm in size, which are widely present and have become one of the major pollutants in the natural environment, and are increasingly recognised as emerging pollutants in agricultural ecosystems. Due to their small size and high mobility, MPs can easily migrate into farmland soils and attach to plant surfaces, thereby altering the physical, chemical and microbial properties of the soil. These changes may affect seed germination, plant growth, and physiological and biochemical functions. This review systematically synthesises current research on the impact of MPs on agricultural soil, focusing on their effects on soil structure, chemical properties and microbial diversity. The positive and negative effects of MPs on plant seed germination, growth, and physiological and biochemical processes are critically analysed. Furthermore, the potential ecological risks of MPs to soil and plant health are discussed. Mitigation strategies and future research priorities are proposed to address MPs contamination in agricultural systems. This study aims to provide both theoretical insights and practical references to support the prevention and control of MPs pollution in farmland soils, thereby contributing to sustainable agricultural development and soil ecosystem resilience.

Keywords: plastic waste; agroecosystems; residue; toxicity; physiology and biochemistry

The excellent properties of plastics, such as tensile strength, durability and chemical resistance, have made them an important part of our daily lives and led to their widespread use in packaging, automotive, electronics, construction, agricultural production, and other fields (Xanthos and Walker 2017, Stubbins et al. 2021, Kaandorp et al. 2023, Shaaban et al. 2024). In agriculture, plastics are extensively used in mulching films, irrigation pipes, greenhouses, and fertiliser packaging, and their intensive application generates considerable plastic residues directly in farmland environments. For example, China alone generated approximately 126 500 tons of agricultural plastic waste in 2022 (Tang 2023). The common plastic waste mainly includes polyethylene terephthalate (PET), polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), polycarbonate (PC), polyamide (PA) and polyurethane (PU) (Jin et al. 2022, Yibo et al. 2024). This plastic waste can be converted into microplastics (MPs, particle size: 1 μm–5 mm) and nanoplastics (NPs, particle size: < 1 μm) through multiple pathways, such as photodegradation, physical wear, hydrolysis and biodegradation (Alimi et al. 2018, Zhang et al. 2021, Lin et al. 2022).

Supported by the National Natural Science Foundation, Project No. 31700367; by the Nanping Branch of China Tobacco Fujian Industrial Limited Company Project No. NYK2017-04-04, and by the China Tobacco Henan Industrial Limited Company Project No. A202001.

https://doi.org/10.17221/180/2025-PSE

MPs have the characteristics of small particle size, light weight, difficult to degrade nature, high hydrophobicity, high chemical stability and easy dispersion, which make them easy to migrate and enter the farmland ecosystem (Li et al. 2020a, Chia et al. 2022). Specifically, MPs enter the farmland ecosystem through plastic film degradation, sewage irrigation, sludge utilisation, organic fertiliser application, plastic landfill and atmospheric sedimentation (Ya et al. 2021, Yang et al. 2021, Yu et al. 2021, Huang et al. 2022). Among them, plastic film residue is the main source of MPs pollution in farmland soil (Qi et al. 2020a, b). The accumulation of MPs in soil can alter soil structure, density, porosity, and the water-gas cycle, thereby influencing water retention and nutrient dynamics (Huang et al. 2020). These changes may affect plant germination, growth, and physiological processes (Zhou et al. 2020a, Liu et al. 2023a, Surendran et al. 2023). Moreover, MPs can attach to the surface of plant leaves under the action of wind and raindrop splashing, interfering with gas exchange and photosynthesis, and can also affect the normal growth and development of plants (O'Brien et al. 2023, Zhu et al. 2024). This highlights the urgency of understanding MPs contamination in agricultural systems, where both soil health and plant productivity are at stake. Therefore, the impact of MPs on plants has become a research hotspot for scholars both domestically and internationally.

Currently, researchers have studied the effects of various MPs on the physical and biochemical properties of farmland soil, as well as on plant growth and development. MPs affect the physical properties (such as porosity and aggregate stability), chemical properties (such as pH value and ion strength) and biological characteristics (such as microbial community diversity and abundance) of farmland soil by altering its physical structure (Huang et al. 2020, Zhou et al. 2020a). The particle size, mass concentration, and type of MPs have significant effects on seed germination, growth and development of plants, and this phenomenon has been confirmed in wheat (Qi et al. 2020c, Taylor et al. 2020), corn (Iqbal et al. 2024), rice (Liu et al. 2022), soybean (Wu et al. 2017), cucumber (Li et al. 2020b) and tobacco (Zhang et al. 2022c). However, despite the growing concern, comprehensive reviews focusing specifically on MPs in farmland systems remain scarce. In its context, this work summarises the current research results on MPs in farmland soil, reviews the effects of MPs on the physical structure, chemical properties, and microbial characteristics of farmland soil, and analyses the effects of MPs on plant seed germination, growth, physiology, and biochemistry. The transport of microplastics in the soil-plant system is illustrated in Figure 1. The potential risks to soil and plants from MPs are introduced, and future research directions and priorities related to plants are discussed. This study aims to provide theoretical support and practical reference for the prevention and control of MPs pollution in farmland soil.

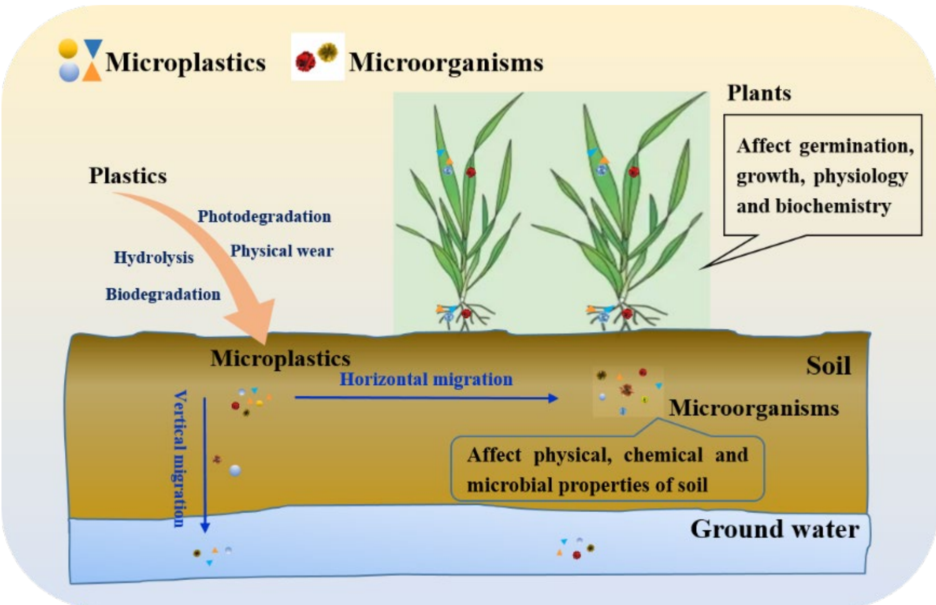

Figure 1. Transport of microplastics in the soil-plant system

https://doi.org/10.17221/180/2025-PSE

EFFECTS OF MICROPLASTICS ON FARMLAND SOILS

Effects of microplastics on soil physical properties. MPs can be embedded into soil pores and porous surfaces through π-π bonds and hydrogen bonding forces, thus altering soil physical properties (Liu et al. 2020, Hu et al. 2023). The combination of MPs and soil aggregates can affect carbon components (Chang et al. 2022a, Rafa et al. 2024). The effects of MPs on soil physical properties are shown in Figure 2 and Table 1. Wang et al. (2024b) reported that the addition of 5% polylactic acid (PLA) MPs can significantly increase the contents of soil organic carbon (SOC) and dissolved organic carbon (DOC) in soil aggregates by 23.7% and 84.2%, respectively. Chen et al. (2024) investigated the impact of varying PE MPs concentrations on soil aggregate carbon stability. The results showed that high concentrations (> 1.0%) of PE MPs could reduce DOC and increase stable carbon components in soil aggregates, such as particulate organic carbon (POC) and mineral-bound organic carbon (MOC). The hydrophobicity of MPs can reduce the water absorption and retention capacity of the soil, and hinder the infiltration and distribution of water along pores, which affects the water absorption efficiency of plant roots (You et al. 2022, Zhang et al. 2022a). Xing et al. (2021) demonstrated that as the MPs content in soil increased from 1% to 7% (*w*/*w*), the high hydrophobicity of MPs hindered soil particle aggregation, leading to an increase in soil porosity and enhanced hydraulic conductivity. Liu et al. (2023b) reported that PLA MPs in soil reduced water retention and permeability, making the soil more susceptible to cracking and shrinkage. Jannesarahmadi et al. (2023) discovered through microscopic imaging technology that the addition of MPs would clog the cracks of bentonite, thereby affecting the evaporation rate of bentonite. This pattern of plugging cracks causes more water to evaporate under dry conditions than under normal conditions (no MPs plugging the gaps).

Migration and transport of MPs in soil. The looseness and porosity of soil provide a prerequisite for the horizontal and vertical migration of MPs, which further expands the range of pollution in soil and groundwater under the action of leaching, gravity, buoyancy and underground runoff (Zhang et al. 2022d, Zhao et al. 2022). Wang et al. (2022c) investigated the migration behavior of polystyrene (PS) MPs in porous media/soil under the action of water flow. The results showed that the migration of MPs is closely related to the particle size, with smaller particles exhibiting significantly higher mobility;

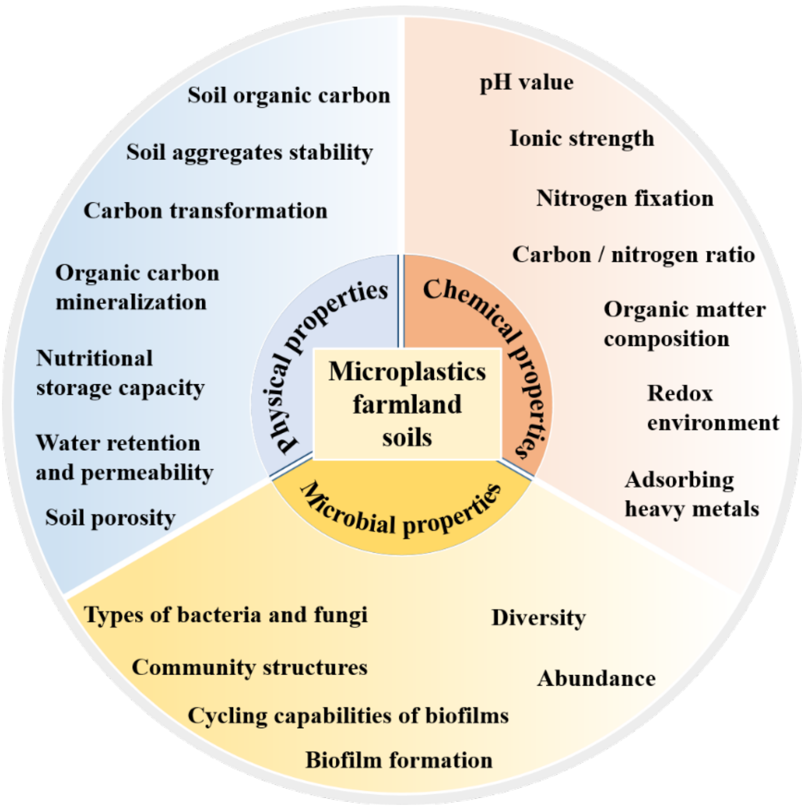

Figure 2. The effects of microplastics on farmland soils

https://doi.org/10.17221/180/2025-PSE

Table 1. The effects of microplastics (MPs) on soil physical, chemical and microbial properties

MPs type (size)	MPs concentration	Effect	Mechanism	Reference
PLA (180 µm)	5% (*w*/*w*)	↑ SOC, DOC content	carbon input from MPs	(Wang et al. 2024b)
PE (600 µm)	2.0% (*w*/*w*)	↓ DOC, ↑ POC, MOC content	surface adsorption (Clay loam)	(Chen et al. 2024)
LDPE (< 50 µm)	7% (*w*/*w*)	↑ soil water conductivity	hydrophobicity of MPs	(Xing et al. 2021)
PLA (40 µm)	10% (*w*/*w*)	↓ soil water retention, permeability, ↓ soil pH, altered redox environment	acidification, redox disturbance	(Liu et al. 2023b)
PE, PVC (50/200 µm)	4.5% (*w*/*w*)	↑ soil water evaporation, ↓ soil porosity	crack blockage (Bentonite)	(Jannesarah-madi et al. 2023)
PS (50 and 500 nm)	0.1 mg/L (aqueous suspension)	smaller particle size → faster MPs migration speed	hydrodynamic transport	(Wang et al. 2022c)
PE, PP (21/29 µm)	3.2% (w/w, sand column)	more dry-wet cycles → deeper penetration depth	cumulative transport effect (sand column)	(O'Connor et al. 2019)
PLA (150–180 µm)	1% (*w*/*w*)	↓ soil mineral N content, ↑ C/N ratio flexibility	N cycling disruption	(Shi et al. 2023)
Nylon (2 mm)	3 g/L (aqueous suspension)	↑ H^+ due to $Pb^{(II)}$ exchange	heavy metal-mediated acidification	(Tang et al. 2020)
PS, PVC (75 µm)	0.5 mg/mL (aqueous suspension)	soil redox environment alteration via $Cr^{(VI)}$ adsorption	redox imbalance	(Zhou et al. 2022)
LDPE (10.4 nm)	6% (*w*/*w*)	aggregation of bacterial and fungal communities	community restructuring	(Gao et al. 2021a)
PE (2 mm)	2 000 pieces/kg	↑ saprophytic fungi abundance	fungal enrichment	(Li et al. 2023a)
PET, PVC (100 µm)	2% (*w*/*w*)	altered bacterial structure	community restructuring	(Zhang et al. 2023b)
PVC (550 µm)	10% (*w*/*w*)	↓ the diversity of bacterial community	community restructuring	(Li et al. 2022b)
PE (200 µm)	2 000 mg/kg (*w*/*w*)	MPs + As, ↑ microbial abundance	metal-MPs interaction	(Zhu et al. 2021)
PE (200 nm)	200 mg/kg (*w*/*w*)	NPs + As, ↓ microbial abundance	metal-MPs interaction	(Zhu et al. 2021)
PE (200 µm)	100 mg/L (aqueous suspension)	↑ biofilm enrichment with higher MPs concentration	biofilm formation	(Li et al. 2024)
PVC, PA, HDPE (150/250/74 µm)	0.5 mg/mL (aqueous suspension)	↑ biofilm enrichment with higher MPs concentration	biofilm formation	(He et al. 2023)
PS (80 nm and 1 µm)	10 mg/L (aqueous suspension)	MPs act as carriers → ↑ virus survival rate	pathogen survival	(Lu et al. 2022)

↑ – increase; ↓ – decrease; → – lead to; *w*/*w* – MPs weight/dry soil weight; PLA – polylactic acid; PE – polyethylene; LDPE – low density polyethylene; PVC – polyvinyl chloride; PS – polystyrene; PP – polypropylene; PET – polyethylene terephthalate; HDPE – high density polyethylene; PA – polyamide

https://doi.org/10.17221/180/2025-PSE

specifically, particles of 50 nm exhibit a migration rate above 85%, while those of 500 nm almost show slow migration. These findings suggest a potential size-related threshold, below which MPs can rapidly migrate and accumulate in deeper soil layers, thereby increasing their environmental persistence and potential biological interactions. O'Connor et al. (2019) reported the migration process of PE and PP MPs in sand column/soil, and found that the number of dry-wet cycles experienced by MPs was positively correlated with the depth of penetration, that is, the more cycles, the greater the depth of penetration. In summary, MPs affect soil physical properties by (*i*) modifying soil aggregation and carbon stability; (*ii*) reducing water-holding capacity *via* pore interference, and (*iii*) enhancing their own mobility under environmental forces. However, the underlying mechanisms remain incompletely understood. For example, the influence of polymer type, shape, and surface charge on soil aggregation or water retention is often overlooked. Future research should prioritise controlled mechanistic studies to clarify these complex interactions.

Effects of microplastics on soil chemical properties. MPs have strong adsorption capacity and can adsorb nutrients (nitrogen, phosphorus, potassium, etc.) and harmful substances (such as heavy metals and organic pollutants) in the soil, and release acidic/alkaline substances during degradation, which affect the pH value, organic matter composition and biological nitrogen fixation (Winkler et al. 2019, Cao et al. 2021, Gao et al. 2021b). The effects of different MPs on soil chemical properties are shown in Figure 2 and Table 1.

Nutrient dynamics and nitrogen cycling. Liu et al. (2023b) discovered that PLA MPs release acidic compounds during degradation, which can decrease the pH value and change the organic matter composition and redox environment of the soil. Shi et al. (2023) explored the inductive impact of new/aged (aged: exposed to ultraviolet light for 14 days) PLA MPs on biological nitrogen fixation, and found that compared to the control group, the biodegradation of both new and aged PLA MPs reduced soil mineral nitrogen content by 91% to 141%, while also expanding the carbon-to-nitrogen (C/N) ratio utilisation range in the soil.

Heavy metal adsorption and mobility. MPs adsorb heavy metal ions and change the soil environment through acidification, ion exchange and other mechanisms, which indirectly enhances the influence of heavy metals on soil chemical properties (Ding et al. 2022, Watson et al. 2023). MPs adsorbing heavy metals (such as Pb and Cr) exhibit strong toxicity to soil because heavy metal ions can react with soil organic matter and minerals, reducing soil pH value and causing soil acidification (Li et al. 2019, Khalid et al. 2021).

pH regulation and redox shifts. Soil acidification accelerates the release of heavy metal ions from the soil solid phase into the soil solution, further intensifying the acidification process (Han et al. 2021, Kicinska et al. 2022). Tang et al. (2020) showed that aging nylon MPs adsorbed $Pb^{(II)}$ through surface carboxyl functional groups complexation with a maximum adsorption capacity of 1.05 mg/g, and the adsorption and release behavior of $Pb^{(II)}$ directly or indirectly alters soil chemical properties (pH, ionic strength, etc.) through toxic effects. Zhou et al. (2022) investigated the adsorption behavior of PS/PVC MPs on the strongly oxidising heavy metal pollutant $Cr^{(VI)}$ and its impact on soil chemical properties, revealing that the adsorption of $Cr^{(VI)}$ by MPs can alter the redox environment of the soil. The mechanism of heavy metal adsorption by MPs affecting soil chemical properties is that MPs adsorb and/or desorb heavy metals through acidity and ion exchange, reducing soil pH and increasing the level of H^+ in the soil (Qi et al. 2020a). During this process, H^+ competes with heavy metals for adsorption sites, decreasing the soil's ability to absorb heavy metals, modifying the decomposition of soil organic matter, and influencing the cycling and availability of nutrients (such as carbon and nitrogen) in the soil (Bostan et al. 2023, An et al. 2024, Chokejaroenrat et al. 2024, Tariq et al. 2024). However, further research is needed to determine whether the effects of MPs on soil chemical properties vary based on MPs size and soil types. Additionally, the synergistic or antagonistic interactions between heavy metals and other pollutants in soil remain unclear.

Effects of microplastics on soil microbial properties. The effects of MPs on soil microbial properties are primarily manifested in the community structure, diversity and abundance of bacteria and fungi (Li et al. 2021, Ma et al. 2023). The effects of different MPs on soil microbial properties are shown in Figure 2 and Table 1. Impacts on community composition and diversity. Gao et al. (2021a) added different concentrations of LDPE MPs into vegetable planting soil and observed that concentrations above 6% significantly promoted the aggregation of bacterial and fungal communities, with notably higher diversity and abundance compared to the control, while concentrations below 0.5% showed minimal impact. This suggests the presence of a concentration-de-

https://doi.org/10.17221/180/2025-PSE

pendent threshold, above which MPs can markedly alter microbial diversity and structure, potentially disrupting soil ecological balance. Li et al. (2023a) observed a significant increase in the abundance of saprophytic fungi treated with PE MPs in soil. Zhang et al. (2023b) explored the impact of different exposure times of 2.0% concentration PET and PVC MPs on soil bacterial communities, and found that short-term exposure (30 days) caused significant changes in bacterial structure, while long-term exposure (360 days) resulted in more similar bacterial community structures compared to the blank control (no MPs exposure for 360 days). Li et al. (2022b) showed that PVC MPs can reduce the diversity of soil bacterial community and inhibit the recovery rate of bacterial community, and this inhibition effect increases with the abundance of MPs. The reason why MPs pollution reduces soil bacterial diversity may be that, on the one hand, chemical toxicity and physical barrier effects can inhibit various sensitive bacteria, and on the other hand, excessive reproduction of dominant bacterial species can occupy the living space of other types of bacteria, leading to a decrease in community diversity (Zhang et al. 2019, Liu et al. 2024). Impacts on functional changes of microorganisms. Wu et al. (2024) found that PS and PVC MPs (10 mg/L) inhibited the specific reduction rates of nitrite and nitrate (SNIRR and SNRR) and reduced the activities of nitrite reductase (NIR) and nitrate reductase (NR). They also increased the size of the symbiotic network, niche breadth and number of keystone species, but reduced microbial cooperation by 13.48%. In addition, exposure to 10 mg/L PVC decreased the specific ammonia oxidation rate (SAOR) and the activity of ammonia monooxygenase (AMO). Li et al. (2025) investigated the effects of PS, PE, and PVC MPs (5%) on nitrogen cycling in soybean rhizosphere soil. PE and PS MPs promoted soybean growth, increased nitrogen content in roots, and enhanced the activity of nitrogen assimilation enzymes. PVC MPs significantly reduced inorganic nitrogen content, inhibited the activities of nitrogen-cycling-related enzymes, and disrupted the microbial community structure in the rhizosphere soil.

MPs as microbial carriers and biofilm promoters. MPs can be used as bacterial and fungal community carriers in soil, providing ideal attachment sites for their growth and promoting the formation of biofilms (He et al. 2023, Li et al. 2023b). Li et al. (2024) exposed freshwater biofilms to PE MPs at different concentrations (0–100 mg/L) for 7 days, and found a positive correlation between MPs concentration and biofilm enrichment. PE MPs treatment enhanced the nitrogen and phosphorus cycling and sulfur cycling capabilities of biofilms, while inhibiting the iron cycling function, suggesting that MPs can be used as carriers to influence biofilm formation and ecological function. He et al. (2023) studied the biofilm formation of PVC, PA and HDPE MPs under a simulated natural environment, and observed that the three MPs could all serve as carriers of bacteria and fungi, leading to biofilm formation. The surface of MPs mainly adsorbs bacteria and other microorganisms through Brownian motion, electrostatic interaction force and van der Waals force (Loiseau and Sorci 2022). Liu et al. (2022) used PS MPs as carriers and T4 bacteriophage as a virus model to study the adsorption capacity of viruses on MPs by purple-side scattering/green fluorescence double-gate flow cytometry. The results showed that PS MPs had a strong adsorption rate (98.6 ± 0.2%) on T4 bacteriophage depending on electrostatic interaction, and could enhance the survival rate of viruses. Effects of co-pollution with heavy metals and MPs. Zhu et al. (2021) revealed the effects of arsenic (As) and PE MPs/NPs composite pollution on soil protozoan communities and bacterial composition and structure, noting that the combined pollution of As + MPs can increase the abundance of soil protista parasites and bacteria, while combined pollution of As + NPs can reduce the abundance of soil protistan consumers. This is because MPs have large particle sizes and low mobility, so MPs typically remain on the root surface or the surface layer of soil, and the As + MPs treatment can provide attachment sites or biofilm formation for soil protozoa, improving their living environment and promoting colonisation and reproduction. In contrast, in the As + NPs treatment, the smaller particle size of NPs allows them to penetrate cell membranes or interact with organelles, exerting direct toxicity on soil protozoan consumers and disrupting their metabolism, phagocytosis and reproduction, ultimately leading to a decrease in their abundance. In conclusion, MPs have a profound impact on soil ecosystems by altering the structure, diversity and abundance of soil microbial communities. MPs can not only adsorb and enrich pollutants in soil, but also act as carriers of bacterial and fungal communities, promote biofilm formation, enhance the survival rate of pathogenic viruses, and thereby disrupt the micro-ecological balance of the soil. However, the degree and direction of these effects likely depend on the specific characteristics of MPs (e.g., polymer type, size, surface

https://doi.org/10.17221/180/2025-PSE

functionalisation, aging status) and soil matrix (e.g., texture, buffering capacity, organic content). Future work should emphasise mechanistic studies across soil types, and explore how MPs-mediated changes influence long-term soil fertility and contaminant fate.

EFFECTS OF MICROPLASTICS ON PLANT SEED GERMINATION

Negative effects. Seed germination is a crucial stage in the life cycle of plants, as it directly influences the early growth and vitality of plants (Li et al. 2022a, Reed et al. 2022). A large number of studies have found that MPs have a significant impact on plant seed germination, mainly affecting germination rate, germination vigor, germination index and vitality index (Dong et al. 2020, Iqbal et al. 2023a). The particle size, concentration and type of MPs are important factors affecting seed germination (Table 2). In most cases, MPs show negative effects on seed germination (Dhevagi et al. 2024, Shi et al. 2024). For example, Wang et al. (2021) studied the effects of different particle sizes and concentrations of PE MPs on soybean seed germination, and the results showed that 6.5 μm PE MPs had more obvious inhibitory effects on soybean seed germination vigor and germination index than 13 μm PE MPs. This is due to the fact that PE particles with smaller diameters have a larger contact area with the seeds, leading to more direct interference with the germination process. At 50 mg/L and 100 mg/L PE MPs (6.5 μm), the germination potential decreased by 20.0% and 15.0%, respectively (Wang et al. 2021). Zeng et al. (2024) observed that PVC and PET MPs (1 g/L) exhibited inhibitory effects on the germination index of non-heading Chinese cabbage seeds, with the inhibition rates of 11.8% and 27.1% for PVC (150 μm) and PET (48 μm), respectively. Zantis et al. (2023) investigated the impact of different concentrations (10^3, 10^5, 10^7 grains/mL) of PS MPs (500 nm) on lettuce seed germination, and found that PS MPs can delay the germination and stem growth of lettuce. In addition, the combined action of MPs and other pollutants intensified the inhibition of seed germination. Bao et al. (2022) explored the physiology and metabolism of wheat under the condition of combined oxytetracycline (OTC) and PE MPs. The combination of PE MPs and OTC can cause toxic effects that inhibit seed germination, leading to a decrease in root elongation, shoot length, fresh weight and vitality index, with the reduction value greater than when only PE MPs are present. The mechanism by which MPs inhibit seed germination is that the accumulation of MPs causes physical blockage of seed surface pores and MPs enter into the interior of seed cells to affect seed physiological activities (Zhang et al. 2022e).

Positive effects. Negative effects are common, but MPs may have a positive effect on plant seed germination under certain conditions. Some related studies have reported that MPs can promote seed germination (Table 2). For example, Zeng et al. (2024) discovered that PE MPs (1 g/L) with small and medium particle sizes (15 μm and 48 μm) enhanced the germination index of non-heading Chinese cabbage seeds, compared to the control, which increased by 9.2% and 8.5%, respectively. Previous results have shown that PVC and PET inhibit the germination of Chinese cabbage seeds, while PE promotes it. This suggests that seeds have species-specific responses to different types of MPs, possibly because PE enhances water absorption, whereas PVC and PET inhibit amylase activity. Wang et al. (2021) found that 6.5 μm PE MPs had almost no effect on the average germination speed of mung bean seeds, but had a promoting effect on mung bean root length, and the promotion degree positively correlated with the concentration of MPs. This promoting effect is due to the unique seed coat structure of mung bean seeds, which can protect them from the toxicity of MPs, and because MPs change the nutrient transfer in the soil environment, resulting in a positive effect on the root growth of mung bean (Wang et al. 2021).

No effects. Few studies have shown that MPs have almost no effect on seed germination. Zhang et al. (2022b) found that 50–100 nm PS NPs/amino-modified polystyrene (PS-NH_2) NPs did not promote or inhibit radicle elongation of hydroponic Chinese cabbage within the concentration range of 0–100 mg/L. The reason for this lack of effect is that the negative charge effect of MPs/NPs can promote the radicle elongation of Chinese cabbage, thus offsetting the inhibitory effect of MPs/NPs on the radicle elongation of Chinese cabbage. The effects of MPs on plant seed germination are shown in Table 2. In summary, various studies consistently indicate that the toxicity of MPs is closely related to particle size, with smaller particles (< 100 μm) exhibiting stronger phytotoxic effects and potential threshold responses. Additionally, different plant species show varying sensitivity to MPs exposure, highlighting species-specific responses. This indicates that both particle size and plant type should be carefully considered when assessing the ecological risks of MPs.

https://doi.org/10.17221/180/2025-PSE

Table 2. The effects of microplastics (MPs) on seed germination, plant growth, physiological and biochemical

Plant type	MPs type (size)	MPs concentration	Effect	Mechanism	Reference
Soybean	PE (6.5 and 13 μm)	500 mg/L (aqueous suspension)	↓ germination potential and speed	physical blockage	(Wang et al. 2021)
Mung bean	PE (6.5 and 13 μm)	500 mg/L (aqueous suspension)	↑ root elongation	soil structure alteration	(Wang et al. 2021)
Non-heading Chinese cabbage	PVC, PET (150/48 μm)	1 g/L (aqueous suspension)	↓ germination index	enzyme inhibition	(Zeng et al. 2024)
Non-heading Chinese cabbage	PE (15 and 48 μm)	1 g/L (aqueous suspension)	↑ germination index	stimulation	(Zeng et al. 2024)
Lettuce	PS (500 nm)	10^7 grains/mL (aqueous suspension)	↓ germination rate and stem growth	cell disruption	(Zantis et al. 2023)
Chinese cabbage	PS/PS-NH_2 (50–100 nm)	10 mg/L (aqueous suspension)	no clear effect	charge interaction	(Zhang et al. 2022b)
Tobacco	LDPE (13 μm)	1 000 mg/L (aqueous suspension)	↓ leaf area, root traits, growth	nutrient uptake inhibition	(Zhang et al. 2022c)
Common bean	LDPE (250–1 000 μm)	2.5% (*w*/*w*)	↓ stem and root growth	soil aeration reduction	(Meng et al. 2021)
Wheat	PPE (3.6–4.0 mm)	0.39% (*w*/*w*)	↓ plant height, stem diameter, leaf area, root glycolysis metabolism	metabolic disruption	(Cui et al. 2024)
Cucurbita pepo L.	PP, PE, PVC, PET (40–50 μm)	0.2% (*w*/*w*)	↓ leaf area, chlorophyll content, photosynthetic efficiency	photosynthesis inhibition	(Colzi et al. 2022)
Maize and peanut	PP, PES (30 μm)	0.4% (*w*/*w*)	↓ biomass, PSII efficiency (F_v/F_m), soluble sugar	PSII disruption	(Zhou et al. 2023)
Corn	PVC (15 μm)	10% (*w*/*w*)	↓ antioxidant enzymes content	oxidative stress	(Zhang et al. 2023a)
Soybean	PE, PLAM (20–60 μm)	1% (*w*/*w*)	↓ POD activity, ↑ CAT activity	redox imbalance	(Lian et al. 2022)
Vicia faba	PE (100 nm)	50 mg/L (aqueous suspension)	↓ CAT activity, ↑ SOD and POD activity	antioxidant enzyme shift	(Jiang et al. 2019)

↑ – increase; ↓ – decrease; *w*/*w* – MPs weight/dry soil weight; PE – polyethylene; PVC – polyvinyl chloride; PET – polyethylene terephthalate; PS – polystyrene; PS-NH_2 – amino modified polystyrene; LDPE – low density polyethylene; PPE – petrochemical polyether; PP – polypropylene; PES – polyester; PLAM – polylactic acid mucopolysaccharides

EFFECTS OF MICROPLASTICS ON PLANT GROWTH, PHYSIOLOGY AND BIOCHEMISTRY

Effects of microplastics on plant growth. MPs have a significant impact on plant growth. Once in the soil, MPs can alter the soil structure and pore distribution, leading to the decrease of water and nutrient absorption function of plants, which in turn weakens the overall growth of plants (Wang et al. 2022a, Jia et al. 2023). The effects of MPs on plant growth are mainly manifested in root elongation, leaf development and stem growth, as shown in Table 2. Meng et al. (2021) revealed the inhibitory effect of different concentrations of LDPE MPs on the growth of common bean stems and roots. High concentration LDPE MPs (2.5%) can significantly reduce the leaves relative chlorophyll content, and

https://doi.org/10.17221/180/2025-PSE

cause the decline of photosynthetic capacity, the slowdown of stem growth and the obstruction of root growth, while low concentration LDPE MPs (0.5%) exhibit almost no effect on common bean growth. Zhang et al. (2022c) investigated the effect of 13 μm LDPE MPs on tobacco growth, and observed that low concentrations MPs (≤ 10 mg/L) slightly inhibited root growth, while high concentrations MPs (≥ 1 000 mg/L) significantly inhibited tobacco leaf area, root configuration and growth characteristics (root length, root area, and root volume). Cui et al. (2024) observed the effects of soil derived petroleum polyether, bio-based polyether, castor oil polyether and straw polyurethane MPs on wheat growth. The results showed that MPs could destroy the metabolic pathways related to glycolysis in wheat roots by transcriptomics and metabolomics, leading to the reduction of plant height, stem diameter and leaf area. Colzi et al. (2022) evaluated the impact of introducing PP, PE, PVC and PET MPs into soil on *Cucurbita pepo* L. growth, and the findings indicated that the four MPs all caused the decrease of leaf area, chlorophyll content and photosynthetic efficiency. This is because MPs can affect nutrient cycling in soil, resulting in poor leaf development, and a reduction in leaf area and plant biomass accumulation (Ren et al. 2021, Yang and Gao 2022). Overall, low concentrations (≤ 0.1% or 10 mg/L) of MPs have a slight inhibitory effect on plant growth, while high concentrations (≥ 1% or 1 000 mg/L) exhibit a severe suppressive effect.

Effects of microplastics on plant physiology and biochemistry. The effects of MPs on plant physiology and biochemistry are mainly manifested in photosynthetic performance, antioxidant performance and soluble protein (Table 2) (Campanale et al. 2022, Naziri et al. 2023). Photosynthetic performance refers to the efficiency of plants converting solar energy into chemical energy through photosynthesis, a process essential for carbon fixation and energy supply, ultimately impacting plant biomass accumulation and yield (Araus et al. 2021, Nowroz et al. 2024).

Disruption of photosynthetic performance. MPs affect the photosynthetic performance of plants by modifying the soil environment and physiological state, resulting in the reduction of photosynthetic efficiency and carbon fixation efficiency, as well as impaired stomatal regulation and disrupted transpiration (Iqbal et al. 2023b). Zhou et al. (2023) explored the effects of polyester (PES) MPs and PP MPs on the physiological and biochemical properties of maize and peanuts. The total biomass, root biomass, maximum photochemical quantum yield (F_v/F_m) of photosystem (PSII), hundred grain weight and soluble sugar contents of maize and peanut were all decreased after PES and PP MPs treatment. Cui et al. (2024) explored that the accumulation of petrochemical polyether (PPE) MPs can suppress glycolysis metabolism in wheat roots. Zhang et al. (2023a) investigated the impact of 10% PVC MPs on corn leaves and observed a decline in the content of antioxidant enzymes. These possible toxic mechanisms suggest that MPs cause mechanical damage by contacting the root system or entering the plant body, hindering nutrient transport, or interfering with plant hormones and signaling pathways, thereby affecting the plant's growth regulation mechanism. In addition, MPs can also indirectly regulate the physiological and biochemical reactions of plants by adsorbing heavy metals (Khalid et al. 2021, Huang et al. 2023). Zong et al. (2021) planted wheat in heavy metal-contaminated soil and found that PS MPs reduced the accumulation of copper and cadmium in wheat seedlings, thereby alleviating heavy metal toxicity. Compared to heavy metals alone treatment, the combined treatment of PS MPs and heavy metals increased the chlorophyll content, improved photosynthesis and reduced the accumulation of reactive oxygen species in wheat. This may be attributed to the adsorption of copper and cadmium heavy metals on the surface-active sites of MPs, which alters their bioavailability in soil, subsequently affecting the plant's toxic response to heavy metals and its physiological and biochemical status. Here, we propose a possible model for the interaction between MPs and heavy metals: (1) MPs enter the soil; (2) MPs adsorb heavy metals through electrostatic interaction or complexation; (3) MPs-heavy metal complexes migrate; (4) MPs regulate the bioavailability of heavy metals to plants; (5) plants absorb heavy metals, and (6) inducing oxidative stress/physiological disorders in plants.

MPs enter the plant through the root system, coming into contact with the cell wall and plasma membrane, causing physical damage, resulting in the rupture or perforation of membrane lipids and disruption of membrane integrity. This membrane damage triggers the cell's defense response, which in turn activates the oxidative stress pathway. MPs induce oxidative stress at the cellular level, disrupting the antioxidant system and amino acid metabolism pathway of plants, and weakening the ability to cope with environmental stress and the growth and devel-

https://doi.org/10.17221/180/2025-PSE

opment of plants (Zhang et al. 2017). MPs-induced oxidative stress can affect the plant antioxidant system through multiple pathways, including reactive oxygen (ROS) species levels disrupt, antioxidant enzymes (such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD)) excessive consume, as well as peroxidation damage to cell membrane lipids (Wang et al. 2024a). Induction of oxidative stress. Lian et al. (2022) demonstrated that PE MPs and polylactic acid mucopolysaccharides (PLAM) MPs can reduce POD activity and increase CAT activity of soybean leaves, significantly affecting amino acid metabolism pathway, disrupting nitrogen metabolic balance, and reducing the ability of soybean to cope with environmental stress. Jiang et al. (2019) reported that treatment with PS MPs (100 nm) reduced root biomass and CAT activity of *Vicia faba*, while increasing SOD and POD activity, with the toxic effect stemming from the accumulation of PS MPs in roots, which blocks cell connections or cell wall pores and obstruct nutrient transport.

Alteration of protein metabolism. Soluble proteins are important metabolites in plant cells, which are involved in a series of physiological and biochemical processes, including enzymatic reaction, metabolic regulation and signal transmission (Guo et al. 2022). MPs inhibit the synthesis and accumulation of soluble proteins in plants by altering the metabolic process, plants consume energy to cope with MPs stress, thereby affecting the growth, development, and stress resistance of plants (Yan et al. 2024). Lian et al. (2022) found that high concentrations (1%) of PLA MPs reduced soluble protein content, weakened anabolic metabolism, and slowed the growth and development of soybeans, indicating that MPs had a negative effect on soybean soluble protein. This may be because soybeans consume a large amount of energy to cope with MPs stress, leading to decreased metabolic function and insufficient energy supply, and thereby affecting the growth and development of soybeans. In summary, MPs inhibit the growth and development of plants by affecting physiological and biochemical indices, such as photosynthetic performance, antioxidant performance, and soluble protein. However, it is worth noting that despite numerous studies indicating the negative impacts of MPs on plants, current research still faces the limitation of a disconnect between environmental concentrations and experimental conditions. In most experiments, the concentrations of MPs used are much higher than the actual level in farmland environments (< 0.1%). While high concentrations are useful for identifying potential hazard thresholds, they may not reflect actual environmental exposure scenarios. In the future, more realistic field experiments need to be conducted to enhance the reliability of environmental risk assessment research.

SOIL-PLANT INTERACTIONS AND SYSTEM-LEVEL FEEDBACK

The accumulation of MPs in the environment not only affects the physicochemical properties and physiological functions of soils and plants, but may also disrupt their interactive mechanisms and system-level feedbacks, thereby altering the structure and ecological functions of the soil-plant system (Zhai et al. 2024). MPs can modify soil physical structures (e.g., aggregate stability and porosity), chemical properties (e.g., pH, electrical conductivity, and cation exchange capacity) and water retention capacity, resulting in interference with water and nutrient cycling and significantly altering the rhizosphere environment and plant-soil interactions. These changes can negatively impact plant growth and development. Moreover, MPs-induced alterations in soil microbial community structure and function may compromise their ecological support roles for plants, such as organic matter decomposition, nutrient transformation and microbial symbiotic interactions, ultimately weakening plant stress resistance. Additionally, plant root responses under MPs stress may further modulate soil microbial activity and chemical properties, forming a complex bidirectional interaction among plants, microbes, and soil. Therefore, to deeply analyse the ecological effects of MPs on soil-plant systems, it is essential to adopt a systems-based perspective that emphasizes the dynamic relationships between soil conditions and plant responses, rather than focusing solely on individual factors.

SOLUTIONS AND MITIGATION STRATEGIES FOR PLASTICS USED IN AGRICULTURE

With the increasing distribution of MPs in agricultural ecosystems, they pose serious challenges to soil health, plant growth and agricultural sustainability. MPs source reduction, soil remediation, biological regulation and green agriculture are effective strategies to solve and alleviate the MPs problem in agriculture (Zhou et al. 2020b, Khan et al. 2023, Nath et al. 2024).

https://doi.org/10.17221/180/2025-PSE

MPs source reduction strategies. Agricultural plastics (such as mulch, greenhouse film, etc.) are an important source of MPs in farmland (Ren et al. 2024). The adoption and promotion of biodegradable film instead of non-degradable film is an effective way to reduce MPs input (Figure 3) (Zhao et al. 2021). For example, PLA and polyadipic acid/butylene terephthalate (PBAT) plastics have good degradation ability in the natural environment, and can be applied to various plant planting patterns, such as corn, cotton, potatoes and other dryland crops (Changlake et al. 2025). The promotion of biodegradable plastics will reduce the production of MPs in farmland. At the same time, management standards for the use of agricultural film should be formulated and implemented, clarifying the technical parameters such as usage scenarios, thickness and degradation cycle of biodegradable film to ensure its safe degradation performance in the environment.

Soil remediation strategies for agricultural MPs. Agricultural soil is the main accumulation site of MPs, so soil remediation plays a crucial role in coping with agricultural MPs pollution (Xu et al. 2025). Reasonable tillage management can effectively mitigate the negative effects of MPs on soil structure and ecological functions. For example, crop rotation and intercropping systems can promote the diversity of plant roots, improve the community structure of microorganisms in soil, and enhance the self-purification and self-recovery abilities of soil (Wezel et al. 2014). The application of organic fertiliser, green fertiliser and biochar in farmland soil can improve the physical and chemical properties of soil, and can also reduce the bioavailability of MPs through adsorption or chemical reaction, thereby reducing their toxicity to the soil ecosystem (Nath et al. 2024). By maintaining the structural stability of topsoil through reduced tillage and no-tillage techniques, the migration and diffusion of MPs in soil can be slowed down, and the interference of MPs on plant roots and microbial communities can be reduced (Bai et al. 2018).

Biological regulation strategies of agricultural ecosystems. The biodiversity of agricultural ecosystems plays an important role in mitigating MPs pollution (Ullah et al. 2025). By regulating and utilising the biological resources in soil, such as microorganisms, plants and animal communities, various ecological

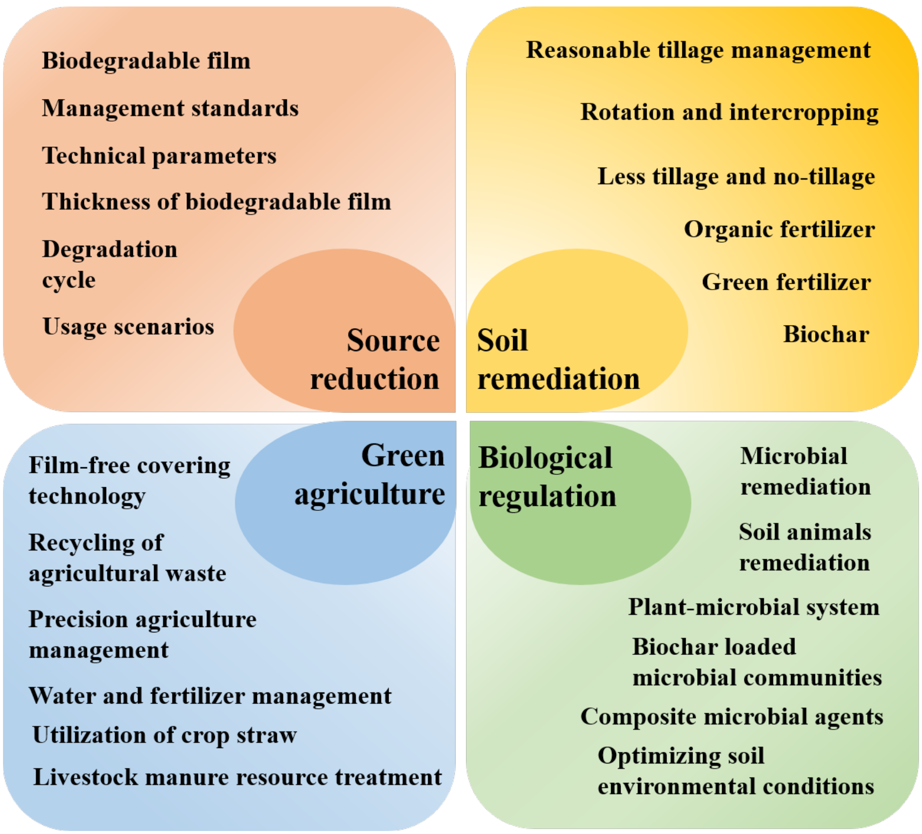

Figure 3. Solutions and mitigation strategies for plastics used in agriculture

https://doi.org/10.17221/180/2025-PSE

benefits can be achieved, including the migration and transformation of MPs, eco-toxicity mitigation and soil function restoration (Yuan et al. 2020, Bhatia et al. 2024). Soil microbial remediation is an important direction of biological regulation. Research has shown that some bacteria and fungi can degrade specific types of plastics, such as *Pseudomonas* sp., *Streptomyces* sp., and *Phanerochaete chrysosporium*, which can degrade PE, PP and PET MPs through their secreted enzymes (Bhatia et al. 2024). Optimising soil environmental conditions (C/N ratio, humidity and pH) can promote the activity of these functional microorganisms and enhance the ability to degrade MPs (Jin et al. 2022). The exploration and development of new biomaterials such as composite microbial agents or biochar loaded microbial communities can also contribute to the bioremediation of MPs pollution in farmland (Dhiman et al. 2023). In addition, the roots and root exudates of some plants can form a "plant-microbe" synergistic degradation system of MPs with microorganisms, thus promoting the restoration of agricultural ecosystems (Zhou et al. 2021). Soil animals (such as earthworms, nematodes, soil arthropods, etc.) can change the spatial distribution and biological accessibility of MPs during feeding, burrowing and moving, promoting chemical reactions between MPs and minerals and organic matter in the soil, thereby reducing the biological toxicity of MPs (Menta and Remelli 2020, Chang et al. 2022b, Rehman et al. 2023). For example, earthworms can accelerate the transformation of MPs and change their physicochemical state through ingestion and excretion processes, which has a positive impact on the stability of soil aggregates (Wang et al. 2022b).

Green agriculture. Developing green agriculture models is an effective way to alleviate MPs pollution at the systemic level (Mallek and Barcelo 2025). Reducing dependence on plastic materials, promoting water and fertiliser management, adopting film-free covering technology and precision agriculture management can help fundamentally reduce the use and residual risks of MPs (Huang et al. 2018, Tahat et al. 2020). Establishing mechanisms for the recycling of agricultural waste and promoting the resource utilisation of crop straw, livestock manure, and other organic waste, such as composting, anaerobic fermentation and bio-carbonisation (Amesho et al. 2023). It can significantly increase the content of soil organic matter and dilute the concentration of MPs, enhancing the anti-disturbance ability of system (Nath et al. 2024).

CONCLUSION AND PROSPECT

This study systematically summarised current research on MPs in farmland soil. It reviewed the effects of MPs on the physical structure, chemical properties and microbial properties of soil, as well as analysed the effects of MPs on plant germination and growth, physiology and biochemistry. MPs can enter farmland through various pathways due to their small size and easy drift. The accumulation of MPs can change soil porosity, water retention capacity and nutrient dynamics, which in turn affects plant growth and development. The influence of MPs varies with particle size, concentration, and type, with notable implications for seed germination and plant health.

The effects of MPs on plants are mainly reflected in seed germination, growth, physiology and biochemistry. The potential risks of MPs to soil and plants are also discussed. At the same time, we propose possible mitigation and/or solution strategies for the issue of agricultural MPs. This work aims to provide theoretical support and practical reference for the prevention and control of MPs pollution in farmland soil.

This work describes the environmental effects of MPs on farmland soil-plant systems. However, current understanding of how MPs influence plants and farmland ecosystems remains limited, and significant knowledge gaps persist regarding their environmental behaviors and underlying mechanisms. As shown in Table 3, future research should further clarify how MPs of different types, sizes, and concentrations affect key plant parameters such as seed germination, growth, photosynthetic efficiency, and antioxidant activity. In addition, the mechanisms governing MPs migration and accumulation in soil-plant systems, their degradation and pollutant release behaviors, and their interactions with soil microbial communities remain poorly characterised. A further challenge lies in developing effective soil remediation strategies and improving crop resilience to MPs stress. These challenges need to be addressed in future studies to better understand the impact of MPs on soil properties, plant health, and agricultural productivity.

Future research prospects. To effectively address the challenges posed by MPs in agricultural ecosystems, future studies should focus on the following key directions:

(1) MPs migration and accumulation mechanisms: it is crucial to understand the transport mechanisms of MPs in soil-plant systems. Research should

https://doi.org/10.17221/180/2025-PSE

Table 3. The research challenges of microplastics (MPs) on farmland soil and plants systems

Research field	Description	Major specific effects of MPs on plants	Suggested priorities	Reference
MPs' migration and accumulation in farmland ecosystems	unclear migration pathways and accumulation patterns within soil-plant systems	smaller MPs (< 100 nm, especially PS and PE) can penetrate root tissues and accumulate in stems and leaves, potentially inhibiting nutrient transport	apply isotope/tracer-labeled MPs with imaging or modeling to track migration	(Jin et al. 2022)
MPs' distribution in soil	no precise distribution model of MPs in different soil types	uneven MPs distribution affects plant root zone exposure and water/nutrient uptake	build spatiotemporal models combining soil properties, land use and MPs traits	(Zhang et al. 2022e)
Impact of MPs on soil physicochemical properties	mechanisms of MPs on soil porosity, water retention, pH and nutrient dynamics	altered soil aeration and reduced water availability can slow seed germination and root elongation	conduct multi-factor experiments to quantify MPs' effects on soil properties	(Tang 2023)
Impact of MPs on soil microbial communities	effects of MPs on microbial diversity, microbiomes and microbial nutrient cycling	microbial imbalance can disturb rhizosphere nutrient cycling, indirectly suppressing plant growth	apply multi-omics and network analyses to detect microbial impacts	(Aralappanavar et al. 2024)
Effects of MPs on oxidase system	mechanism of MPs' effects on SOD, CAT, and POD	excessive ROS generation and enzymatic stress, especially under PS or PVC exposure	establish dose-response curves and toxicity thresholds for MPs by type and size	(Li et al. 2022c)
MPs degradation and removal	decomposition and/or removal mechanism of MPs in soil	persistent MPs increase long-term phytotoxicity risks	study natural degradation, microbial breakdown and removal technologies under field conditions	(Du et al. 2021)
Repair strategy for farmland	MPs adversely affects soil health and crop productivity	MPs may reduce plant yield and biomass accumulation	develop and test microbial and phytoremediation strategies	(Arif et al. 2024)

SOD – superoxide dismutase; CAT – catalase; POD – peroxidase; PS – polystyrene; PE – polyethylene; ROS – reactive oxygen species; PVC – polyvinyl chloride

https://doi.org/10.17221/180/2025-PSE

investigate the influence of environmental factors (such as moisture, temperature and compaction) and soil characteristics (such as texture, organic matter and root architecture) on MPs migration. In the future, with the advancement of advanced tracking technologies, isotope labeling and imaging techniques can be used to study the migration pathways and accumulation patterns of MPs in soil-plant systems and develop their migration and distribution prediction models. Future studies could hypothesise that smaller, uncharged MPs migrate more readily through the soil-plant system and are more likely to be taken up by roots *via* apoplastic pathways. MPs migration experiments using fluorescently labeled and confocal microscopy could help visualise their movement from soil to plant tissues under climate change (e.g., moisture and temperature fluctuations).

(2) Degradation and pollutant release: the degradation process of MPs and the behavior of releasing harmful substances and/or adsorbed pollutants in this process require further investigation. Assessing the long-term impacts of MPs degradation on soil pH and redox environments, especially the dynamic evolution patterns under the complex interaction of soil-heavy metal-organic pollutants. A testable hypothesis could be that MPs and heavy metal compounds exposed to alternating redox conditions exhibit accelerated degradation and higher release rates of adsorbed contaminants. Long-term soil microcosm studies could simulate these redox cycles and monitor changes in MPs structure, pollutant release, and associated shifts in soil chemistry.

(3) Plant physiological and biochemical responses: although some studies have reported the inhibitory effects of MPs on seed germination, growth, development, physiology and biochemistry of plants, the physiological and molecular mechanisms remain unclear. The effects of MPs on plant photosynthesis, nutrient absorption, oxidative stress response and hormone signaling pathways should be further studied. Toxicity biomarkers in plants exposed to MPs can be detected through proteomics, transcriptomics, and metabolomics, helping to explore adaptive responses. For example, experiments could expose model plants (e.g., rice) to MPs of different sizes and types under controlled conditions, then use transcriptomic analysis to identify gene expression changes linked to oxidative stress, metal transporter activity, or hormone biosynthesis, helping to identify toxicity pathways.

(4) Soil microbial ecology and functional disruption: MPs can change the composition of microbial community and inhibit nutrient cycling and organic decomposition of microbial community. The potential of MPs to alter microbial diversity, gene expression and metabolic potential can be analysed using high-throughput sequencing, metagenomics and microbial networks. Exploring microbiome interactions with soil matrix will help to better understand the feedback mechanism between soil matrix and soil ecosystem function. Future experiments may hypothesise that MPs reduce microbial nitrogen cycling activity by disrupting keystone nitrifying/denitrifying reactions. Stable isotope probing (SIP) with ^{15}N-labeled substrates and metagenomic profiling could be employed to track functional changes in microbial communities in MPs-contaminated soils.

(5) Genetic improvement and crop resilience: facing the stress of agricultural soil MPs on plants, it is an effective approach to cultivate crop varieties with high stress resistance to MPs. Genome and gene editing techniques can be used to identify and modify genes related to MPs uptake, migration and degradation in key plant organs to develop plant varieties with higher MPs tolerance. In addition, seed germination, growth and development, physiology and biochemistry of different plant varieties and the function of antioxidant enzyme system can be analysed to select and breed MPs-resistant crops. A working hypothesis might be that certain plant root exudate profiles reduce MPs uptake or oxidative damage. By comparing transcriptomic and metabolomic responses across plant genotypes exposed to MPs, candidate genes linked to MPs resistance could be targeted for CRISPR-based editing.

(6) Remediation and soil restoration technologies: in order to reduce MPs pollution in agricultural soil, comprehensive remediation strategies need to be explored more deeply. For example, microorganisms and microbial complexes can be explored to degrade MPs for bioremediation. Plant species with high MPs adsorption and/or transformation capacity can be selected for phytoremediation. Efficient soil improvement methods can be developed, such as improving the ability to use biochar, compost and clay minerals to fix or degrade MPs. Efficient physical and

https://doi.org/10.17221/180/2025-PSE

chemical treatment methods should be developed to enhance the capabilities of existing methods for filtration, extraction and photooxidative degradation of MPs. Future experiments could test the hypothesis that microbial consortia enriched with plastic-degrading enzymes (e.g., PETase-producing strains) show enhanced degradation efficiency in compost-amended soils. Pilot-scale trials combining biochar and microbial inocula under field-relevant MP concentrations would help validate these approaches.

REFERENCES

Alimi O.S., Budarz J.F., Hernandez L.M., Tufenkji N. (2018): Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environmental Science and Technology, 52: 1704–1724.

Amesho K.T.T., Chinglenthoiba C., Samsudin M.S.A.B., Lani M.N., Pandey A., Desa M.N.M., Suresh V. (2023): Microplastics in the environment: an urgent need for coordinated waste management policies and strategies. Journal of Environmental Management, 344: 118713.

An Q., Wen C., Yan C. (2024): Meta-analysis reveals the combined effects of microplastics and heavy metal on plants. Journal of Hazardous Materials, 476: 135028.

Aralappanavar V.K., Mukhopadhyay R., Yu Y., Liu J., Bhatnagar A., Praveena S.M., Li Y., Paller M., Adyel T.M., Rinklebe J., Bolan N.S., Sarkar B. (2024): Effects of microplastics on soil microorganisms and microbial functions in nutrients and carbon cycling – a review. Science of the Total Environment, 924: 171435.

Araus J.L., Sanchez-Bragado R., Vicente R. (2021): Improving crop yield and resilience through optimization O photosynthesis: panacea or pipe dream? Journal of Experimental Botany, 72: 3936–3955.

Arif Y., Mir A.R., Zielinski P., Hayat S., Bajguz A. (2024): Microplastics and nanoplastics: source, behavior, remediation, and multi-level environmental impact. Journal of Environmental Management, 356: 120618.

Bai Z., Caspari T., Gonzalez M.R., Batjes N.H., Mader P., Bunemann E.K., de Goede R., Brussaard L., Xu M., Santos Ferreira C.S., Reintam E., Fan H., Mihelic R., Glavan M., Toth Z. (2018): Effects of agricultural management practices on soil quality: a review of long-term experiments for Europe and China. Agriculture, Ecosystems and Environment, 265: 1–7.

Bao Y., Pan C., Li D., Guo A., Dai F. (2022): Stress response to oxytetracycline and microplastic-polyethylene in wheat (*Triticum aestivum* L.) during seed germination and seedling growth stages. Science of the Total Environment, 806: 150553.

Bhatia S.K., Kumar G., Yang Y.-H. (2024): Understanding microplastic pollution: tracing the footprints and eco-friendly solutions. Science of the Total Environment, 914: 169926.

Bostan N., Ilyas N., Akhtar N., Mehmood S., Saman R.U., Sayyed R.Z., Shatid A.A., Alfaifi M.Y., Elbehairi S.E.I., Pandiaraj S. (2023): Toxicity assessment of microplastic (MPs): a threat to the ecosystem. Environmental Research, 234: 116523.

Campanale C., Galafassi S., Savino I., Massarelli C., Ancona V., Volta P., Uricchio V.F. (2022): Microplastics pollution in the terrestrial environments: poorly known diffuse sources and implications for plants. Science of the Total Environment, 805: 150431.

Cao Y., Zhao M., Ma X., Song Y., Zuo S., Li H., Deng W. (2021): A critical review on the interactions of microplastics with heavy metals: mechanism and their combined effect on organisms and humans. Science of the Total Environment, 788: 147620.

Chang J., Fang W., Liang J., Zhang P., Zhang G., Zhang H., Zhang Y., Wang Q. (2022a): A critical review on interaction of microplastics with organic contaminants in soil and their ecological risks on soil organisms. Chemosphere, 306: 135573.

Chang X., Fang Y., Wang Y., Wang F., Shang L., Zhong R. (2022b): Microplastic pollution in soils, plants, and animals: a review of distributions, effects and potential mechanisms. Science of the Total Environment, 850: 157857.

Changlake O., Kaewkam P., Lin K.-Y.A., Sirivithayapakorn S., Kobwittaya K. (2025): Generation of biodegradable microplastics from commercially available PBAT and PLA-based plastic bags in water: impacts of UVA and water medium. Journal of Hazardous Materials, 496: 139207.

Chen Z., Wan Q., Zhou P., Li H., Liu Y., Lu Y., Li B. (2024): Microplastics can inhibit organic carbon mineralization by influencing soil aggregate distribution and microbial community structure in cultivated soil: evidence from a one-year pot experiment. Agronomy-Basel, 14: 2114.

Chia R.W., Lee J.-Y., Jang J., Kim H., Kwon K.D. (2022): Soil health and microplastics: a review of the impacts of microplastic contamination on soil properties. Journal of Soils and Sediments, 22: 2690–2705.

Chokejaroenrat C., Hammawiboon N., Poompoung T., Weaoseng P., Laobuthee A., Techauay K., Angkaew M., Worachananant P., Sakulthaew C. (2024): Impacts of microplastic decomposition using heat-activated persulfate on antibiotic adsorption and environmental toxicity. Marine Pollution Bulletin, 205: 116576.

Colzi I., Renna L., Bianchi E., Castellani M.B., Coppi A., Pignattelli S., Loppi S., Gonnelli C. (2022): Impact of microplastics on growth, photosynthesis and essential elements in cucurbita pepol. Journal of Hazardous Materials, 423: 127238.

Cui J., Tian H., Qi Y., Hu X., Li S., Zhang W., Wei Z., Zhang M., Liu Z., Abolfathi S. (2024): Impact of microplastic residues from polyurethane films on crop growth: unraveling insights through transcriptomics and metabolomics analysis. Ecotoxicology and Environmental Safety, 283: 116826.

Dhevagi P., Sahasa R.G.K., Poornima R., Ramya A. (2024): Unveiling the effect of microplastics on agricultural crops – a review. International Journal of Phytoremediation, 26: 793–815.

Dhiman S., Sharma C., Kumar A., Pathak P., Purohit S.D. (2023): Microplastics in aquatic and food ecosystems: remediation coupled with circular economy solutions to create resource from waste. Sustainability, 15: 14184.

Ding T., Wei L., Hou Z., Li J., Zhang C., Lin D. (2022): Microplastics altered contaminant behavior and toxicity in natural waters. Journal of Hazardous Materials, 425: 127908.

Dong Y., Gao M., Song Z., Qiu W. (2020): Microplastic particles increase arsenic toxicity to rice seedlings. Environmental Pollution, 259: 113892.

Du H., Xie Y., Wang J. (2021): Microplastic degradation methods and corresponding degradation mechanism: research status and future perspectives. Journal of Hazardous Materials, 418: 126377.

Gao B., Yao H., Li Y., Zhu Y. (2021a): Microplastic addition alters the microbial community structure and stimulates soil carbon dioxide emissions in vegetable-growing soil. Environmental Toxicology and Chemistry, 40: 352–365.

Gao X., Hassan I., Peng Y., Huo S., Ling L. (2021b): Behaviors and influencing factors of the heavy metals adsorption onto microplastics: a review. Journal of Cleaner Production, 319: 128777.

Guo M., Zhao F., Tian L., Ni K., Lu Y., Borah P. (2022): Effects of polystyrene microplastics on the seed germination of herbaceous ornamental plants. Science of the Total Environment, 809: 151100.

Han X., Wang S., Yu X., Vogt R.D., Feng J., Zhai L., Ma W., Zhu L., Lu X. (2021): Kinetics and size effects on adsorption of $Cu^{(II)}$, $Cr^{(III)}$, and $Pb^{(II)}$ onto polyethylene, polypropylene, and polyethylene terephthalate microplastic particles. Frontiers in Marine Science, 8: 785146.

He S., Tong J., Xiong W., Xiang Y., Peng H., Wang W., Yang Y., Ye Y., Hu M., Yang Z., Zeng G. (2023): Microplastics influence the fate of antibiotics in freshwater environments: biofilm formation and its effect on adsorption behavior. Journal of Hazardous Materials, 442: 130078.

Hu J., Lim F.Y., Hu J. (2023): Characteristics and behaviors of microplastics undergoing photoaging and advanced oxidation processes (AOPs) initiated aging. Water Research, 232: 119628.

Huang D., Wang X., Yin L., Chen S., Tao J., Zhou W., Chen H., Zhang G., Xiao R. (2022): Research progress of microplastics in soil-plant system: ecological effects and potential risks. Science of the Total Environment, 812: 151487.

Huang F., Hu J., Chen L., Wang Z., Sun S., Zhang W., Jiang H., Luo Y., Wang L., Zeng Y., Fang L. (2023): Microplastics may increase the environmental risks of Cd *via* promoting Cd uptake by plants: a meta-analysis. Journal of Hazardous Materials, 448: 130887.

Huang Y., Chen Z.-X., Yu T., Huang X.-Z., Gu X.-F. (2018): Agricultural remote sensing big data: management and applications. Journal of Integrative Agriculture, 17: 1915–1931.

Huang Y., Liu Q., Jia W., Yan C., Wang J. (2020): Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environmental Pollution, 260: 114096.

Iqbal B., Javed Q., Khan I., Tariq M., Ahmad N., Elansary H.O., 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. South African Journal of Botany, 160: 369–375.

Iqbal B., Zhao T., Yin W., Zhao X., Xie Q., Khan K.Y., Zhao X., Nazar M., Li G., Du D. (2023b): Impacts of soil microplastics on crops: a review. Applied Soil Ecology, 181: 104680.

Iqbal S., Li Y., Xu J., Worthy F.R., Gui H., Faraj T.K., Jones D.L., Bu D. (2024): Smallest microplastics intensify maize yield decline, soil processes and consequent global warming potential. Journal of Hazardous Materials, 486: 136993–136993.

Jannesarahmadi S., Aminzadeh M., Raga R., Shokri N. (2023): Effects of microplastics on evaporation dynamics in porous media. Chemosphere, 311: 137023.

Jia L., Liu L., Zhang Y., Fu W., Liu X., Wang Q., Tanveer M., Huang L. (2023): Microplastic stress in plants: effects on plant growth and their remediations. Frontiers in Plant Science, 14: 1226484.

Jiang X., Chen H., Liao Y., Ye Z., Li M., Klobucar G. (2019): Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. Environmental Pollution, 250: 831–838.

Jin T., Tang J., Lyu H., Wang L., Gillmore A.B., Schaeffer S.M. (2022): Activities of microplastics (MPs) in agricultural soil: a review of MPs pollution from the perspective of agricultural ecosystems. Journal of Agricultural and Food Chemistry, 70: 4182–4201.

Kaandorp M.L.A., Lobelle D., Kehl C., Dijkstra H.A.A., van Sebille E. (2023): Global mass of buoyant marine plastics dominated by large long-lived debris. Nature Geoscience, 16: 689–694.

Khalid N., Aqeel M., Noman A., Khan S.M., Akhter N. (2021): Interactions and effects of microplastics with heavy metals in aquatic and terrestrial environments. Environmental Pollution, 290: 13203.

Khan A., Jie Z., Wang J., Nepal J., Ullah N., Zhao Z.-Y., Wang P.-Y., Ahmad W., Khan A., Wang W., Li M.-Y., Zhang W., Elsheikh M.S., Xiong Y.-C. (2023): Ecological risks of microplastics contamination with green solutions and future perspectives. Science of the Total Environment, 899: 165688.

Kicinska A., Pomykala R., Izquierdo-Diaz M. (2022): Changes in soil pH and mobility of heavy metals in contaminated soils. European Journal of Soil Science, 73: 13203.

Li H.-Z., Zhu D., Lindhardt J.H., Lin S.-M., Ke X., Cui L. (2021): Long-term fertilization history alters effects of microplastics on soil properties, microbial communities, and functions in diverse farmland ecosystem. Environmental Science and Technology, 55: 4658–4668.

Li J., Song Y., Cai Y. (2020a): Focus topics on microplastics in soil: analytical methods, occurrence, transport, and ecological risks. Environmental Pollution, 257: 113570.

Li K., Zhang M., Jia W., Xu L., Huang Y. (2023a): Deciphering the effects of LDPE microplastic films on diversity, composition and co-occurrence network of soil fungal community. Applied Soil Ecology, 182: 104716.

https://doi.org/10.17221/180/2025-PSE

Li S., Cai M., Zheng Y., Xu D., Liu H., Song Y., Wang C. (2024): Comprehensive understanding the impacts of polyethylene microplastics (PE-MPs) on freshwater biofilms: tracking from growth, microbial community structure to element metabolisms. Journal of Water Process Engineering, 68: 104716.

Li W., Niu Y., Zheng Y., Wang Z. (2022a): Advances in the understanding of reactive oxygen species-dependent regulation on seed dormancy, germination, and deterioration in crops. Frontiers in Plant Science, 13: 826809.

Li W., Wang Z., Li W., Li Z. (2022b): Impacts of microplastics addition on sediment environmental properties, enzymatic activities and bacterial diversity. Chemosphere, 307: 135836.

Li X., Mei Q., Chen L., Zhang H., Dong B., Dai X., He C., Zhou J. (2019): Enhancement in adsorption potential of microplastics in sewage sludge for metal pollutants after the wastewater treatment process. Water Research, 157: 228–237.

Li Y.-Q., Zhang C.-M., Yuan Q.-Q., Wu K. (2023b): New insight into the effect of microplastics on antibiotic resistance and bacterial community of biofilm. Chemosphere, 335: 139151–139151.

Li Y., Liu L., Meng X., Qiu J., Liu Y., Zhao F., Tan H. (2025): Microplastics affect the nitrogen nutrition status of soybean by altering the nitrogen cycle in the rhizosphere soil. Journal of Hazardous Materials, 490: 137803.

Li Z., Li R., Li Q., Zhou J., Wang G. (2020b): Physiological response of cucumber (*Cucumis sativus* L.) leaves to polystyrene nanoplastics pollution. Chemosphere, 255: 127041.

Li Z., Chang X., Hu M., Fang J.K.-H., Sokolova I.M., Huang W., Xu E.G., Wang Y. (2022c): Is microplastic an oxidative stressor? Evidence from a meta-analysis on bivalves. Journal of Hazardous Materials, 423: 127211.

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

Lin Z., Jin T., Zou T., Xu L., Xi B., Xu D., He J., Xiong L., Tang C., Peng J., Zhou Y., Fei J. (2022): Current progress on plastic/microplastic degradation: fact influences and mechanism. Environmental Pollution, 304: 119159.

Liu D., Iqbal S., Gui H., Xu J., An S., Xing B. (2023a): Nano-iron oxide (Fe_3O_4) mitigates the effects of microplastics on a ryegrass soil-microbe-plant system. ACS Nano, 17: 24867–24882.

Liu P., Lu K., Li J., Wu X., Qian L., Wang M., Gao S. (2020): Effect of aging on adsorption behavior of polystyrene microplastics for pharmaceuticals: adsorption mechanism and role of aging intermediates. Journal of Hazardous Materials, 384: 121193.

Liu R., Liang J., Yang Y., Jiang H., Tian X. (2023b): Effect of polylactic acid microplastics on soil properties, soil microbials and plant growth. Chemosphere, 329: 138504.

Liu X., Yu Y., Yu H., Sarkar B., Zhang Y., Yang Y., Qin S. (2024): Nonbiodegradable microplastic types determine the diversity and structure of soil microbial communities: a meta-analysis. Environmental Research, 260: 119663.

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. Journal of Hazardous Materials, 421: 126700.

Loiseau C., Sorci G. (2022): Can microplastics facilitate the emergence of infectious diseases? Science of the Total Environment, 823: 153694.

Lu J., Yu Z., Ngiam L., Guo J. (2022): Microplastics as potential carriers of viruses could prolong virus survival and infectivity. Water Research, 225: 119115.

Tahat M., Alananbeh K., Othman Y., Leskovar D. (2020): Soil health and sustainable agriculture. Sustainability, 12: 4859.

Ma J., Xu M., Wu J., Yang G., Zhang X., Song C., Long L., Chen C., Xu C., Wang Y. (2023): Effects of variable-sized polyethylene microplastics on soil chemical properties and functions and microbial communities in purple soil. Science of the Total Environment, 868: 161642.

Mallek M., Barcelo D. (2025): Sustainable analytical approaches for microplastics in wastewater, sludge, and landfills: challenges, fate, and green chemistry perspectives. Advances in Sample Preparation, 14: 100178.

Meng F., Yang X., Riksen M., Xu M., Geissen V. (2021): Response of common bean (*Phaseolus vulgaris* L.) growth to soil contaminated with microplastics. Science of the Total Environment, 755.

Menta C., Remelli S. (2020): Soil health and arthropods: from complex system to worthwhile investigation. Insects, 11: 54.

Nath S., Enerijiofi K.E., Astapati A.D., Guha A. (2024): Microplastics and nanoplastics in soil: sources, impacts, and solutions for soil health and environmental sustainability. Journal of Environmental Quality, 53: 1048–1072.

Naziri A., Mina T., Manoli K., Beretsou V.G., Christou A., Michael C., Agathokleous E., Fatta-Kassinos D. (2023): Looking into the effects of co-contamination by micro(nano)plastics in the presence of other pollutants on irrigated edible plants. Science of the Total Environment, 892: 164618.

Nowroz F., Hasanuzzaman M., Siddika A., Parvin K., Caparros P.G., Nahar K., Prasad P.V.V. (2024): Elevated tropospheric ozone and crop production: potential negative effects and plant defense mechanisms. Frontiers in Plant Science, 14: 1244515.

O'Brien S., Rauert C., Ribeiro F., Okoffo E.D., Burrows S.D., O'Brien J.W., Wang X., Wright S.L., Thomas K.V. (2023): There's something in the air: a review of sources, prevalence and behaviour of microplastics in the atmosphere. Science of the Total Environment, 874: 162193.

O'Connor D., Pan S., Shen Z., Song Y., Jin Y., Wu W.-M., Hou D. (2019): Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. Environmental Pollution, 249: 527–534.

Qi R., Jones D.L., Li Z., Liu Q., Yan C. (2020a): Behavior of microplastics and plastic film residues in the soil environment: a critical review. Science of the Total Environment, 703: 134722.

https://doi.org/10.17221/180/2025-PSE

Qi Y., Beriot N., Gort G., Lwanga E.H., Gooren H., Yang X., Geissen V. (2020b): Impact of plastic mulch film debris on soil physicochemical and hydrological properties. Environmental Pollution, 266: 115097.

Qi Y., Ossowicki A., Yang X., Lwanga E.H., Dini-Andreote F., Geissen V., Garbeva P. (2020c): Effects of plastic mulch film residues on wheat rhizosphere and soil properties. Journal of Hazardous Materials, 387: 121711.

Rafa N., Ahmed B., Zohora F., Bakya J., Ahmed S., Ahmed S.F., Mofijur M., Chowdhury A.A., Almomani F. (2024): Microplastics as carriers of toxic pollutants: source, transport, and toxicological effects. Environmental Pollution, 343: 123190.

Reed R.C., Bradford K.J., Khanday I. (2022): Seed germination and vigor: ensuring crop sustainability in a changing climate. Heredity, 128: 450–459.

Rehman S.u., De Castro F., Aprile A., Benedetti M., Fanizzi F.P. (2023): Vermicompost: enhancing plant growth and combating abiotic and biotic stress. Agronomy (Basel, Switzerland), 13: 1134.

Ren S., Wang K., Zhang J., Li J., Zhang H., Qi R., Xu W., Yan C., Liu X., Zhang F., Jones D.L., Chadwick D.R. (2024): Potential sources and occurrence of macro-plastics and microplastics pollution in farmland soils: a typical case of China. Critical Reviews in Environmental Science and Technology, 54: 533–556.

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

Shaaban M., Wang X.-L., Song P., Hou X., Wei Z. (2024): Microplastic pollution and e-waste: unraveling sources, mechanisms, and impacts across environments. Current Opinion in Green and Sustainable Chemistry, 46: 100891.

Shi J., Wang Z., Peng Y., Zhang Z., Fan Z., Wang J., Wang X. (2023): Microbes drive metabolism, community diversity, and interactions in response to microplastic-induced nutrient imbalance. Science of the Total Environment, 877: 162885.

Shi W., Wu N., Zhang Z., Liu Y., Chen J., Li J. (2024): A global review on the abundance and threats of microplastics in soils to terrestrial ecosystem and human health. Science of the Total Environment, 912: 169469.

Stubbins A., Law K.L., Munoz S.E., Bianchi T.S., Zhu L. (2021): Plastics in the earth system. Science, 373: 51–55.

Surendran U., Jayakumar M., Raja P., Gopinath G., Chellam P.V. (2023): Microplastics in terrestrial ecosystem: sources and migration in soil environment. Chemosphere, 318: 137946.

Tang K.H.D. (2023): Microplastics in agricultural soils in China: sources, impacts and solutions. Environmental Pollution, 322: 121235.

Tang S., Lin L., Wang X., Feng A., Yu A. (2020): $Pb^{(II)}$ uptake onto nylon microplastics: interaction mechanism and adsorption performance. Journal of Hazardous Materials, 386: 121960.

Tariq M., Iqbal B., Khan I., Khan A.R., Jho E.H., Salam A., Zhou H., Zhao X., Li G., Du D. (2024): Microplastic contamination in the agricultural soil-mitigation strategies, heavy metals contamination, and impact on human health: a review. Plant Cell Reports, 43: 65.

Taylor S.E., Pearce C.I., Sanguinet K.A., Hu D., Chrisler W.B., Kim Y.-M., Wang Z., Flury M. (2020): Polystyrene nano- and microplastic accumulation at *Arabidopsis* and wheat root cap cells, but no evidence for uptake into roots. Environmental Science Nano, 7: 1942–1953.

Ullah F., Wang P.-Y., Saqib S., Zhao L., Ashraf M., Khan A., Khan W., Khan A., Chen Y., Xiong Y.-C. (2025): Toxicological complexity of microplastics in terrestrial ecosystems. iScience, 28: 111879.

Wang F., Feng X., Liu Y., Adams C.A., Sun Y., Zhang S. (2022a): Micro(nano)plastics and terrestrial plants: up-to-date knowledge on uptake, translocation, and phytotoxicity. Resources, Conservation and Recycling, 185: 106503.

Wang J., Liu W., Wang X., Zeb A., Wang Q., Mo F., Shi R., Liu J., Yu M., Li J., Zheng Z., Lian Y. (2024a): 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. Science of the Total Environment, 907: 167920.

Wang J., Song M., Lu M., Wang C., Zhu C., Dou X. (2024b): Insights into effects of conventional and biodegradable microplastics on organic carbon decomposition in different soil aggregates. Environmental Pollution, 359: 124751.

Wang L., Liu Y., Kaur M., Yao Z., Chen T., Xu M. (2021): Phytotoxic effects of polyethylene microplastics on the growth of food crops soybean (*Glycine max*) and mung bean (*Vigna radiata*). International Journal of Environmental Research and Public Health, 18: 10629.

Wang Q., Adams C.A., Wang F., Sun Y., Zhang S. (2022b): Interactions between microplastics and soil fauna: a critical review. Critical Reviews in Environmental Science and Technology, 52: 3211–3243.

Wang Y., Xu L., Chen H., Zhang M. (2022c): Retention and transport behavior of microplastic particles in water-saturated porous media. Science of the Total Environment, 808: 152154.

Watson M., Tubic A., Solic M., Nikic J., Isakovski M.K., Agbaba J. (2023): Impact of microplastics on the fate and behaviour of arsenic in the environment and their significance for drinking water supply. Processes, 11: 2241.

Wezel A., Casagrande M., Celette F., Vian J.-F., Ferrer A., Peigne J. (2014): Agroecological practices for sustainable agriculture. A review. Agronomy for Sustainable Development, 34: 1–20.

Winkler A., Santo N., Ortenzi M.A., Bolzoni E., Bacchetta R., Tremolada P. (2019): Does mechanical stress cause microplastic release from plastic water bottles? Water Research, 166: 115082.

Wu T., Ding J., Zhao Y.-J., Ding L., Zang Y., Sun H.-J., Zhong L., Pang J.-W., Li Y., Ren N.-Q., Yang S.-S. (2024): Microplastics shaped performance, microbial ecology and community assembly in simultaneous nitrification, denitrification and phosphorus removal process. Science of the Total Environment, 929: 172651.

Wu Y., Gong W., Yang W. (2017): Shade inhibits leaf size by controlling cell proliferation and enlargement in soybean. Scientific Reports, 7: 9259.

Xanthos D., Walker T.R. (2017): International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. Marine Pollution Bulletin, 118: 17–26.

Xing X., Yu M., Xia T., Ma L. (2021): Interactions between water flow and microplastics in silt loam and loamy sand. Soil Science Society of America Journal, 85: 1956–1962.

Xu D., Jin T., Xi B., Gao H., Li X., Huang L., Song J. (2025): Distribution characteristics, influencing factors, and future prospects of MPS derived from agricultural mulching film in farmland soil: a review. Current Opinion in Environmental Science and Health, 47: 100652.

Ya H., Jiang B., Xing Y., Zhang T., Lv M., Wang X. (2021): Recent advances on ecological effects of microplastics on soil environment. Science of the Total Environment, 798: 149338.

Yan Y., Yang H., Du Y., Li X., Li X. (2024): Effects and molecular mechanisms of polyethylene microplastic oxidation on wheat grain quality. Journal of Hazardous Materials, 474: 134816.

Yang C., Gao X. (2022): Impact of microplastics from polyethylene and biodegradable mulch films on rice (*Oryza sativa* L.). Science of the Total Environment, 828: 154579.

Yang L., Zhang Y., Kang S., Wang Z., Wu C. (2021): Microplastics in soil: a review on methods, occurrence, sources, and potential risk. Science of the Total Environment, 780: 146546.

Yibo L., Genshen Y., Yu C., Lei X., Ma X., Xing X. (2024): Microplastics in the agricultural soils: pollution behavior and subsequent effects. Land Degradation and Development, 35: 4455–4471.

You X., Wang S., Li G., Du L., Dong X. (2022): Microplastics in the soil: a review of distribution, anthropogenic impact, and interaction with soil microorganisms based on meta-analysis. Science of the Total Environment, 832: 154975.

Yu Z.-F., Song S., Xu X.-L., Ma Q., Lu Y. (2021): Sources, migration, accumulation and influence of microplastics in terrestrial plant communities. Environmental and Experimental Botany, 192: 104635.

Yuan J., Ma J., Sun Y., Zhou T., Zhao Y., Yu F. (2020): Microbial degradation and other environmental aspects of microplastics/plastics. Science of the Total Environment, 715: 136968.

Zantis L.J., Rombach A., Adamczyk S., Velmala S.M., Adamczyk B., Vijver M.G., Peijnenburg W., Bosker T. (2023): Species-dependent responses of crop plants to polystyrene microplastics. Environmental Pollution, 335: 122243.

Zeng X., Yang X., Tang X., Xu L., Hu J., Wang M., Wang-Pruski G., Zhang Z. (2024): The effect of microplastics with different types, particle sizes, and concentrations on the germination of non-heading chinese cabbage seed. Agriculture-Basel, 14: 2056.

Zhai Y., Bai J., Chang P., Liu Z., Wang Y., Liu G., Cui B., Peijnenburg W., Vijver M.G. (2024): Microplastics in terrestrial ecosystem: exploring the menace to the soil-plant-microbe interactions. TrAC Trends in Analytical Chemistry, 174: 117667.

Zhang H., Huang Y., An S., Zhu Z. (2022a): A review of microplastics in soil: distribution within pedosphere compartments, environmental fate, and effects. Water, Air, and Soil Pollution, 233: 380.

Zhang H., Liang J., Luo Y., Tang N., Li X., Zhu Z., Guo J. (2022b): Comparative effects of polystyrene nanoplastics with different surface charge on seedling establishment of chinese cabbage (*Brassica rapa* L.). Chemosphere, 292: 133403.

Zhang K., Hamidian A.H., Tubic A., Zhang Y., Fang J.K.H., Wu C., Lam P.K.S. (2021): Understanding plastic degradation and microplastic formation in the environment: a review. Environmental Pollution, 274: 116554.

Zhang K., Gao N., Li Y., Dou S., Liu Z., Chen Y., Ma C., Zhang H. (2023a): Responses of maize (*Zea mays* L.) seedlings growth and physiological traits triggered by polyvinyl chloride microplastics is dominated by soil available nitrogen. Ecotoxicology and Environmental Safety, 252: 114618.

Zhang M., Zhao Y., Qin X., Jia W., Chai L., Huang M., Huang Y. (2019): Microplastics from mulching film is a distinct habitat for bacteria in farmland soil. Science of the Total Environment, 688: 470–478.

Zhang R., Huang L., Deng Y., Chi J., Zhang Y., Wei Z., Zhang M. (2017): Phenolic content and antioxidant activity of eight representative sweet corn varieties grown in south China. International Journal of Food Properties, 20: 3043–3055.

Zhang S., Gao W., Cai K., Liu T., Wang X. (2022c): Effects of microplastics on growth and physiological characteristics of tobacco (*Nicotiana tabacum* L.). Agronomy-Basel, 12: 12112692.

Zhang X., Chen Y., Li X., Zhang Y., Gao W., Jiang J., Mo A., He D. (2022d): Size/shape-dependent migration of microplastics in agricultural soil under simulative and natural rainfall. Science of the Total Environment, 815: 152507.

Zhang X., Li Y., Lei J., Li Z., Tan Q., Xie L., Xiao Y., Liu T., Chen X., Wen Y., Xiang W., Kuzyakov Y., Yan W. (2023b): Time-dependent effects of microplastics on soil bacteriome. Journal of Hazardous Materials, 447: 130762.

Zhang Z., Cui Q., Li C., Zhu X., Zhao S., Duan C., Zhang X., Song D., Fang L. (2022e): A critical review of microplastics in the soil-plant system: distribution, uptake, phytotoxicity and prevention. Journal of Hazardous Materials, 424: 127750.

Zhao S., Zhang Z., Chen L., Cui Q., Cui Y., Song D., Fang L. (2022): Review on migration, transformation and ecological impacts of microplastics in soil. Applied Soil Ecology, 176: 104486.

Zhao Z.-Y., Wang P.-Y., Wang Y.-B., Zhou R., Koskei K., Munyasya A.N., Liu S.-T., Wang W., Su Y.-Z., Xiong Y.-C. (2021): Fate of plastic film residues in agro-ecosystem and its effects on aggregate-associated soil carbon and nitrogen stocks. Journal of Hazardous Materials, 416: 125954.

Zhou B., Wang J., Zhang H., Shi H., Fei Y., Huang S., Tong Y., Wen D., Luo Y., Barcelo D. (2020a): Microplastics in agricultural soils

https://doi.org/10.17221/180/2025-PSE

on the coastal plain of hangzhou bay, east China: multiple sources other than plastic mulching film. Journal of Hazardous Materials, 388: 121814.

Zhou J., Wen Y., Marshall M.R., Zhao J., Gui H., Yang Y., Zeng Z., Jones D.L., Zang H. (2021): Microplastics as an emerging threat to plant and soil health in agroecosystems. Science of the Total Environment, 787: 147444.

Zhou W., Wang Q., Wei Z., Jiang J., Deng J. (2023): Effects of microplastic type on growth and physiology of soil crops: implications for farmland yield and food quality. Environmental Pollution, 326: 121512.

Zhou Y., Wang J., Zou M., Jia Z., Zhou S., Li Y. (2020b): Microplastics in soils: a review of methods, occurrence, fate, transport, ecological and environmental risks. Science of the Total Environment, 748: 141368.

Zhou Z., Sun Y., Wang Y., Yu F., Ma J. (2022): Adsorption behavior of $Cu^{(II)}$ and $Cr^{(VI)}$ on aged microplastics in antibiotics-heavy metals coexisting system. Chemosphere, 291: 132794.

Zhu D., Li G., Wang H.-T., Duan G.-L. (2021): Effects of nano- or microplastic exposure combined with arsenic on soil bacterial, fungal, and protistan communities. Chemosphere, 281: 130998.

Zhu L., Kang Y., Ma M., Wu Z., Zhang L., Hu R., Xu Q., Zhu J., Gu X., An L. (2024): Tissue accumulation of microplastics and potential health risks in human. Science of the Total Environment, 915: 170004.

Zong X., Zhang J., Zhu J., Zhang L., Jiang L., Yin Y., Guo H. (2021): Effects of polystyrene microplastic on uptake and toxicity of copper and cadmium in hydroponic wheat seedlings (*Triticum aestivum* L.). Ecotoxicology and Environmental Safety, 217: 112217.

Received: April 25, 2025
Accepted: November 20, 2025
Published online: December 9, 2025