



REVIEW ARTICLE

Microplastics as carriers of heavy metals and pesticides in agricultural soil

Niranjana Sasidharan¹, Rajeev Kumar Gupta^{1*}, Meraj Ahmed², Anurag Malik³, Manish Dev Sharma⁴, Priya Sharma⁵, Princy Thakur² & Palvi Dogra⁶

¹Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara 144 411, Punjab, India

²Department of Science and Agricultural Chemistry, School of Agriculture, Lovely Professional University, Phagwara 144 411, Punjab, India

³Division of Research and Innovation, Uttaranchal University, Dehradun 248 007, Uttarakhand, India

⁴Department of Biotechnology, School of Basic and Applied Sciences, Shri Guru Ram Rai University, Patel Nagar, Dehradun 248 001, Uttarakhand, India

⁵School of Pharmacy and Emerging Sciences, Baddi University of Emerging Sciences and Technology, Baddi 173 205, Himachal Pradesh, India

⁶Department of Agronomy, Rayat Bahra University, Mohali 140 301, Punjab, India

*Correspondence email - rajeev.30662@lpu.co.in; rkg1103@pau.edu

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Abstract

Microplastics (MPs) are increasingly pervasive in agricultural soils, primarily originating from plastic mulching, wastewater irrigation, atmospheric deposition and biosolid amendments. Their small size, high surface area, hydrophobicity and variable surface charge enable MPs to adsorb and transport toxic metals and persistent organic pollutants (POPs), thereby enhancing contaminant persistence, mobility and bioavailability in soil-plant systems. This vector effect increases the risk of crop contamination and the transfer of pollutants into the food chain, posing potential threats to the ecosystem and human health. Beyond chemical interactions, MPs alter soil physical properties such as porosity, water retention and aeration, with cascading effects on microbial diversity, enzyme activity and nutrient cycling processes critical for soil fertility. Despite their ecological relevance, MPs remain difficult to detect in complex soil matrices and standardised methods for toxicity assessment are lacking. Future research should focus on improved analytical tools, long-term field investigations and predictive modelling to better understand MP behaviour and cumulative impacts, thereby supporting evidence-based regulations and sustainable agricultural practices to mitigate plastic pollution and protect soil health.

Keywords: adsorption mechanisms; heavy metals; microplastics; pesticides; pollutant transport; soil contamination

Introduction

According to the general definition, microplastics (MPs), i.e. plastic particles less than 5 mm are now widespread pollutants in the land-based environment (1). Agricultural soils have emerged as important sinks for microplastics, largely due to plastic mulching practices, irrigation with contaminated water and the widespread use of biosolids and compost amendments (Fig. 1) (2). Although the influence of MPs on marine ecosystems has been widely studied, the infiltration of these elements into soil systems has attracted relatively recent research attention (3). Owing to their biological activity and complex structure, these soils not only act as sinks for MPs but also interact with other environmental pollutants (4). Due to their high surface area and hydrophobic nature, MPs act as effective vectors for chemicals such as heavy metals, pesticides and persistent organic pollutants (POPs), thereby influencing contaminant mobility and ecological risks in agroecosystems. The hydrophobic nature, large surface area and diverse polymer compositions of MPs confer high affinity for a wide range of environmental contaminants, including heavy metals, pesticides and POPs (5). Such interactions cannot be considered passive; MPs may

actively adsorb pollutants and transport them across soil horizons, thereby altering their bioavailability and toxicity. The MPs interact with pesticides and heavy metals primarily through adsorption. Hydrophobic pesticides bind to MPs via van der Waals forces and hydrophobic interactions, whereas heavy metals bind via electrostatic attraction, complexation and ion exchange, particularly on aged MPs with oxygen-containing functional groups.

These interactions are influenced by polymer type, particle size, surface ageing, pH and ionic strength. Once bound, MPs act as vectors, enhancing the transport, persistence and potential bioavailability of pesticides and heavy metals. Changes in environmental conditions can trigger desorption, leading to secondary contamination and increased ecological risk (Fig. 2).

This dual role as both pollutant carriers and contaminants themselves raises significant concerns about soil health, crop safety and broader ecological impacts.

The knowledge on the adsorption of pollutant and mobilisation processes of MPs would be essential to determine their fate in the environment and mitigation measures. It is a

Microplastics (MPs) in agricultural soils

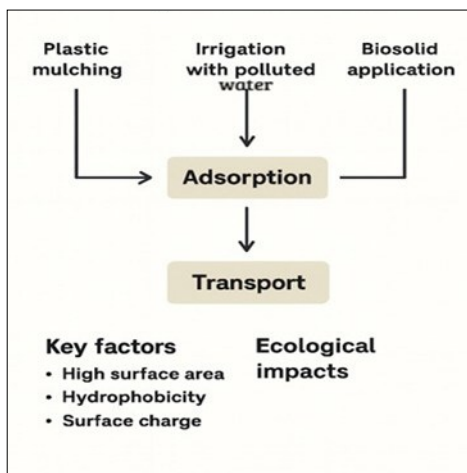


Fig. 1. Microplastics in agricultural soils.

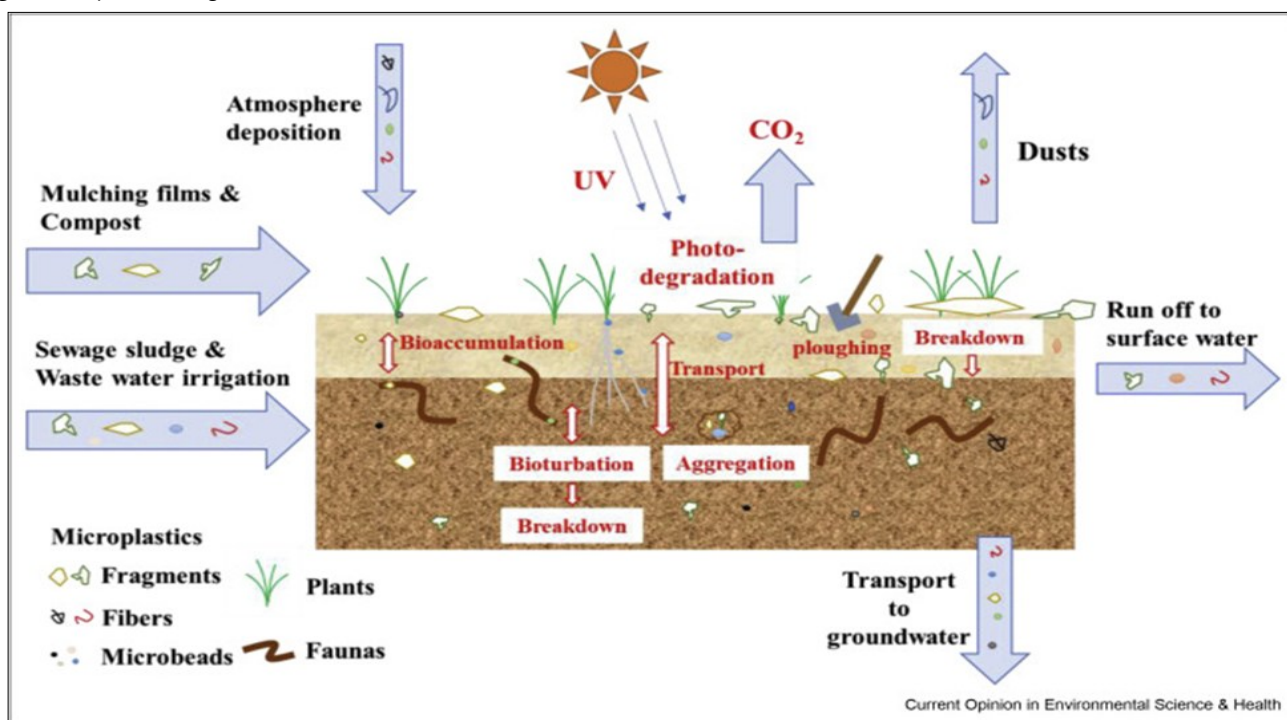


Fig. 2. Microplastics interference.

synthesis of the existing literature on the physicochemical interactions between MPs and pollutants, the factors that affect their transport in soils and the implications for agroecosystems. It also identifies key knowledge gaps and offers suggestions for moving forward to sustain agricultural activities amid increasing plastic pollution (Fig. 3).

Mechanisms of adsorption

Microplastics (MPs) have a strong ability to adsorb a wide range of environmental pollutants due to their unique physicochemical properties. Adsorption is mainly determined by several mechanisms that involve hydrophobic interactions, electrostatic forces and surface complexation (4, 6). Nonpolar organic compounds, i.e. pesticides and POPs, are bound mainly through hydrophobic interactions, since MPs, particularly those made of polyethylene (PE), polypropylene (PP) and polystyrene (PS), have nonpolar surfaces that are easily attracted by them (7).

Electrostatic interactions become important as MPs age, oxidise, or form biofilms, as their surfaces develop charges that

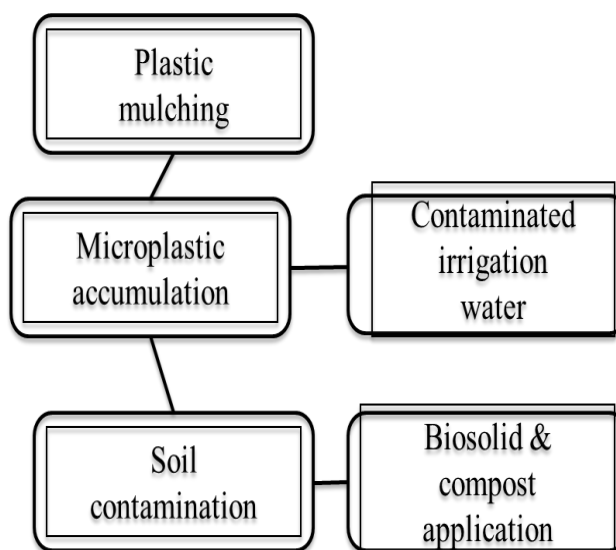


Fig. 3. Flow chart of plastic mulch.

attract and bind charged species, e.g., heavy metal ions. Also, surface complexation is a surface reaction that occurs when functional groups (carbonyl, hydroxyl or carboxyl) on the MPs surface coordinate to metal ions, thereby increasing adsorption strength (8). The adsorption level is also affected by environmental conditions, including pH, ionic strength and natural organic matter, which can alter the MPs surface and the speciation of pollutants. Besides, the shape, size and extent of weathering of MPs influence their surface area and porosity, thereby altering their adsorption capacity (Fig. 4). All these processes allow MPs to act as mobile vectors of contaminants, facilitating their retention and transport in agricultural soils and potentially affecting soil health and crop safety (9, 10).

Pollutants are adsorbed by MPs via:

Hydrophobic interactions: Nonpolar pesticides and organic pollutants are attached to MPs surfaces.

Electrostatic attraction: The charged heavy metal ions react with functional groups on aged or oxidised MPs.

Van der Waals forces and hydrogen bonding: Increase binding of polar molecules.

Research has indicated that PE, PS and PP have different adsorption capacity, based on morphology and surface chemistry (Fig. 5).

Microplastics (MPs) substantially alter the environmental behaviour, bioavailability and ecological impacts of co-occurring pesticides and heavy metals, acting as adsorptive vectors that can increase contaminant persistence and toxicity. For heavy metals, systematic data show that MPs such as polyvinyl alcohol have high adsorption capacities for example, 2810.62mg Pb/kg MPs and 2732.84mg Cd/kg MPs, with polymer type, age and environmental conditions significantly influencing adsorption strength and mobility of metals in soils and water bodies, potentially exacerbating toxicity in ecosystems. Meta-analyses indicate that MPs can increase the bioavailability of copper (Cu), lead (Pb), cadmium (Cd), iron (Fe) and manganese (Mn) in soils, thereby extending their migratory and hazardous range and increasing environmental risk. Pesticide interactions with MPs particularly hydrophobic pesticides with high $\log K_{ow}$ —lead to significant adsorption onto plastic surfaces, reducing

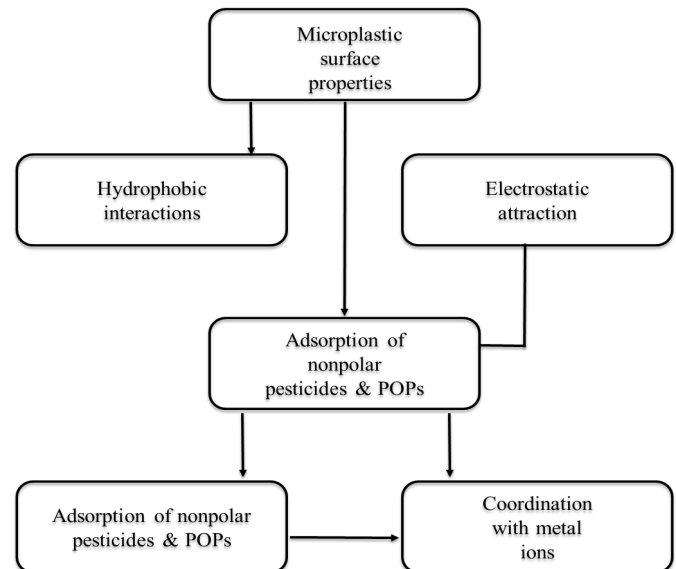


Fig. 5. Flow chart microplastic properties.

bioavailability to target organisms, slowing degradation and extending half lives in the environment, which can diminish pest control efficacy and potentially increase non-target toxicity. Combined pollution of MPs and heavy metals also has measurable effects on plant and soil health: studies report that combined contaminants can reduce plant biomass by up to 87.5 % and alter other growth traits, while MPs influence heavy metal uptake and accumulation, which may heighten phytotoxicity and oxidative stress in plants. Interactions with soil microbial communities further disrupt nutrient cycling and soil fertility and the ingestion or uptake of MPs with adsorbed contaminants by biota enhances transfer through food webs, amplifying ecological risk beyond the impacts of single pollutants.

Transport dynamics in soil

Physical, chemical and biological processes that affect MPs dynamics in agricultural soils can be complicated by a complex interplay of factors that can determine the mobility of these materials and the ultimate fate of the pollutants attached to them (11). When MPs are introduced into the soil by any of the above methods (mulching, irrigation or biosolid application), they may move vertically and horizontally in soil pores, particularly when water moves in the soil due to rainfall or irrigation. They are small and less densely populated, making them prone to leaching and percolation into deeper soil layers or even groundwater (12). Bioturbation by soil fauna, including earthworms, insects and burrowing animals, can also contribute to MPs redistribution and the transport of attached contaminants is largely, in many cases, facilitated (13). It is also dependent on the presence of plant roots, which can alter soil chemistry and enhance the movement of MPs. Root uptake, on the contrary, could facilitate translocation of MPs and related pollutants to plant tissues (14). Further, soil texture, moisture level and organic matter content moderate MPs transport through aggregation, retention and desorption processes. Notably, MPs can act as vectors for heavy metals, pesticides and other toxic substances, further increasing their environmental exposure and potentially amplifying their bioavailability (15). The fact that this is a dynamic movement not only makes it challenging to monitor pollutants but also raises concerns about long-term soil pollution, crop safety and ecosystem health.

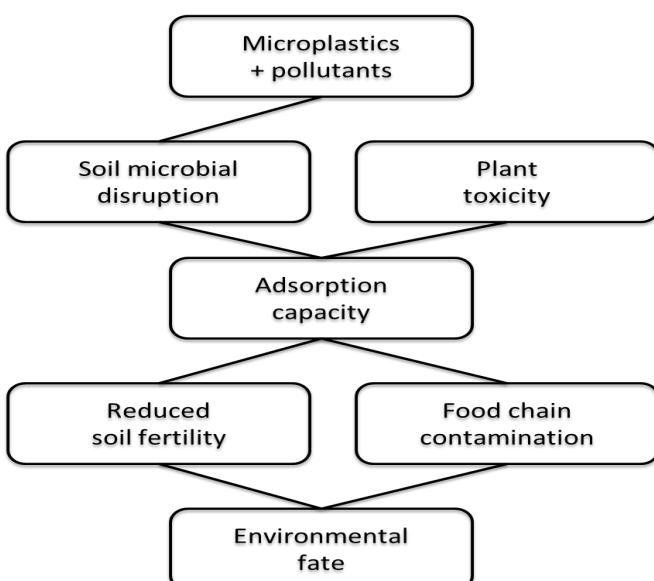


Fig. 4. Flow chart microplastic contaminants.

After adsorption, MPs can be used to mediate the movement of pollutants by:

Movement of soil pores: MPs move both vertically and horizontally, particularly during irrigation or rainfall.

Bioturbation: MPs and pollutants are redistributed by earthworms and soil fauna.

Root uptake and translocation: There is new evidence that MPs can enter the plant systems with adsorbed toxins.

Influencing factors

The adsorption and transport of pollutants in agricultural soils by MPs are influenced by multiple interconnected factors (4). The physicochemical properties of microplastics themselves are key factors: polymer type, particle size, surface area and degree of wear. Smaller MPs may have porous or rough surfaces, leading to higher adsorption capacities due to increased contact and reactive sites (16). Interactions with heavy metals and organic pollutants may increase due to chemical composition and surface functional groups that can be modified during environmental ageing or under UV radiation. The properties of soil are also crucial; pH levels determine the ionisation of MPs and pollutants and therefore their binding affinity. Also, organic matter may partially compete with MPs for adsorbed pollutants or alter MPs' surface properties (7). Moisture content and temperature also influence the MP mobility and the rate of pollutant desorption and wet soils are easier to transport (Fig. 6).

Also, the characteristics of pollutants, including solubility, molecular weight and polarity, dictate their affinity for MPs (Fig. 7). The soil structure can be disrupted by external factors, including agricultural practices, tilling, irrigation frequency and fertiliser application (1, 17). All these factors together determine the environmental fate of MPs and their threat to soil ecosystems and agricultural productivity (9).

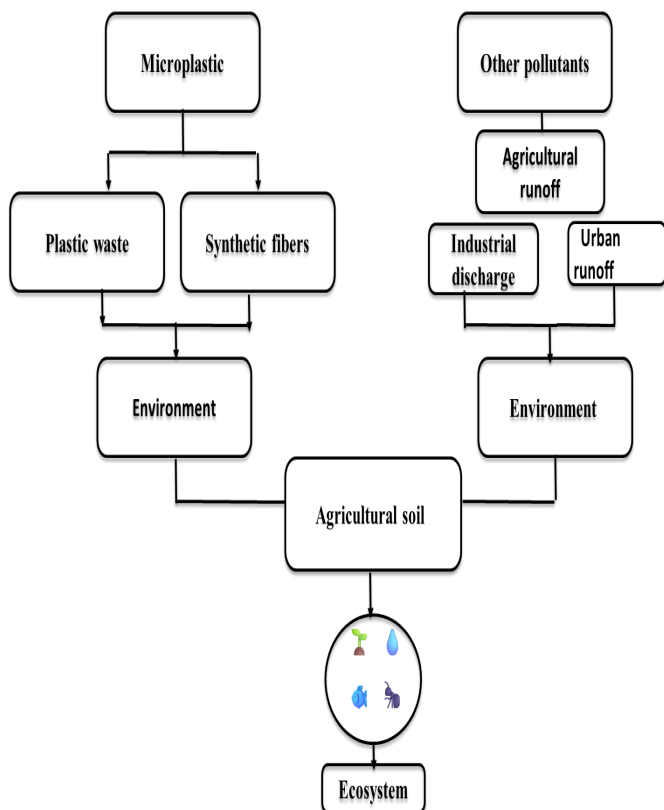


Fig. 6. Flow chart microplastic and other pollutants.



Fig. 7. Influencing factors.

These are some of the variables that influence adsorption and transport:

Type and size of microplastic: Smaller MPs are more mobile and have more surface area.

Soil pH and organic matter: Affect the metal interaction with speciation and MPs.

Pollutant properties: Binding affinity is determined by solubility, charge and molecular weight.

Emerging dimensions of microplastic pollution in agricultural soils

A key urgent area of microplastic research is the conversion of MPs to nanoplastics (NPs) due to environmental weathering. As these particles become smaller, they become even more active and can penetrate deeply into the pores of soil and plant tissues, raising acute questions about nanotoxicity and ecological implications. The spread of antibiotic resistance is another current problem caused by microplastics (18). There are biofilms on their surfaces that frequently harbour resistant microbes, which serve as hotspots of horizontal gene transfer and can pose a threat to soil health and food security. The connection between MPs and climate change has become popular as well. Research indicates that microplastics may affect the respiratory rates of microbes and the production of greenhouse gases, potentially disrupting carbon cycling and soil organic matter turnover. Organic farming systems, which are generally considered safer, are not spared either. The MPs can be introduced into these soils through compost, manure and biodegradable plastics, posing a threat to certification standards and consumer confidence (19).

Microplastics not only interferes with chemistry but also with biology. They can interfere with mycorrhizal fungi, which are essential for nutrient exchange and plant resilience. They also alter soil carbon dynamics by influencing humification and microbial carbon use efficiency, potentially biasing carbon budgeting models. The biochemical front has shown that MPs suppress key soil enzymes, such as dehydrogenase, urease and phosphatase, which are required for nutrient cycling and the maintenance of soil fertility (20). Neither is soil fauna, such as earthworms and nematodes. Consumption of microplastics can cause oxidative stress and reproductive and behavioural problems, eventually

disrupting bioturbation and ecosystem balance. Besides, the MPs tend to have a synergistic effect with agrochemicals, increasing the mobility and persistence of fertilisers and pesticides, making it more challenging to determine the environmental risk.

Finally, scientists are modelling the movement of microplastics through the soil-plant-atmosphere nexus. There are indications that they may be able to migrate via evapotranspiration and root exudates; therefore, it is imperative to develop predictive models to understand the entire journey of the organism in the environment. The incorporation of these contemporary subjects will not just enhance the scientific rigour of your writing but also make your manuscript the centre stage of soil pollution and agroecological research (21, 22).

Microplastics to nano plastics transformation: the implications to soil nanotoxicology

Even though MPs have already become an issue in agricultural soils, they are further degraded into nanoparticles (NPs) during environmental weathering (UV radiation, mechanical abrasion and degradation by microorganisms, etc.) (23). This conversion makes a tremendous difference in their physicochemical characteristics, making them more active and reactive and mobile. Compared to MPs, NPs can penetrate deeper into soil matrices, interact more closely with soil biota and even translocate into plant tissues, raising new questions for soil nanotoxicology. The smaller size and better surface-to-volume ratio of NPs increase their adsorption capacity, making them powerful carriers of heavy metals, pesticides and POPs (24). They are colloidal in nature and tend to pass through conventional soil filtration systems, increasing the likelihood of groundwater contamination and the bioavailability of toxicants. In addition, NPs may disrupt cellular membranes and enzymatic processes and cause oxidative stress, resulting in alterations in microbial community structure and function.

New research findings indicate that NPs can modify gene expression in soil microbes, disrupt positive microbial interactions and disrupt nutrient cycling processes, including N fixation and P solubilisation. Their contact with root exudates and soil colloids further complicates their behaviour, potentially increasing their uptake by plants and the food chain (25). The identification and determination of NPs in soil are technically challenging due to their small size and complex behaviour within organic and inorganic soil materials. Such limitations are being addressed through advanced methods such as Raman spectroscopy, atomic force microscopy and nanoparticle tracking analysis. Nevertheless, there is an immediate need to understand the chronic impacts of NPs on soil health and the sustainability of agroecosystems, using standardised procedures and long-term field trials.

Microplastics as a vector of antibiotic resistance genes (ARGs).

It is also becoming established that MPs in agricultural soils can act as physical and chemical pollutants and as biological vectors that promote the transfer of antibiotic resistance genes (ARGs). Their surfaces, particularly due to age and weathering, provide ideal environments for microorganisms to settle and form biofilms. Such biofilms frequently harbour a wide range of microbial species, including antibiotic-resistant bacteria, which form microenvironments that support horizontal gene transfer (HGT) (26). The adsorption of antibiotics, heavy metals and other selective agents by the porous, hydrophobic nature of MPs puts

pressure on microbial populations, leading to the growth of resistant strains. It has been demonstrated that MPs can harbour plasmids and integrons, which are mobile genetic elements that facilitate the distribution of ARGs across soil compartments (27). This mobility allows MPs to serve as shuttles, ferrying ARGs from hotspots, such as manure-amended soil or wastewater-irrigated fields, to the rest of the territory, thereby spreading pollution to otherwise unpolluted areas. In farms, the presence of MPs, organic manure, pesticides and leftover antibiotics used in livestock farming increases the risk. MPs can remain in soil for long periods, thereby preserving microbial habitats and facilitating the propagation of ARGs. Additionally, they can interact with soil colloids and root exudates, which are likely to stimulate microbial processes in the vicinity of plant rhizospheres and increase the likelihood of ARG absorption by plant-associated microbes (28). The consequences are far-reaching: ARGs carried along by MPs may enter the food chain via crops and pollute groundwater and soil microbes. This is a growing threat that requires combined approaches to monitoring, including both microplastic detection and molecular tools for ARG profiling. Methods like qPCR, metagenomics and fluorescence *in situ* hybridisation (FISH) are under consideration in order to track ARGs on MP surfaces and determine their ecological effects.

Climate change interactions of microplastics with soil biogeochemistry feedback

The combination of climate change and MPs pollution in agricultural soils is a complicated and increasingly topical issue in soil biogeochemistry. Although the two stressors may have independent effects on the health of the soil, their interaction can have symbiotic or antagonistic effects that may modify the primary processes of the soil (29). Higher temperatures, shifts in precipitation and more frequent extreme weather events are climate-related factors that will accelerate the degradation of MPs into smaller particles, including NPs, making them more mobile and reactive. The increased temperature and variation in the moisture regime affect microbial metabolism and enzymatic activity, which, in turn, influence the interactions of MPs with soil organic matter and nutrient cycles. For example, MPs can alter microbial respiration rates, leading to carbon dioxide (CO₂) and nitrous oxide (N₂O) emissions, both of which are major greenhouse gases. Moreover, MPs may interfere with soil aggregation and porosity, which affect water retention and aeration, both of which are vital during drought and flood periods aggravated by climate change (30).

The stabilisation of carbon by the presence of MPs can also disrupt the carbon pathways. Changes in microbial carbon use efficiency and humification processes may shift the carbon balance toward labile forms, thereby reducing long-term carbon sequestration in soils. Besides, MPs can adsorb and carry climate-sensitive contaminants, including pesticides and heavy metals, which can also interact with soil temperature and moisture dynamics. New evidence indicates that MPs can act as climate-sensitive vectors, altering the fate and transport of co-contaminants under changing environmental conditions (31). This positive feedback process, in which climate change increases MPs transformation rates and MPs contribute to greenhouse gas fluxes, represents a new threat to soil biogeochemical stability. These interactions can only be understood through combined field studies and modelling techniques that consider the behaviour of

climatic variables and the modelling behaviour of MPs.

Microplastic contamination in organic farming systems

Organic farming systems are widely seen as ecologically friendly, with lower chemical input requirements than conventional farming. Recent research has shown that these systems are not resistant to MPs pollution. Although MPs do not enter organic soils through synthetic inputs, such as plastic mulch films and chemical, fertilisers there are still multiple ways in which they enter the soil, making the notion of organic purity seemingly false and raising a question of the health of the soil and the safety of foods (32). The use of compost and livestock or municipal waste manure is one of the key sources of MPs in organic farming. These organic amendments have traces of debris, plastic bags, feed bags or pollution streams of waste. Even composts may contain MPs if upstream waste segregation is poor. Also, biodegradable plastics, which are increasingly used in organic systems, are not fully degraded in the field, forming MPs that contaminate soil over the long term (33).

Another path of MP entry is the irrigation using untreated or partly treated wastewater and is particularly common in areas with water shortages. The contamination is further worsened by atmospheric deposition, which involves wind-driven plastic waste and microfibers from neighbouring urban or industrial regions. These MPs may accumulate in soil over time, altering their physical structure, water retention capacity and microbial dynamics (21).

There is also the hindrance of beneficial soil organisms, such as mycorrhizal fungi and nitrogen-fixing bacteria, by MPs, which are essential to organic nutrient cycling. Emerging evidence indicates that crops could absorb MPs, raising concerns about bioaccumulation and consumer exposure. Regulatorily, there is a blind spot in the absence of standardised testing procedures on MPs in organic certification processes. Organic labels can be undermined if contamination goes unnoticed due to insufficient supervision. To eliminate this situation, the quality of compost should be better controlled, waste management methods should be made more effective and MPs-free organic inputs should be developed (22).

Disruption of mycorrhizal symbiosis by microplastics

Mycorrhizal fungi are important in soil in agriculture because they form mutualistic interactions with plant roots, improving nutrient uptake, soil structure and plant resilience to stress. Nonetheless, recent findings indicate that MPs may disrupt this vital symbiosis, posing an underground threat to soil fertility and agroecosystem stability (34). Microplastics, particularly irregularly shaped and reactive ones, may block the contact zones of root-fungus physically, hindering colonisation and hyphae growth. Their existence in the rhizosphere can also modify the exudation of the roots which are critical chemical signals in mycorrhizal establishment. Also, MPs can take up agrochemicals and heavy metals into the root zone and make the soil chemically hostile, which inhibits fungal growth and symbiotic signalling (35).

In addition to the effect of physical and chemical interference, the microbial equilibrium in the rhizosphere can be disrupted by MPs. Mycorrhizal fungi also compete with other soil microbes for space and resources and the introduction of MPs usually alters the microbial community composition, benefiting opportunistic or pathogenic species. This imbalance in microorganisms could impair the performance of fungi and host plants in nutrient exchange, especially

phosphorus and nitrogen, which are highly mycorrhizal nutrients (36). The experimental works have reported low rates of mycorrhizal colonisation and poor germination of spores in soils polluted with MPs. These are usually polymer-specific and the influence of PE and PS is greater in terms of their ability to inhibit, as they are hydrophobic and tend to accumulate toxic co-contaminants. The long-term effects include reduced plant growth, loss of drought tolerance and deterioration of soil aggregation, undermining the sustainability of agricultural productivity.

Influence of microplastics on soil carbon stabilisation and turnover

Microplastics are also emerging as disruptive interfering systems in the carbon dynamics of soil, with effects on soil carbon stabilisation and turnover of organic carbon in farm ecosystems. Their presence in soil can modify the physical structure, microbial activity and microbial pathways that regulate carbon cycling, with effects on long-term soil fertility and climate mitigation strategies (29). The influence of MPs on soil aggregation represents a key pathway through which MPs affect carbon stabilisation. Soil microaggregates play a crucial role in protecting organic matter from microbial degradation; however, the presence of MPs can disrupt aggregate formation, thereby interfering with this protective mechanism. This interference reduces the physical protection of carbon, which is vulnerable to mineralisation and loss as carbon dioxide (CO₂). Moreover, MPs can affect the composition and functioning of microbial communities, which cause humification, which is the transformation of labile organic matter into stable humus (37).

Microplastics also affects microbial carbon use efficiency (CUE), one of the determinants of carbon retention in biomass or its release as CO₂. Research indicates that MPs have the potential to inhibit CUE through the generation of oxidative stress, enzyme modulation and a change in metabolism of microbes. These modifications may hasten the breakdown of organic materials and slow the buildup of microbial remains, which are essential for long-term carbon storage (38). In addition, organic pollutants and heavy metals can be adsorbed onto MPs, thereby inhibiting the activity of microbial decomposers and altering soil chemistry. This can selectively degrade some carbon compounds, leaving others intact, thereby imbalancing the natural process of carbon turnover. Polymer type, size and surface chemistry of MPs can also affect their interactions with organic matter in soil, with aged or oxidised MPs exerting more substantial effects because they can be more surface-receptive. These interactions are further modulated by the environment, i.e. soil moisture, temperature and pH. An example is in wet soils, where MPs can increase the mobility of dissolved organic carbon and in dry soils, where they may block microbial access to substrates. These site-specific effects further complicate the prediction of MPs impacts on carbon cycling, highlighting the need for site-specific investigations.

Enzymatic inhibition in soil due to microplastic exposure

The enzymes present in the soil are crucial catalysts that promote nutrient cycling, decomposition of organic matter and general soil fertility. Nevertheless, the introduction of MPs into farm soils has been shown to disrupt enzyme activity and cause biochemical imbalances, thereby affecting soil health and crop yields (39). This inhibition is commonly polymer-specific and depends on the size, shape and surface chemistry of MPs and their interactions with co-contaminants. Some of the essential enzymes that microplastics can block include dehydrogenase, urease, phosphatase and β

-glucosidase and each is significantly important in soil metabolic activities. Such is the activity of dehydrogenase as a biomarker of microbial respiration, which is predisposed to oxidative stress caused by MPs and changes in microbial community structure. Nitrogen mineralisation may be inhibited by MPs adsorption of the ammonium ions or by the interference of the microbial nitrogen metabolism. In the same way, the phosphatase activity, which is crucial in mobilisation of P, may be inhibited by MPs which attach phosphate or change pH levels in rhizosphere (40).

Enzyme inhibitors have complex mechanisms. Physical mechanisms by which MPs prevent enzyme-substrate interactions include changes in soil porosity and moisture retention. The MPs can chemically adsorb heavy metals and pesticides, which are enzyme inhibitors or alter the redox potential of the soil. Biologically, MPs can begin shifting microbial communities away from enzyme-producing taxa, thereby lowering enzyme production. These impacts tend to be magnified under stress conditions such as drought, salinity, or heavy agrochemical loads. Experimental research has shown that enzyme activity is dose-dependent and decreases with increasing levels of MPs, especially in soils contaminated with PE, PS and PP (41). The ageing of MPs with oxidised surfaces is likely to provide a greater inhibitory capacity because of their greater reactivity and pollutant adsorption capacity. The presence of natural organic matter could counteract these effects, but overall, biochemical functionality in MPs-contaminated soils is likely to decrease.

Sub-lethal impact of microplastics on soil fauna.

The soil fauna, such as earthworms, nematodes, springtails and arthropods, has a significant role in preserving soil structure, nutrient cycling and decomposing organic matter. Although the acute toxicity of MPs is not well documented, there is increasing evidence of sub-lethal impacts that may affect the physiology, behaviour and ecological processes of these organisms, ultimately affecting the health and productivity of soil and agriculture (21). Oxidative stress is among the most frequently reported effects. Reactive oxygen species (ROS) can be produced by MPs, particularly those having reactive surfaces or adsorbed pollutants in the soil, which cause cellular damage, lipid peroxidation and dysfunction of antioxidant defences in soil organisms. In earthworms, for example, both PE MPs and PS MPs have been associated with high levels of malondialdehyde and decreased catalase activity, indicating an oxidative imbalance (42).

The other issue is reproductive toxicity. MPs can disrupt hormone regulation, gametogenesis and success in reproductive achievement. Investigations on nematodes and springtails have revealed that they become less fruitful, mature more slowly and exhibit altered sex distributions because of exposure to MPs. Co-contaminants, such as heavy metals or pesticides, adsorbed onto MPs surfaces could exacerbate these effects (23). There are also changes in behaviour, such as the altered burrowing behaviour, feeding rates and locomotion. These interruptions may reduce bioturbation and mixing of soil layers by fauna, which are essential to aeration, water infiltration and the distribution of organic matter. This, in turn, influences the activity of microbes and the availability of nutrients to plants. Internal abrasion, gut blockage and decreased nutrient absorption of MPs may occur during the physical ingestion of the substance. Although most soil organisms can excrete MPs, repeated

exposure may result in bioaccumulation, particularly of smaller or NPs (43). This raises questions about trophic transfer and long-term ecological impacts. Notably, the effects are frequently polymer-dependent, sub-lethal and dose-dependent. Weathered MPs with rugged surfaces and adsorbed toxicants exhibit greater biological effects. These interactions are further modulated by environmental factors, including soil pH, moisture and organic matter content, necessitating field evaluation of these processes.

Synergistic toxicity of microplastics with agrochemicals

Microplastics (MPs) in agricultural soil rarely act independently. Their exposure to agrochemicals, e.g., fertilisers, pesticides, herbicides and fungicides, could result in synergistic toxicity, greatly increasing environmental risks and exceeding the effects of the individual agrochemicals. The situation of co-contamination is especially worrisome in highly cultivated areas where the remnants of plastics and the chemical inputs live together in intense levels. The MPs are hydrophobic and have a high surface area, allowing them to adsorb a wide variety of agrochemicals (14). These compounds can have longer half-life in the ground than in nature because they are bound and not broken down by microbial or photolytic processes, which can protect them. This increases their half-life in the environment and their chances of being washed into groundwater or picked up by vegetation. As an example, MPs can improve the mobility of hydrophobic pesticides such as chlorpyrifos or atrazine and make them enter soil horizons and reach sensitive ecological compartments.

Agrochemicals, when combined with MPs, can also enhance biological toxicity. It has been demonstrated that MPs become stronger sources of oxidative stress, enzyme inhibition and DNA damage in soil organisms when loaded with heavy metals or pesticide residues, compared with their individual effects. When earthworms, nematodes and microbial communities are exposed to these mixtures, they tend to reduce reproduction, alter behaviour and disrupt nutrient cycling. In addition, MPs can interfere with the degradation kinetics of agrochemicals (43). The MPs can decrease their immediate bioavailability by adsorbing active ingredients, retard their breakdown and forming depots of latent toxicity. By contrast, in specific circumstances, MPs can also serve as vectors that deliver focal doses of agrochemicals to particular soil microenvironments, thereby worsening local effects. Environmental factors, including pH, temperature and organic matter content, further modulate these interactions. For example, acidic soils can increase the desorption of metal ions from MP surfaces and high organic matter can also compete with MPs for pesticide uptake. The nature of the polymer is also important- PE and PS are more likely to exhibit significant synergies because they are more likely to be attracted to nonpolar compounds.

Modelling microplastic movement across the soil-plant-atmosphere continuum

The environmental fate of MPs in agricultural systems demands a holistic perspective that considers their distribution across interacting compartments, i.e., soil, plants and the atmosphere. Recent developments in environmental modelling have begun to delve into this continuum and complex pathways for how MPs move, convert and interact with biotic and abiotic components have been identified (16). The MPs enter the soil compartment through different pathways, such as the disintegration of plastic

mulch, irrigation with polluted water and the use of organic amendments. When present in the soil, MPs may move up and down and laterally through water flow, bioturbation and root interactions. They affect their retention, aggregation and possible leaching into deeper layers or groundwater due to their size, density and surface chemistry (44).

The interaction between plants and MPs occurs primarily during root uptake and rhizosphere dynamics. Root exudates may alter the surface characteristics of MPs, increase their mobility, or allow the co-contaminants to adsorb. Recent studies indicate that MPs, particularly NPs, can move from roots to shoots and invade food-bearing tissues, posing a hazard to food safety (45). These interactions can only be modelled by combining root architecture, soil texture and MPs physicochemical characteristics. The atmospheric route is frequently neglected, yet it is becoming increasingly relevant. Releases of MP can occur through wind erosion of non-moist soils, volatilisation of plastic additives, or through transpiration from plant surfaces. Primary sources of MPs also include atmospheric deposition in areas around urban or industrial areas (46). These bidirectional flows must be incorporated into the model to ensure a proper exposure assessment. Simulated models depicting MPs movement along this continuum should account for dynamic factors such as temperature, moisture, microbial activity and farming practices (47). It is being investigated using a coupled transport-reaction model, agent-based simulation and machine learning to forecast MPs behaviour across different agroecological conditions. These models may help determine hot spots of accumulation, predict long-term effects and inform mitigation measures.

Ecological and agricultural effects

Microplastics (MPs) in agricultural soils pose complex ecological and agricultural risks, mainly because they can adsorb and release hazardous pollutants, such as heavy metals, pesticides and persistent organic compounds (Fig. 8). At the environmental level, MPs alter soil microbial communities by altering enzyme activities, nutrient cycling and microbial diversity, which are necessary to ensure the soil remains fertile and the system can withstand changes (13). Such disturbances can reduce decomposition rates and distort the turnover of organic material, ultimately influencing soil structure and productivity. Agriculturally, MPs and their adsorbed contaminants may interact with plant life by altering root morphology, reducing nutrient uptake and increasing the levels of toxic contaminants in the rhizosphere (14). There are even emerging indications that plants may absorb MPs to the greatest extent in areas where bioaccumulation of contaminants in edible tissues is observed, posing a threat to human food safety and health (48, 49). Moreover, MPs can alter soil water penetration and aeration, affect crop yields and increase susceptibility to drought and erosion.

The passive accumulation of MPs and their concomitants is also likely to impair soil remediation efforts and make sustainable farming less feasible. All these effects emphasise the need to have measures such as monitoring, regulating and reducing the problem of MPs pollution in agroecosystems.

Soil health decline: MPs interfere with the microbial communities and enzyme functions.

Crop toxicity: Pesticides and metals adsorbed may damage the

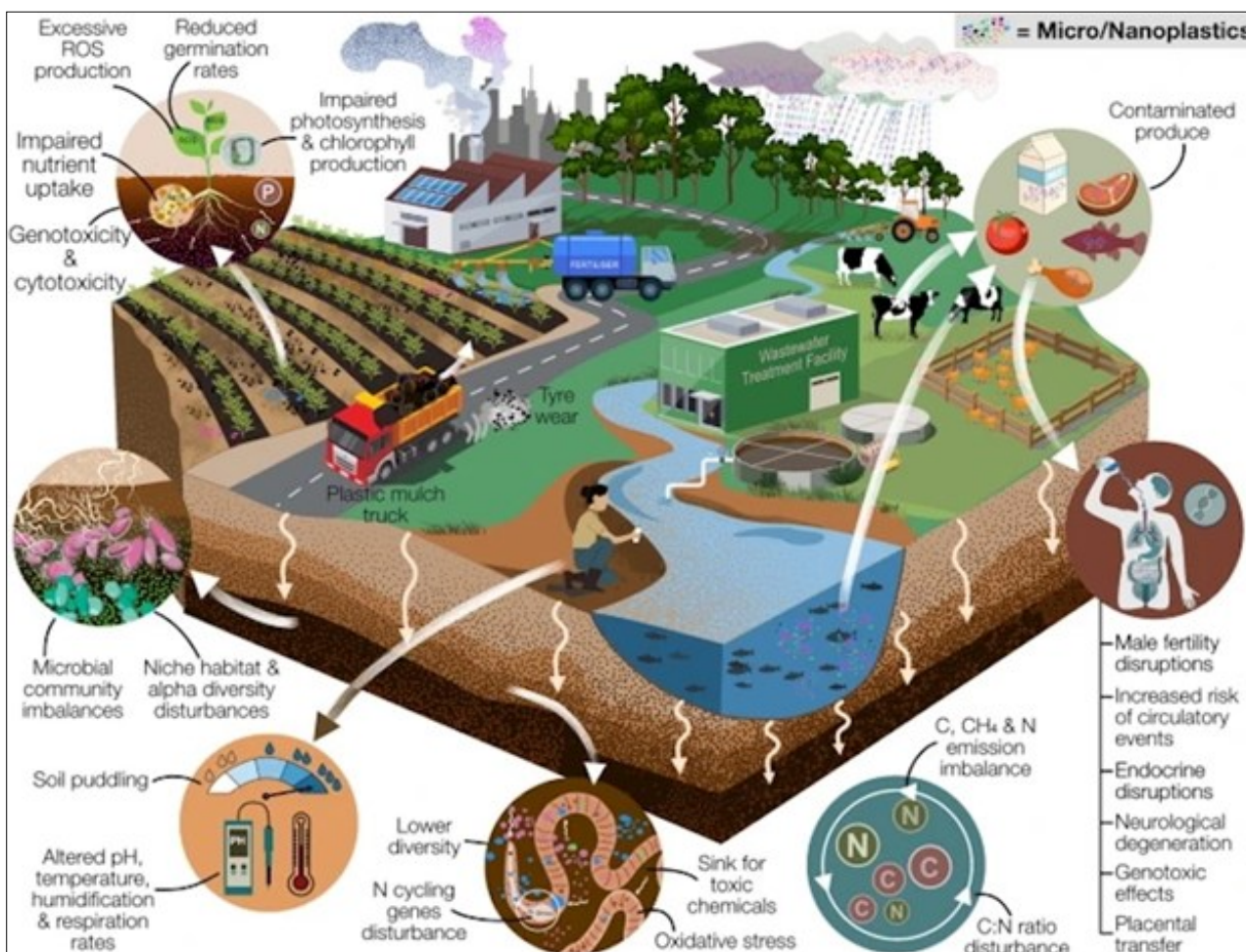


Fig. 8. Ecological and agricultural prospectus.

growth and yield of crops.

Pollution of the food chain: MPs and contaminants can make their way up the food chain, thus being dangerous to human health.

Research gaps and future directions

Although increasing attention is being paid to MPs pollution in agricultural soils, these studies have several critical gaps that prevent a complete understanding of its environmental behaviour and long-term effects. A key weakness is that due to the absence of standardised approaches to the detection and quantification of MPs in complex soil matrices, the data remains inconsistent and it proves difficult to compare studies (50). Also, most of the currently available research is laboratory-based and short-term, with no measures of the chronic effects of MPs and their respective pollutants in real field settings (3). The relationships between MPs and soil biota, especially how they affect microbial communities, enzyme processes and nutrient recycling, are least understood. In addition, the methods by which MPs affect the bioavailability and toxicity of adsorbed contaminants, i.e., heavy metals and pesticides, require further exploration, particularly across different soil types and climatic conditions (51). The potential for MPs to enter the food chain through plant uptake and the associated implications for human health remain poorly understood. The next generation of studies is recommended to focus on long-term field studies, develop a robust analytical framework and investigate how MPs interact with other emerging pollutants (52). It is crucial to deepen our understanding of these areas to inform policy decisions, promote sustainable agricultural practices and reduce the risks posed by MPs pollution in terrestrial ecosystems.

Field studies (long-term): Requirement to determine long-term effects and fate of pollutants.

Standardised procedures: To detect and measure MPs in soils.

Remediation measures: Invention of biodegradable MPs and soil cleansing methods.

Conclusion

Microplastics (MPs) have emerged as a critical but under recognized threat to agricultural soils, as they enhance the mobility of hazardous substances and facilitate the transport of heavy metals, pesticides and POPs into croplands. Their behaviour in soil is highly context-dependent, influenced by soil texture, biological activity and management practices, complicating prediction and risk assessment. Once introduced, MPs can disrupt microbial communities, impair nutrient cycling, reduce plant growth and enter the food chain, posing risks to ecosystem integrity, agricultural productivity and human health.

From a policy perspective, these findings highlight the urgent need for regulations that limit plastic inputs in agriculture, promote biodegradable alternatives and mandate systematic monitoring of MPs in soils. In agriculture, adopting improved plastic management, waste-reduction strategies and farmer awareness programs is essential to safeguard soil health and long-term productivity. For future research, priorities include long-term field studies capturing climatic and seasonal variability, standardised methods for MPs detection and quantification and integrated risk-assessment frameworks that link ecological, agronomic and human health outcomes.

Addressing microplastic contamination in farmland requires coordinated scientific efforts, evidence-based policymaking and active stakeholder engagement. Proactive action today is essential to protect soil functions, ensure food system resilience and secure environmental sustainability for future generations.

The addition of MPs to hazardous substances increases their transport into agricultural landscapes, making them a significant environmental concern. The increasing use of plastics in agriculture, therefore, demands the attention of researchers, policymakers and farmers, as microplastics can act as carriers of various pollutants.

Authors' contributions

RKG, NS and AM done the conceptualisation, supervision, editing, final drafting. Experimentation and manuscript writing was done by RKG, NS, MDS, AM, PS and PT. NS, MA, AS and PD recorded the data. All authors have read and approved the final manuscript.

Compliance with ethical standards

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