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REVIEW

Microplastics and heavy metals dynamics: a potential threat to soil health and food safety

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Abstract

Microplastics (MPs) and adsorbed heavy metals (HMs) pose a potential threat to agricultural soil, crops, and is a challenge for food safety. MPs < 1 µm in size are absorbed by crops from the agricultural soil and cause physiological disturbances in plant bodies, ultimately affecting plant metabolic activities. Furthermore, MPs adsorb HMs on their surfaces, affecting their availability for plants. Previous research studies have focused on the adsorption/desorption of HMs but lack a clear mechanism, duration of adsorption, and influencing factors under field conditions. Most research studies have focused on laboratory-controlled experiments, while very limited research exists under field conditions where MPs–soil–plant interactions and complex soil chemistry are discussed. Therefore, research in field conditions (where other influencing factors also exist) is needed for a better understanding of the MPs adsorption/desorption mechanism, duration of desorption, influencing factors, and their effects on plant physiology for different HMs. This review discusses adsorption/desorption of HMs, impact on soil health, and crop physiology. Significant research gaps exist in MPs transport, adsorption/desorption mechanisms, influencing factors, and impacts on crop physiology, which need to be studied in field conditions. Filling the gaps in existing knowledge and enhancing interdisciplinary research will be crucial in creating effective strategies to reduce the effects of MPs pollution in agricultural systems, which will ensure environmental sustainability and food safety.

Keywords Microplastics · Heavy metals · Adsorption/desorption · Field conditions · Food safety

Introduction

Plastic waste is a global concern impacting agricultural soil health and crop physiology. Global gross production of virgin plastics was estimated to be 400 million tons annually, with a compound annual growth rate of 6.4% (Tathavadekar 2025). Most plastic waste is recalcitrant and persists in the environment, but the majority are broken into smaller pieces through weathering (Ganguly et al. 2026; Mohsin & Zaid 2025). Plastic pieces smaller than 5 mm are considered MPs, and they have significant environmental concerns due to their prevalent presence and potential environmental impacts. MPs are considered as significant contaminants in agricultural soil, where they adversely impact soil health,

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microbial community, and crop physiology (Nwankwo et al. 2025; Tariq et al. 2024). Additionally, MPs act as vectors for HMs and other contaminants, potentially improving their bioavailability for crop plants (Mo et al. 2026; Pathak et al. 2026). MPs also affect soil structure by altering soil particles compaction, porosity, and water-holding capacity, which ultimately affect soil health and plant physiology (Lozano et al. 2021a, b; Shah et al. 2023). These MPs are introduced into agricultural soil through various pathways, including sewage sludge, agricultural processes, atmospheric deposition, urban runoff, and the degradation of plastics used in farming (Bhowmik & Saha 2026). This accumulation of MPs alters soil health, plant growth, and ultimately affects food production (Hasan & Tarannum 2024). Therefore, understanding the impacts of MPs contamination in the soil environment is necessary for advancing effective agricultural management strategies.

The study of MPs and associated contaminants in the agricultural environment is crucial, as it addresses the dual challenge of environmental pollution and food safety, mainly concerning the MPs adsorption/desorption dynamics for HMs, affecting plant physiology, and causing threats to agricultural productivity. MPs have profound adsorption/desorption capacities for HMs due to their large surface area and hydrophobic properties, which can lead to bioaccumulation and ultimately entry into the food chain, creating risk to human beings (Mo et al. 2026). This adsorption process is a noncovalent interaction in which HMs retain on the MPs surfaces and alter their availability to crops and soil microorganisms (Sharma et al. 2024). Therefore, a comprehensive study is crucial not only for environmental pollution management, but also for ensuring sustainable agricultural practices and food safety, in the pace of growing MPs pollution (Xiao et al. 2024). This review paper aims to evaluate the current research studies about the impacts of MPs on soil health plant physiology, with particular focus on MPs adsorption/desorption potential for different HMs, while identifying key research gaps for sustainable agricultural practices and their management.

Microplastic types

MPs are classified into primary and secondary, based on their origin (Fig. 1). Primary-microplastics (PMPs) are intentionally synthesized at microscopic sizes for use in personal care products, air-blasting media, industrial abrasives, and as precursors in plastic production (Mathew et al. 2024; Song et al. 2024). These PMPs enter the environment directly in their small form and are often more uniform in size and shape (Mathew et al. 2024). In contrast, secondary-microplastics (SMPs) are generated through the fragmentation and degradation of larger plastic items, such as bottles, bags, fishing gear, packaging, and agricultural films. This degradation is accelerated by environmental factors, such as temperature changes, mechanical abrasion, ultraviolet (UV) radiation, and microbial activity, to form highly heterogeneous MPs particles which differ in size, shape, and composition (polymer type) (Wang et al. 2026).

Structurally, MPs exist in different morphological forms, such as fibers (made of synthetic textiles), films (made of degraded plastic bags), fragments (weathered plastics), foams (made of polystyrene packaging, insulation) and pellets (made of raw plastic materials) (Lozano et al. 2021a). MPs are composed of different types of polymers, such as polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), polyamide (PA), polyurethane (PU), and polycarbonate (PC) (Fig. 1). The surface morphology of each type of polymer has specific physico-chemical characteristics, and their distribution in the environment, persistence, and interactions with other pollutants, including HMs and organic contaminants (Ali et al. 2026; ul Haq et al. 2020). With this diversity of MPs origin, structure, and polymer composition, the study of MPs pollution and its environmental impacts is challenging (Singh & Demirsöz, 2022).

Sources of MPs in agricultural soil

Many sources contribute MPs to agricultural soil, including sewage sludge, agricultural processes, atmospheric deposition, urban runoff, improper waste management, and industrial activities (Kumari et al. 2025). In agricultural soil, the biosolids and sewage sludges are the most important sources of MPs (Khan et al. 2026). Mahon et al., (2017) identified that MPs that are found in sewage sludges are used in agriculture as fertilizers, which leads to soil contamination. Roughly 63,000–430,000 tons of MPs are added to European farmland per year via sewage sludge application (Piehl et al. 2018). In addition to biosolids, agricultural practices also contribute to contamination of MPs in terms of plastic mulching and films (Tolba et al. 2026). Moreover, Radfard et al., (2023) identified that MPs numbers were high in both biosolid-untreated (664 MP/kg), and treated fields (874 MP/kg). However, there is a lack of significant difference between untreated and treated soils. Furthermore, MPs concentrations are higher in the summer suggesting that runoff, erosion, and wind transport may be removing MPs from these systems (Radfard et al. 2023). Furthermore, the application of fertilizers and pesticides also contains MPs as an additive or as packaging material, which can worsen the problem (Liu et al. 2024). Another notable pathway of MPs is the atmospheric deposition to enter the agricultural soil. Research studies showed that MPs can be transported through the air and can be placed onto the soil surface, even in the less contaminated rural areas. Research studies have found that atmospheric deposition estimation ranges from

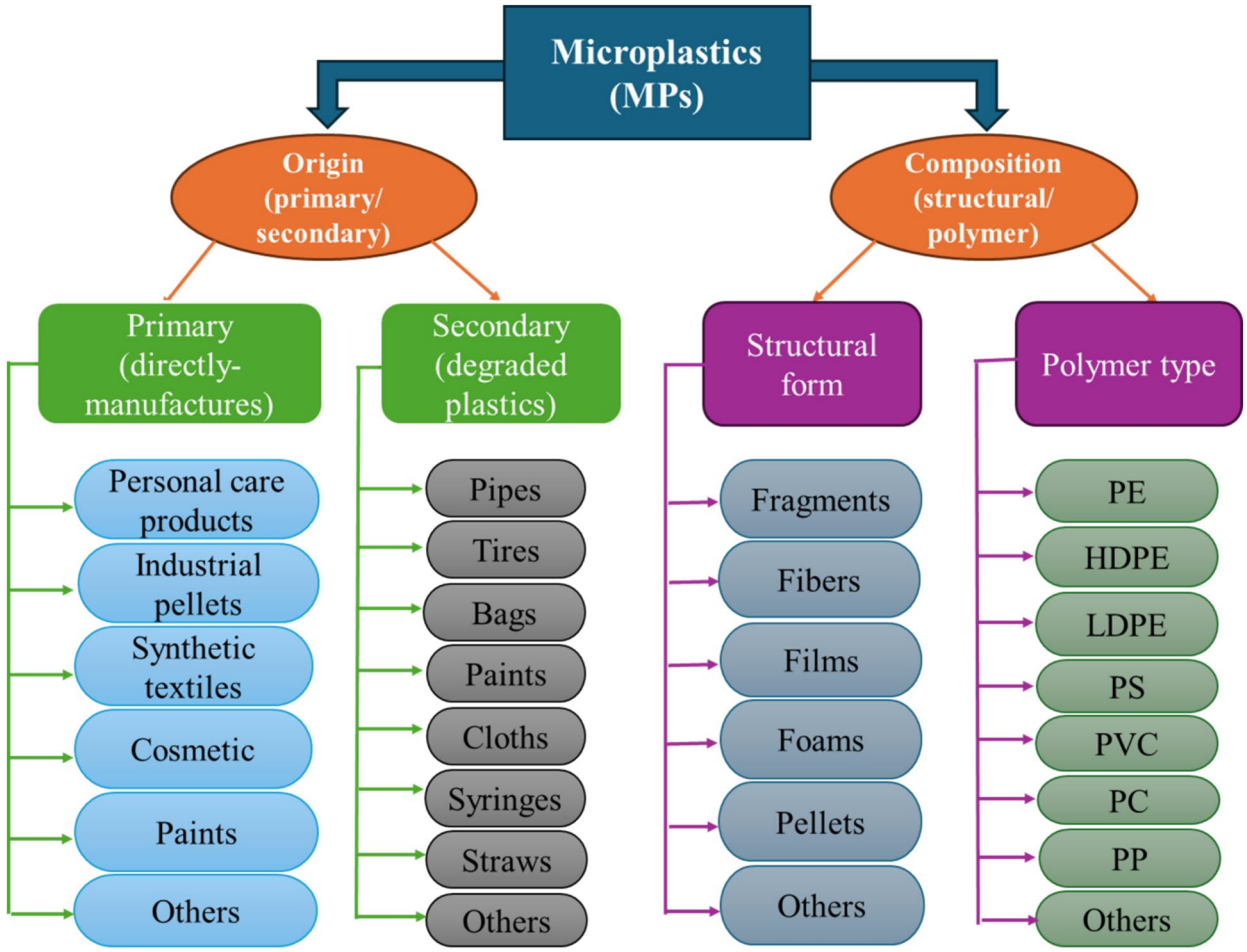

Fig. 1 MPs types (based on origin, polymer type, and structural form), *PE* polyethylene, *HDPE* high-density polyethylene, *LDPE* low-density polyethylene, *PS* polystyrene, *PVC* poly-vinyl chloride, *PC* polycarbonate, *PP* polypropylene

136.5 to 512 MPs particles per square meter per day (Shah et al. 2025a, b). Atmospheric deposition enables the horizontal distribution of MPs contamination across geographical locations, further exacerbating the problem of soil contamination. In addition to this, another important source of MPs in agricultural soil is the urban runoff, particularly in urban areas. Urban runoff comprises stormwater, which may carry MPs along the streets, buildings, and other surfaces on the land to the water bodies nearby and eventually to the agricultural lands (Salehi et al. 2025). Most studies found that tire wear particles are the main contributors to contamination in agricultural soil, underscoring the role of urban infrastructure in enabling MPs transport (Fig. 2).

Mechanisms of MPs transport and accumulation in soil

The transport of MPs involves several mechanisms, which are determined by different environmental factors and biotic activities. The application of sludge-based fertilizers is one of the main pathways for the entry of MPs into agricultural soil. Research also indicates that over time, sludge compost products that include MPs may accumulate in agricultural soils (Garbounis et al. 2026). The vertical transport of MPs within the soil profile is mediated by earthworms (Fig. 3). Upon intake of MPs by earthworms, the MPs partially decompose and are dispersed into the soil (Zhang et al. 2022). Another mechanism that may help to transport MPs is runoff, but its role is usually regarded as less than that of other mechanisms. The runoff of MPs can also be dependent on morphology, size, and polymer type. Polymers of light density, such as polypropylene, are more susceptible to wind and surface runoff, especially at certain times of the year (Radford et al. 2023). Earthworms and other soil biota play a crucial role in the transportation of MPs. These organisms can incorporate MPs into their burrows and help them to transport further in the soil (Fig. 3). The distribution of MPs may shift with this process, becoming more accessible to other soil organisms and possibly entering food webs (de Souza et al. 2018; Radford et al. 2023). The MPs

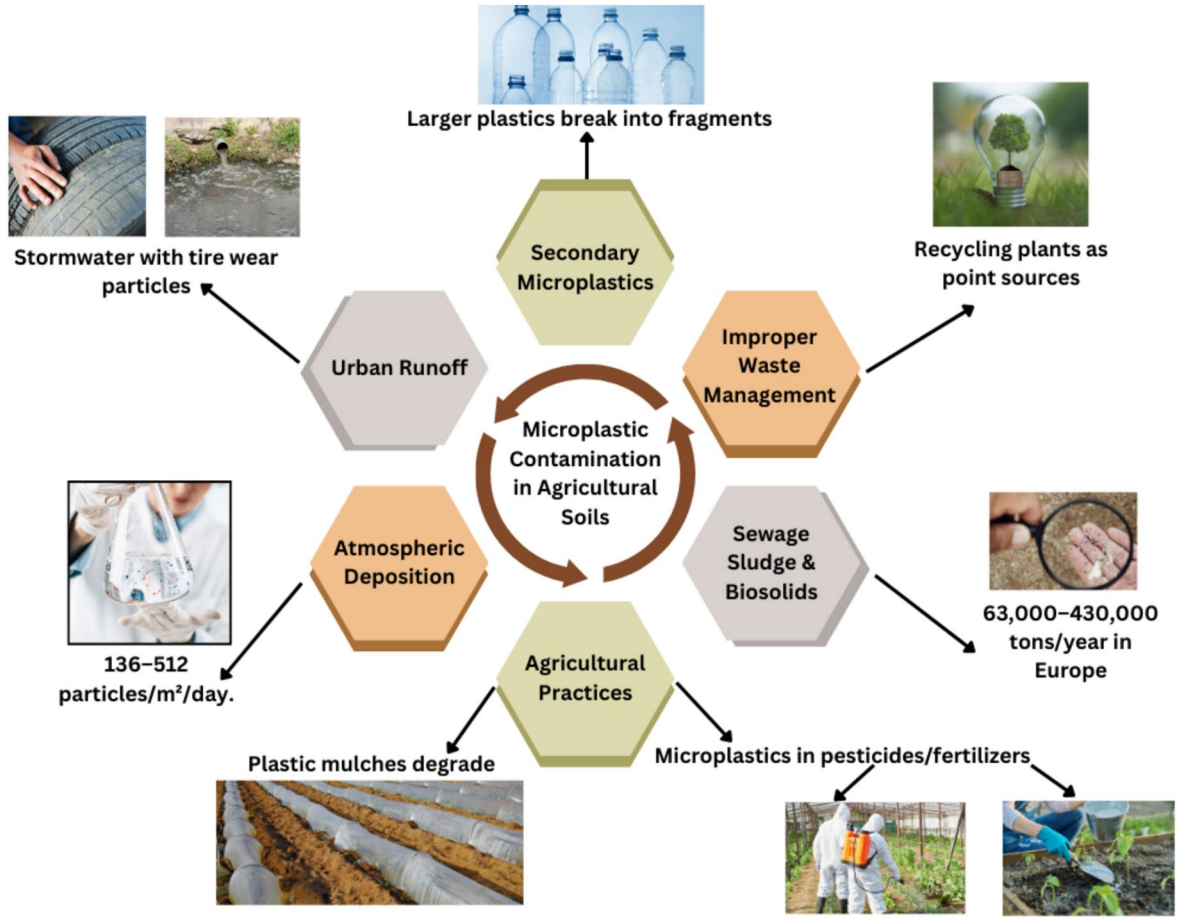

Fig. 2 Sources of MPs in agricultural soil

are also transported through the water-current pathways in soil, such as earthworm burrows, which are created when water flows quickly through the burrows. These earthworm burrows enhance vertical dispersion of MPs, allowing them to reach deeper soil horizons effectively (Zhang et al. 2025a, b, c). Moreover, small sized MPs accumulate more in soil due to their easy mixing process and faster vertical diffusion. Smaller MPs have an impact on behavior and interactions with soil components because of more likely to remain in soil aggregates (Li et al. 2025; Luo et al. 2024).

Impacts of MPs on agricultural soil and plant physiology

Impacts on soil health

MPs cause substantial changes in the key properties of soil, such as structure, porosity, aggregation, bulk density, and water-holding capacity. Such physical alterations can limit the exchange of gases, water infiltration, root penetration and eventually disturb soil health. The extent of such effects is extremely context-specific and depends on MPs shape (e.g., fibers, fragments, films), size, aging, soil texture, and organic matter content (Preininger et al. 2024; Sarfraz et al. 2025). MPs are also capable of altering the soil chemistry, including pH and hydrophobicity, which can change the availability and mobility of nutrients. Moreover, MPs have the potential to be carriers of HMs and organic pollutants, forming mobile complexes and influencing the behavior and bioavailability of contaminants in the rhizosphere (Wang et al. 2024; Yang et al. 2025). All these physical and chemical alterations have the potential to decrease soil fertility and resilience, but other studies have also indicated temporary or condition-specific gains (Rehman et al. 2025).

By prioritizing soil health, MPs undermine the structural and chemical integrity of soils, potentially making them less fertile, resilient, and able to sustain crops in the long term. The effects of MPS may include the disruption of soil aggregation, reduced water retention, as well as disrupted nutrient cycling, which lead to less favorable conditions of root growth and microbial activity. MPs with their co-contaminants (HMs and organic) change soil chemistry and can increase the mobility and bioavailability of toxic substances, increasing risks to soil quality (Wang et al. 2024; Yang et al.

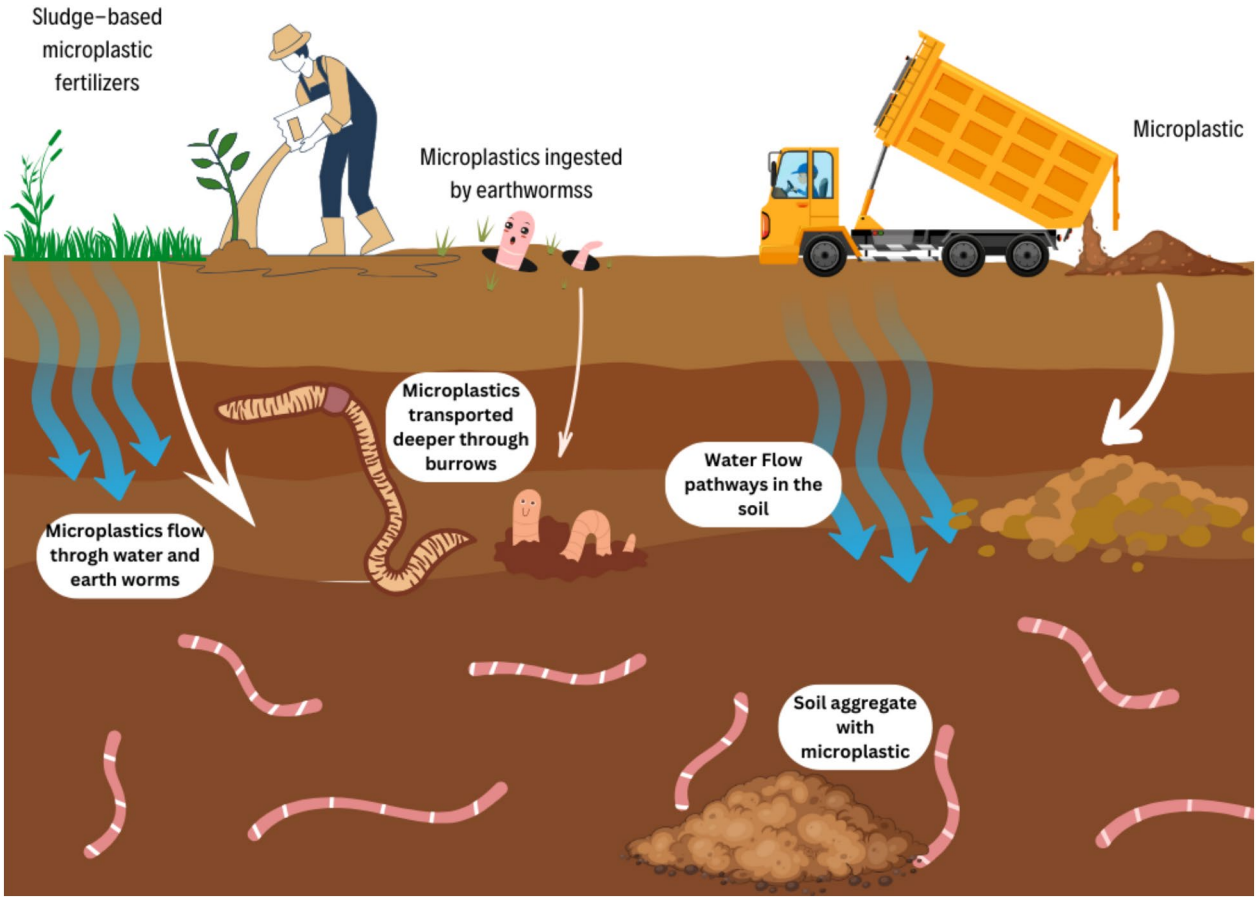

Fig. 3 Mechanism of MPs transport in soil and accumulation

2025). Mitigation strategies should thus consider both physical and chemical effects with emphasis on sustainable soil amendments, such as biochar, compost, and other organic amendments, that can enhance soil structure, increase soil retention, and alleviate effects of co-contaminants. Biodegradable plastics and other less harmful alternatives should be considered not only in terms of limiting the accumulation of MPs, but also in terms of their long-term interactions with the soil systems. To preserve soil health and ecosystem services in agricultural settings, comprehensive management strategies that combine soil amendment strategies, plastic input reduction, and thorough evaluation of possible trade-offs are needed (Ren et al. 2025; Sharma et al. 2023; Verma et al. 2023).

Impacts on soil microbial flora

MPs have a great influence on the soil microbial flora, changing their structure and functions (Fig. 4 and Table 1). It has been found out that the introduction of MPs changes the microbial community of the soil and, in turn, the ratio of pathogenic and beneficial microorganisms (de Souza et al. 2018; Li et al. 2024). These changes can be attributed to the direct interactions with microorganisms and modifications to soil physicochemical properties, such as increased nutrient availability and hydrophobicity (Fu et al. 2023). Moreover, MPs may also influence enzymatic processes required in nutrient cycles, thus disrupting the health and fertility of the soil. Other researchers show that MPs present new niches, which can stimulate the activity of microbes, and in general, their impact is to slow down the beneficial activity of microbes, which may potentially decrease crop yield (Kim et al. 2023; Lin et al. 2020; Shi et al. 2025). Additionally, harmful pathogens may be encouraged during transportation by MPs, which increases environmental issues (Yang et al. 2023). Thus, more knowledge about the processes by which MPs disrupt the soil microbial communities is needed to implement efficient management strategies to mitigate plastic pollution and its consequences on agricultural ecosystems (Šerá et al. 2022).

MPs can also change the microbial composition and modify the activity of essential enzymes involved in the carbon, nitrogen, and phosphorus cycle, such as β-glucosidase, cellobiosidase,

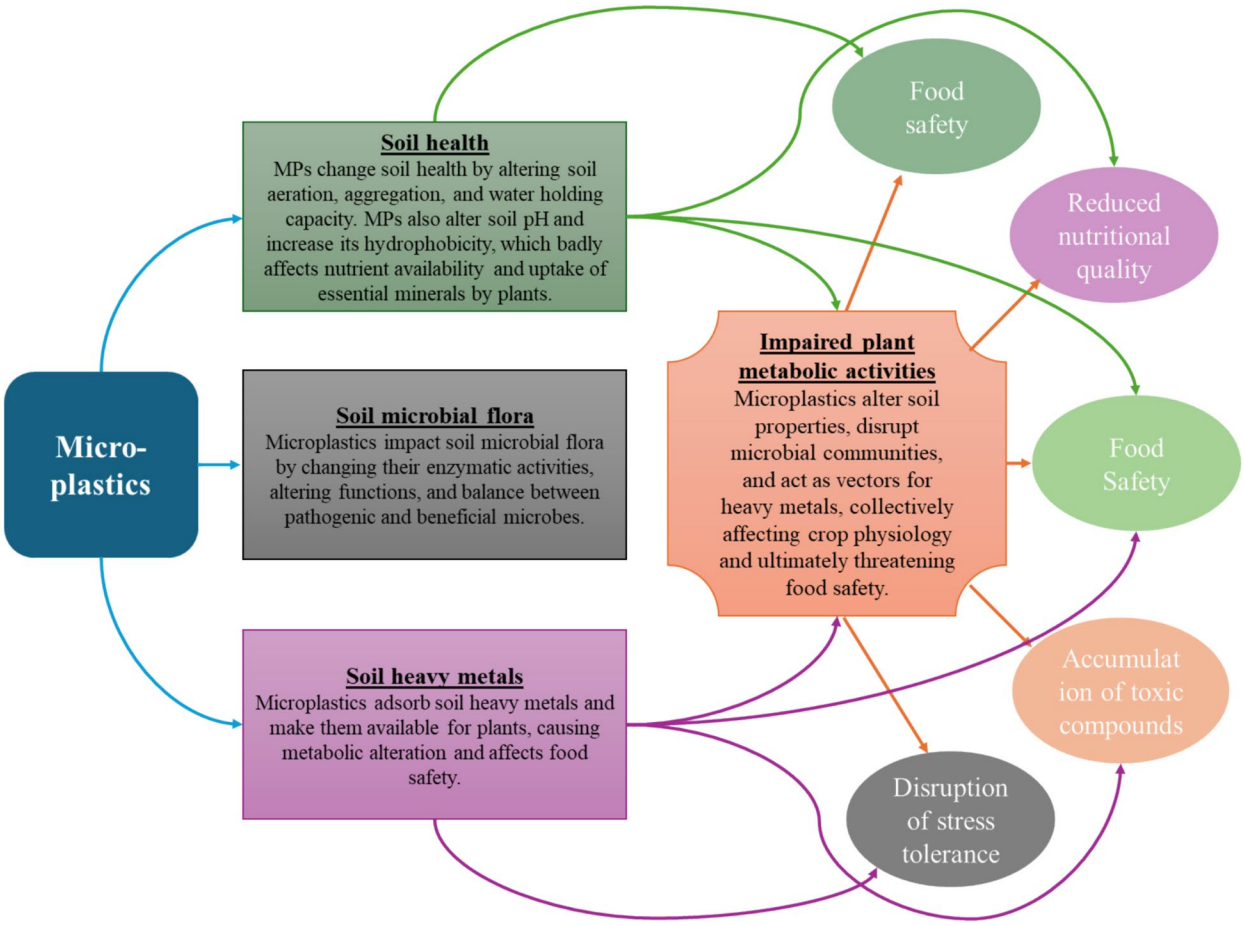

Fig. 4 MPs and HMs alter soil and plant systems, causing physiological/metabolic changes that threaten food safety, nutrition yield, and stress resilience

N-acetyl-β-glucosaminidase, phosphatases, urease, and catalase, through changes in soil structure, moisture regimes, and the introduction of novel carbon sources from MPs surfaces, aging products, or adsorbed contaminants (Rehman et al. 2025; Sun et al. 2024). The effects are influenced by particle size and type of polymer, with smaller MPs or particular polymers having a higher likelihood of interacting with microbes and entering the rhizosphere, changing metabolic pathways and reactive oxygen species (ROS) generation, which can cause stress or reprogram microbial metabolism (Anas et al. 2025; Liu et al. 2025a, b). Co-exposure with HMs, antibiotics, or other contaminants can intensify toxicity, often reducing microbial biomass, lowering mineralization rates, and altering carbon-use efficiency (Liang et al. 2021; Zhang et al. 2025a, b, c). Collectively, these dynamics highlight the convergence of MP properties, environmental factors, and co-contaminants to inhibit nutrient changes through microbial processes, and the necessity of integrated mechanistic paradigms for connecting MPs properties with soil ecology.

Impact on plant physiology

The problem of MPs and their impact on plant physiology is a crucial field of agricultural ecology. The MPs cause functional stress responses in plants that may cause significant alterations in metabolic processes (Fig. 4 and Table 1). The other toxicological effects of MPs include the generation of reactive oxygen species (ROS), which may impact oxidative stress and ultimately cause plant tissue damage. This oxidative stress impairs important functions of plants, ultimately changing the growth and development of plants (Fu et al. 2024; Zhang et al. 2022). MPs absorption by plants depends on the size and shape of the particles; smaller ones are more easily absorbed, and bigger fragments can be excluded at the root surface (Lozano & Rillig 2020; Srećkov et al. 2025). MPs enter the vascular system, target shoots and leaves, and potentially disrupt the photosynthetic machinery of plants (Boots et al. 2019; Khan et al. 2025; Maity et al. 2022). In crops, MPs adhere to the root hair surfaces, which have been reported to impair water and nutrient uptake, root elongation, and biomass accumulation, which is a combination of

Table 1 Effects of MPs on plant growth/physiology and soil health

Plastic polymer	Concentration	Plant used	Effects on crops	Effects on soil health	Citation
PMFs	0.5% w/w	*Oryza sativa*	Reduce N uptake (by 30%), and limited crop growth	PMFs reduced soil porosity, disrupted N cycling, and increased N leaching	Ingraffia et al. (2021)
MPs (not specified)	not specified	crops	Negatively impact carbon and nitrogen metabolism, inducing chromosomal aberrations and DNA damage	MPs alter soil microbial community composition and disrupt root–microbe interactions, indirectly affecting crop growth	Jiang et al. (2024)
MPs (not specified)	not specified	crops	Alter soil biophysical properties, including water-holding capacity, bulk density, texture, aeration, and microbial community	MPs degrade soil health by altering its biophysical properties and enhancing pollutant bioavailability	Dhoble & Dama (2024)
HD-PE, PVC, PS	5% w/w	*Raphanus sativus*	No significant changes in N, P, K, or Zn contents; however, Cu decreased in all treatments, while Mg and Fe decreased specifically under PVC and PS treatments	MPs increased the persistence and severity of soil water repellency (SWR), and reduced water sorptivity, bulk density, and hydraulic conductivity	Lincmaierová et al. (2023)
PBAT, PBS, PCL, PP		*Eruca sativa*	PBS and PCL reduced aboveground biomass and leaf number	Specific MPs (PBS, PCL) altered plant–soil interactions	Ma et al. (2024)
MPs with AMF	not specified	*Allium cepa*	AMF inoculation buffered the effects of MPs by balancing nutrient availability and plant uptake	Soil MPs reduced K, Mg, and S, but increased Zn availability, while AMF buffered these effects by enhancing balanced nutrient uptake	Moreno-Jiménez et al. (2022)
HD-PE, PP with humic acid	HD-PE (60%), PP (40%)	*Vigna mungo*	Humic acid countered the toxic effects of MPs and enhanced the growth of black gram and modified the rhizosphere microbial community	Humic acid mitigated MPs-induced microbial soil disruption, restoring beneficial bacteria	Virachabadoss et al. (2024)
MPs (not specified)	Fib:0.1%, Film: 0.2%, Foam: 0.3%, Frag:0,4%	*Daucus carota*	All shapes increased plant biomass. Overall promote plant performance	MPs of different shapes reduce soil aggregation and microbial activity	(Lozano et al. 2021a, b)
PE	not specified	*Oryza sativa cultivars (Nangeng 5055 (NG) and Jiafengyou 6 (JFY))*	PE influenced the grain quality of common rice and some properties of tested soils with both rice cultivars	Polyethylene MPs alter/change soil properties and improve grain quality in common rice	Wu et al. (2024a, b)

Table 1 (continued)

Plastic polymer	Concentration	Plant used	Effects on crops	Effects on soil health	Citation
MPs (not specified)	not specified	*Oryza sativa*	Combined invasion of *Solidago canadensis* and MPs contamination negatively impact the rice root growth, posing risks to crop yield and food safety	Combined invasion of *Solidago canadensis* and MPs contamination exacerbates soil stress, impairing root function and soil–plant interactions	Li et al. (2023)
PEUU, PE	not specified	*Solanum lycopersicum*	A newly developed sprayable, biodegradable PEUU mulch provided comparable water savings to polyethylene mulches without harming plant growth	Degraded PE-MPs impair soil structure and nutrient cycling, while biodegradable PEUU shows no harmful soil effects	Borrowman et al. (2025)
PE	not specified	*Not specified*	not studied	MPs from greenhouse mulch films degrade soil structure, lowering bulk density, increasing porosity, and reducing cation exchange capacity and microbial activity	Saljnikov et al. (2025)
MPs (not specified)	not specified	Plant community	Our results showed that at the community level, shoot and root mass increased with MPs (microfibers)	Soil microfibers reduced bulk density and boosted community biomass, but altered species dominance, favoring invasive and allelopathic plants	Lozano & Rillig (2020)
MPs (10 different types)	0.4% (w/v)	*Triticum aestivum (Tobak variety)*	Multiple MPs had complex, soil-dependent effects, altering wheat growth and physiology without predictable patterns based on MPs diversity alone	Increase soil bulk density, improved aeration, and better penetration of roots in the soil	Chen et al. (2025)
MPs (not specified)	not specified	*Pinellia ternata*	Indole-3-acetic acid (IAA) mitigates MPs-induced oxidative stress in *Pinellia ternata* and helps sustain secondary metabolite levels, protecting the medicinal quality	MPs induced oxidative stress in *Pinellia ternata* and likely disrupted soil-mediated plant support	Zhang et al. (2025a, b, c)

Table 1 (continued)

Plastic polymer	Concentration	Plant used	Effects on crops	Effects on soil health	Citation
PE (200 µm), PAN (200 µm), PET (200 &10 µm)	not specified	*Oryza sativa*	Different types of MPs altered soil properties, nitrogen dynamics, and amino acid profiles in rice, with some (PAN and PET) unexpectedly enhancing grain yield through improved nitrogen uptake	Altered soil pH, NH_4^+-N, NO_3^--N, and significantly decreased soil urease activity (by 5.0–12.2%)	Chen et al. (2022)
Polyester fibers, PVC	not specified	*Triticum aestivum*	Wheat roots promoted vertical MPs transport, with fibers adhering to roots and PVC fragments penetrating deeper via soil pores	No direct soil chemistry effects reported	Tumwet et al. (2024)
MPs (Biodegradable)	not specified	Not specified	BIO-MPs inhibit plant growth through oxidative stress, and PGPB inoculation reduces the damage	Inhibited most bacteria; Kosakonia sp. O21 tolerated MPs	Carneiro et al. (2025)
PEM and BDM	0.24% w/w	Not specified	Biodegradable mulches provide a sustainable alternative to polyethylene films by supporting soil health and reducing plastic pollution	PE leads to MPs accumulation and reduced aeration; BDM enhances microbial diversity and soil structure	Renumala et al. (2025)
PE	0, 0.25, 0.50, 0.75, and 1.00% (w/w)	*Vigna mungo*	MPs exert a dose-dependent negative effect on plant growth and yield	Decreased bulk density, available P and K; increased EC, organic carbon, microbial biomass carbon, NO_3-N, NH_4-N, and altered enzyme activities and microbial community	Sahasa et al. (2023)
MPs (not specified)	not specified	*Not specified*	MPs and HMs interact synergistically, worsening soil–plant risks and food safety threats	MPs increase HMs bioavailability; HMs alter MP behavior, together disrupting soil–plant systems	Kumar et al. (2022)
PE	not specified	*Zea mays*	PE MPs altered maize mineral uptake and shifted rhizosphere microbes, with effects depending on polymer molecular weight	Low MW reduced microbes; high MW increased bacteria/fungi and pollutant-degraders	Lian et al. (2021)
MPs > 10 µm	not specified	*Lactuca sativa*	Lettuce roots did not absorb MPs > 10 µm, even under damage, suggesting limited uptake risk for leafy crops	Not assessed	Li et al. (2020a, b)

Table 1 (continued)

Plastic polymer	Concentration	Plant used	Effects on crops	Effects on soil health	Citation
PBAT, PBS, PLA (biodegradable); PE, PS (conventional)	1% (w/w)	*Zea mays*	Both biodegradable and conventional MPs altered maize growth, physiology, and molecular pathways, with distinct antioxidant and photosynthetic responses	MPs altered soil variables and microbial communities	Sun et al. (2025)
PE	1% (w/w)	*Brassica napus*	PE MPs reduced rape yield, but N fertilization offset these effects, stabilizing soil microbes and crop productivity	Decrease water retention, altered C/N and N forms; stabilized with N addition	Wang et al. (2025a, b)
LDPE and PP	Equivalent to 1, 10, 25, 50 years mulch use	*Zea mays*	Long-term (> 10 years) LDPE and PP use harms maize growth, while short-term impacts are negligible	Decrease microbial biomass after ≥ 10 years exposure	Graf et al. (2023)
PS	not specified	*Lactuca sativa*	MPs had limited effects on lettuce growth	Food waste improved soil chemistry (higher pH, EC, nutrients, and cations), but reduced microbial diversity, while MPs + biochar strongly suppressed enzyme activities	Palansooriya et al. (2024)

Ps polystyrene, *HD-PE* High-Density Polyethylene, *PBAT* Polybutylene adipate-co-terephthalate, *PBS* Polybutylene succinate, *PCL* Polycaprolactone, *PP* Polypropylene, *AMF* Arbuscular mycorrhizal fungi, *PEUU* Polyester–Urethane–Urea, *PE* Polyethylene, *PAN* Polyacrylonitrile, *PET* Polyethylene terephthalate, *PVC* Polyvinyl Chloride, *BDM* biodegradable mulch, *PEM* Polyethylene mulch, *PBAT* Poly-butylene adipate-co-terephthalate, *PBS* Poly-butylene succinate, and *PLA* Polylactic acid, *LDPE* Low density polyethylene, *PGPB* Plant growth promoting bacteria, *PMFs* polyester-MPs fibers, *EC* Electrical conductivity

physical blockage and chemical stressors caused by MPs (additives, surface-bound contaminants) onto the rhizosphere and systemic transport in a plant (Srećkov et al. 2025; Wong & Taylor 2025). Physiological effects include photosynthetic pigments and gaseous exchange; multiple studies have found a decrease in chlorophyll content and impaired photosynthetic rate in crops exposed to MPs.

The effects of MPs on crop physiology include disruption of primary and secondary metabolism, changes in carbon and nitrogen partitioning, and a shift in nutrient balance. On a metabolic scale, ROS generated by MPs have the potential to initiate signaling pathways that reprogram metabolism of amino acids, sugars, and organic acids. Several studies document changes in pigment composition, carbohydrate status, and antioxidant metabolite profiles in MPs-exposed plants, contributing to variable outcomes across species and MPs types (Mina & Jiahuib 2023; Wang et al. 2024). At the same time, MPs may interfere with nutrient uptake, either physically (interfering with the root-soil interface) or by changing soil–plant chemical equilibrium, and may carry sorbed contaminants (HMs, organic pollutants) that can further influence nutrient deficiencies or toxicities in crops (Anand & Sheel 2025; Yang et al. 2025).

The effects of MPs on plant growth are not uniform, but are different from species to species. Some plants are vulnerable to MPs while others are resilient, leading to varied degrees of growth inhibition (Fu et al. 2024; Manan et al. 2022; Zhang et al. 2022). In comparison, the native plant species are more susceptible as compared to the invasive plant species, showing a different response to MPs stress (Fu et al. 2024; Shah et al. 2025a, b; Zhang et al. 2022). Therefore, further research is necessary to understand the varied and complicated interactions between different plant species and MPs in their environments. The MPs accumulation in plant tissues can lead to changes in root morphology, such as reduced diameter, which may delay the plant's ability to absorb water and nutrients efficiently (Miao et al. 2023; Zhang et al. 2022). This has the potential to alter the root and shoot proportion of MPs accumulation, which impacts the general plant development and crop yield (Asmat et al. 2022; Fu et al. 2024; Khan et al. 2025; Zhang et al. 2022). Additionally, the deposition of MPs in edible plant components raises the issue of food safety since it can cause changes in nutritional value of crops and result in reduced concentration of necessary minerals and vitamins (Miao et al. 2023; Zhang et al. 2022) (Fig. 5).

Circular bioeconomy and policy integration

Circular bioeconomy principles should be incorporated into study design and interpretation to make the applied relevance of MPs research in agroecosystems more relevant. These involve focusing on prevention approaches, which could be limiting MPs inputs using sustainable packaging materials, enhancing waste valorization, using recycled materials, as well as encouraging reuse and safe recycling (Ullah et al. 2025). More sustainable utilization of such plastic inputs as mulch films and biosolids can be guided by lifecycle thinking and material flow analysis (Deng et al. 2024; Ren et al. 2025). Combining these strategies with soil health indicators can bring out co-benefits, such as better soil organic matter and microbial stability (Iswahyudi et al. 2026). Bioremediation strategies, such as microbial degradation and phytoremediation, offer sustainable solutions aligned with circular systems, with emerging innovations, such as insect gut microbiota (*Zophobas atratus*), showing additional potential (Asmat et al. 2022; Rani et al. 2024; Shaji et al. 2025; Sutanto et al. 2025).

It is necessary to foster the implementation of the circular bioeconomy in MPs management through effective policy integration. The detection and reporting of MPs should be standardized to enhance comparability and inform decision-making (Gündoğdu et al. 2022; Shaji et al. 2025). Policies must support biodegradable/recoverable plastics and circular systems, such as closed-loop mulch systems, recycling of organic waste (Deng et al. 2024; Rani et al. 2024; Shimly et al. 2025). Risk assessment and management can be further enhanced with the help of advanced biomonitoring tools (Shaji et al. 2025). Nevertheless, the use of bioplastics should be evaluated with care considering the life cycle to prevent unintentional formation of MPs (Sokra & Meta 2026). Overall, a combination of the circular bioeconomy principles and policy, bioremediation, and monitoring strategies presents a viable approach to sustainable MPs mitigation.

Adsorption and desorption of HMs

The adsorption and desorption of HMs on MPs in agricultural soils is an area of growing concern due to its potential to influence soil health, nutrient dynamics, and crop productivity. MPs, with their high surface area, hydrophobicity, and functionalized surfaces, act as effective sorbents for metals, such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) (Han et al. 2021; ul Haq et al. 2020; Wu et al. 2024a, b). By binding these metals, MPs can alter their speciation, partitioning them among exchangeable, bound, and dissolved forms, which directly affects their bioavailability to plants and soil biota (Azhar et al. 2025; Rehman et al. 2025; Ren et al. 2025). Adsorption is largely physical, with MPs typically reaching equilibrium within 24 h under standard conditions, although aging, weathering, and polymer type can significantly modify surface chemistry and binding affinity (Chen et al. 2024). These interactions can sequester metals temporarily, but environmental fluctuations, such as pH shifts, redox changes, and ionic strength variations,

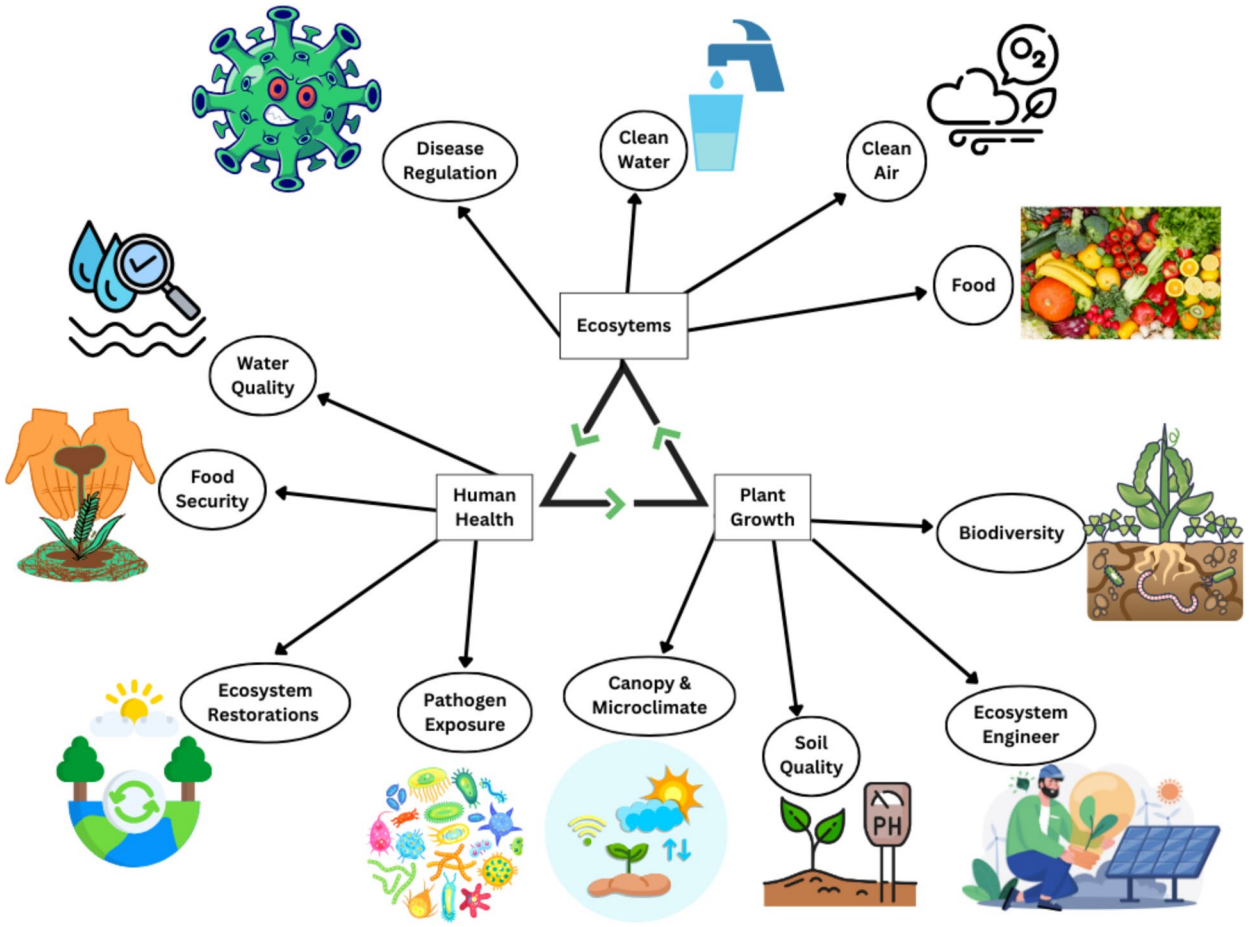

Fig. 5 Impacts of MPs on soil ecosystem, plant growth, and human health

can trigger desorption, leading to episodic increases in metal mobility and toxicity in the rhizosphere (Jadhav & Medyńska-Juraszek 2025b).

Beyond simply serving as metal carriers, MPs act as dynamic vectors that influence soil nutrient cycles. Metals adsorbed onto MPs can compete with essential micronutrients for binding sites, modifying the availability of nutrients, such as iron (Fe), manganese (Mn), and zinc (Zn), to plants and microbes. Such competitive ion interactions may alter nutrient uptake, disrupt enzymatic functions, and shift metal–nutrient balance in crops, particularly under conditions of high HM contamination or in soils with low buffering capacity (Medyńska-Juraszek & Jadhav 2022). The presence of MPs can also change the chemical environment in the rhizosphere by modifying pH, redox potential, and the local concentration of dissolved organic matter, further influencing metal speciation, solubility, and translocation within plant tissues (Masciarelli et al. 2024; Yadav & Ramakrishna 2023). Collectively, these processes demonstrate that MPs do not act as inert particles, but as active modulators of metal behavior and nutrient dynamics in soil–plant systems.

MP-mediated alterations in metal availability also have cascading effects on soil microbial communities and enzymatic activities. Microbes in the rhizosphere mediate critical processes, such as carbon and nitrogen cycling, phosphorus mineralization, and detoxification of metals, all of which can be disrupted by changes in metal speciation and mobility caused by MPs (Radford et al. 2023; Rehman et al. 2025). For example, an increase in bioavailable HMs due to MP desorption can inhibit sensitive microbial taxa or shift community composition toward metal-tolerant species, thereby affecting enzyme activities, such as β-glucosidase, urease, and phosphatases, that govern soil fertility. Aging MPs and their surface modifications can exacerbate these effects by providing heterogeneous adsorption sites, promoting localized hotspots of metal accumulation and release in the rhizosphere (Medyńska-Juraszek & Jadhav 2022). Understanding these complex interactions is essential for predicting the long-term ecological consequences of MPs in agroecosystems and for developing targeted soil management strategies that mitigate HM risks while sustaining crop productivity and soil microbial health.

Furthermore, the adsorption of HMs on MPs surfaces is influenced by polymer polarity, surface functional groups, aging, biofilm formation, solution chemistry (pH, salinity, ionic strength), and co-contaminants. Polar MPs, such as PVC, typically show higher HM uptake than non-polar polymers, such as PS or PE, due to polar sites that enable electrostatic interactions, complexation, and hydrogen bonding with metal ions (Mina & Jiahuib 2023). Aging, such as UV radiation and oxidation, adds oxygen-containing functional groups (e.g., carbonyl, hydroxyl), and roughens surface features, providing more binding sites even to non-polar MPs (Laishram et al. 2025; Liu et al. 2025a, b; Manan et al. 2025). Mechanistic analyses reveal electrostatic interactions, complexation with functional groups, hydrogen bonding, and π interactions in the retention of HMs, and biofilms further alter the surface chemistry and accessibility (Laishram et al. 2025; Zhao et al. 2022). Environmental factors, including pH, salinity, and competing ions or organics, strongly modulate adsorption, underscoring that polymer polarity alone is insufficient to predict HMs behavior (Jimenez-Skrzypek et al. 2024; ul Haq et al. 2020). Thus, the evaluation of HMs risks in soils and agroecosystems needs to consider the polymer type, aging status, environmental chemistry, as well as biofilm effects, and polar MPs, such as PVC, tend to be high-risk carriers of HMs in similar conditions (Biswas et al. 2024; Mina & Jiahuib 2023).

Aging effect on MPs-HMs interactions

In real-field conditions, MPs undergo aging through photo-oxidation and mechanical abrasion, which reshapes their surfaces by increasing surface area and adding oxygen-containing groups, such as hydroxyl (-OH) and carbonyl (-C = O). These changes boost their ability to adsorb HMs, such as Cd, Cu, Pb, and Cr, often leading to higher adsorption densities and altered metal forms compared with virgin MPs (da Costa et al. 2024; Jadhav & Medyńska-Juraszek 2025b). Aging-induced surface roughness and new polar functionalities enhance electrostatic interactions, hydrogen bonding, and complexation with HMs ions, increasing metal retention and sometimes their mobility under changing soil pH, ionic strength, or redox conditions (Saravanakumar et al. 2024; Sathyamoorthy et al. 2022). As a result, aged MPs can act as more effective vectors of HMs, altering their availability to crops and soil microbes (Hullebusch et al. 2005; Wang et al. 2025a, b).

These aging-driven changes also influence rhizosphere processes and microbial activity by modifying metal speciation and competition with essential nutrients. Aged MPs can retain and later release metals under dynamic soil conditions, potentially causing micronutrient imbalances or increasing metal toxicity, which affects nutrient cycling and soil health (Jadhav & Medyńska-Juraszek 2025b; Masciarelli et al. 2024). The extent of these effects depends on polymer type and particle size, as UV-aged PS, PE, and PET show different adsorption capacities, while interactions with natural organic matter further influence HM mobility and bioavailability (Sathyamoorthy et al. 2022; Tenea et al. 2024). The consideration of aging effects in MPs risk assessment is thus necessary to predict the HMs exposure accurately and develop strategies to safeguard crop productivity and food safety in MPs-contaminated soils (Jadhav & Medyńska-Juraszek 2025b; Omo-Okoro et al. 2025).

Role of soil organic matter (SOM) in HMs adsorption and MPs interaction

The importance of soil organic matter (SOM) in HMs adsorption and interaction with MPs is multifactorial and highly context-dependent. SOM in agricultural soils is a main sorbent of HMs because of the high concentration of reactive functional groups (carboxyl and phenolic moieties). These assemblies facilitate HMs binding by inner and outer-sphere complexation, cation exchange, and electrostatic bonds, which control HMs speciation, mobility, and bioavailability. Simultaneously, SOM is an active agent that affects the behavior of MPs by changing their surface properties due to natural aging and exposure to dissolved organic matter (DOM). As an example, MPs may be covered with SOM-derived humic and fulvic substances, and the loading of HMs to MPs may occur through bridging interactions, thereby increasing HMs loading onto MPs. Moreover, environmental conditions, including pH, mineral structure (e.g., oxides and clays), and dynamics of SOM are also very important to regulate HMs sorption in soils. At higher pH, HMs immobilization tends to be preferred, and in any case, DOM may promote HMs mobility via soluble organo-metal complex, or immobilization at mineral surfaces (Kacprzak et al. 2022; Maqsood & Łobos-Moysa 2025; Yang et al. 2025; Zhou et al. 2023).

These particles are secondary and condition-dependent sorption substrates in the context of MPs, with their ability to bind HMs depending significantly on the type of polymer, surface chemistry, size, and aging. Although pristine MPs (e.g., PE, HDPE), usually have a limited adsorption capacity. The processes of aging, biofilm growth, and the coating of biomass can greatly increase the reactivity and affinity of MPs towards HMs. Research indicates that MPs adsorb metals, including Pb, Cu, Cd, and Zn, by both electrostatic interactions and surface complexation, which is very variable and metal specific. Notably, these interactions can be facilitated via SOM and DOM, which serves as an intermediary between HMs and MPs, thus modifying HMs partitioning between soil, MPs, and the soil solution. The fact that several HMs ions can adsorb on the same surface further complicates this system because both SOM and MPs can

Table 2 MPs adsorption/desorption potential for different HMs

MPs type	Matal's type	Adsorption/desorption/capacity in mg/g	Key findings	Citation
PS	Cu	Quick desorption	Cu desorption rate is high in PS	Zhang et al. (2023)
PE	Cu (II)	1.23	MPs adsorb Cu (II) and release under acidic conditions	Sathyamoorthy et al. (2022)
Not identified	Cu, Pb, Ni, Zn	Adsorption: Cu > Pb > Ni > Zn/ Desorption: Ni > Zn > Pb > Cu	pH, salinity control metals partitioning, mobility, and desorption behavior	Miranda et al. (2022)
PPAN	Hg2 +	371.75	PPAN membrane shows high Hg2 + adsorption, reusable performance	Cheng et al. (2023)
PET, PVC, PE, PP, PS, PVA,	As, Mn, Cu, Pb, Cd, Zn, Cr, Sb, Co, Ni, Fe, Sn, Hg	As > Mn > Cu > Pb > Cd > Zn > Cr > Sb > C o > Ni > Fe > Sn > Hg	MPs adsorption capacity depends on MPs-types and environmental conditions	Zhu et al. (2023)
PP	Pb, Cu, Zn, Cd	High	Salinity affects the HMs adsorption over MPs surfaces	Barus et al. (2023)
Not identified	Cd, Cu, Zn, Pb	More	HMs adsorbed on MPs surfaces pose long-term cancer risk	Adji et al. (2022)
PS, PLA	Ni	alkali aging > alternating dry–wet aging > freeze–thaw cycling	Aging enhances MPs-Ni adsorption, increases desorption variability	Xie et al. (2025)
PS, PLA	Cd2 +, Cu2 +, Zn2 +	Cd2 +, Cu2 +, Zn2 + by 0.0028, 0.017, 0.03	MPs aging slightly enhance HMs adsorption capacity	Liu et al. (2025a, b)
PP, PS, PVC, HDPE, LDPE, PES, PET-Glitter	Pb, Cu, Co, Ni, Cr, Cd	High for: Pb, Cd	MPs alter soil pH, changes HMs mobility and adsorption	Jadhav & Medyńska-Juraszek (2025b)
PS, PP	Cd, Ni, Pb	High	MPs (PS and PP) effectively adsorb Cd, Ni, and Pb; adsorption is influenced by pH, kinetics	Tenea et al. (2024)
PLA	Cd, Cr	Cd (4.52), Cr (3.78)	Aged environmental-simulating microplastics (EMPs) and PLA-MPs enhance Cd and Cr adsorption, affecting soil metal mobility	Liao et al. (2025; Tenea et al. (2024)
PE	Pb	Reduced with high MPs dose	High-density polyethylene MPs reduce soil lead adsorption, increase desorption, and enhancing mobility and risks	Shirkhorshidi, et al. (2023)
PE, PP, PS, PET, PVC	Pb, Sn	Pb (13.5), Sn (0.081)	PVC plastic litter on beaches, leaches toxic metals, such as Pb/Sn., acting as a transport vector	Nakashima et al. (2012)
PE, PA, PET, PS, PVC	Ni, Cd, Pb, Cu, Ti	Ni (1.1), Cd (23.6), Pb (219.7), Cu (19.6), Ti (1046.0)	Pigmented MPs and paint particles carry toxic metals, threatening ecosystems	Imhof et al. (2016)
PE, PP, PS, PVC	Cd, Pb	Cd (3390), Pb (5330),	Adsorbed HMs (Cd, Pb, and Br) on MPs surface pose risks to sea birds	Massos & Turner (2017)
PP, PE		Ni (2.39), Cd (17.56), Pb (131.1), Cu (500.6), Zn (14,815.3), Ti (38,823.7)	Freshwater MPs carry HMs mainly from inherent load	Wang et al. (2017)
PP, PE, HDPE	Al, Cu, Fe, Mn, Zn, Ti	Al (45), Cu (1.0), Fe (228.0), Mn (9.0), Zn (8.0), Ti (3.0)	Beach-collected MPs-pellets adsorb more metals than virgin ones	Vedolin et al. (2018)

Table 2 (continued)

MPs type	Matal's type	Adsorption/desorption/capacity in mg/g	Key findings	Citation
PP, PVC, PE	Pb	Max: Pb (0.095)	Pb exposure from MPs mainly comes from additives/residues, not surface adsorption	Turner et al. (2020)
PE, PP, PS, PET, PA, PVC	As, Cd, Cu, Fe, Mn, Ni, Zn	As (0.00), Cd (0.00), Cu (0.89), Fe (302.0), Mn (18.6), Ni (0.15), Zn (19.6)	MPs carry Fe, Zn, Mn; western sites higher due to Pearl River	Li et al. (2020a, b)
PP, PE, PES, PVC, nylon	Pb, Cu	Pb (2.21), Cu (0.36)	MPs adsorb and carry Pb, Cu, threatening aquaculture	Ta & Babel (2020)
PE, PP, PET	Cr, Ni, Cu, Zn, Pb, As, Cd, Hg	Cr (15.70), Ni (6.0), Cu (23.25), Zn (185.3), Pb (51.5), As (6.53), Cd (0.85), Hg (0.08)	Wetlands accumulate MPs (PET, PE, PP) carrying HMs mostly independent of sediment concentrations	Deng et al. (2020)
PE, PET	As, Cd, Cr, Cu, Ni, Pb, Zn	As (4.51), Cd (5.78), Cr (342.2), Cu (119.5), Ni (75.5), Pb (104.6), Zn (1191.5)	MPs in wetlands carry HMs, harming aquatic biota	Sarkar et al. (2021)

share or absorb binding sites. Ecologically, such interactions have the potential to affect HM bioavailability to plants and soil organisms, and to redistribute HMs by MPs mobility. Overall, while SOM remains the dominant sink for HMs in soils, MPs function as secondary, dynamic carriers, and their role as vectors is conditional upon environmental factors, such as SOM content, MP aging, and DOM composition (Iftikhar et al. 2024; Jadhav & Medyńska-Juraszek 2025a; Shirin et al. 2024; Weber et al. 2022; Yang et al. 2025; Zhou et al. 2023) (Table 2).

Research gaps and future studies direction

In this review paper, we have highlighted important research gaps about MPs and HMs interactions that demand more comprehensive studies for understanding. Previous studies of MPs largely focused on the characterization and quantification of MPs, and MPs-adsorption/desorption of HMs are largely studied in laboratory-controlled conditions. Very limited research is available on MPs-HMs interactions in field conditions, where many factors, such as pH, EC, TDS, and SOM, affect the adsorption/desorption process. Moreover, these MPs-adsorbed HMs disturb soil health, alter soil microbial communities, disturb plant physiology, and ultimately cause a problem of food safety. Moreover, the synergistic impacts of MPs and HMs vary from species to species and different environmental conditions, which are not fully elucidated. Many recent studies tend to focus either on ecotoxicological effects or agricultural impacts and often overlook integrating these findings into practical management strategies. Therefore, comprehensive research is vital to inform policy decisions aimed at mitigating the adverse effects of MPs pollution on food production and ensuring food safety.

In addition, recent research highlights the adsorption capacity of MPs for different HMs and their change in soil mobility, but the interactive effects on crop plants remain unclear. Most studies have focused on laboratory-controlled experiments, while very limited research exists under field conditions where MPs-soil–plant interactions, seasonal variations, and complex soil chemistry can meaningfully influence results. Moreover, the mechanisms controlling the adsorption/desorption dynamics of HMs on various MPs types, their bioavailability, and subsequent uptake by plants are still unclear. Further research needs to combine high-quality analytical methods, field monitoring over time, and plant physiological research to solve the mystery of how adsorption/desorption of MPs influences plant development, nutrient balance, and crop production. Such initiatives are crucial in designing sound risk evaluation models and long-term management plans to manage agroecosystems that are increasingly being challenged by MPs and HMs contamination.

Ultimately, by filling these research gaps, it will be possible to develop comprehensive guidelines and interventions that can be used to control MPs pollution in agricultural lands and ensure food safety. The new findings should be integrated into policy frameworks to introduce best practices that can reduce plastic waste in forming systems and ensure soil health. With increasing awareness of people, there is a need to incorporate scientific knowledge in policy formulation to ensure sustainable agricultural practices to control environmental pollution and ensure food safety.

Conclusion

The widespread distribution of MPs in agricultural soil poses threats and complications to soil health, plant physiology, and food safety. MPs not only alter soil health, but also cause ecotoxicological hazards that may threaten the sustainability of agriculture and food safety. MPs also adsorb HMs on its surfaces, which poses a potential threat to agricultural soil and crops, and is a challenge for food production. Most research studies have focused on laboratory-controlled experiments, and very limited research exists in field conditions to study MPs and HMs interactions and their impacts on food safety. This review highlights the critical need for comprehensive research in field conditions to address MPs adsorption/desorption mechanisms, duration of adsorption, and field influencing factors that affect food safety. Addressing the research gaps in current knowledge and advancing interdisciplinary studies will be important in developing effective strategies for mitigating the impacts of MPs and HMs pollution in agroecosystems, ultimately safeguarding food safety and promoting environmentally sustainable practices.

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