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REVIEW ARTICLE

Tiny toxins, big problems: the hidden threat of microplastic in agroecosystems

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Abstract

Microplastic pollution has become a critical environmental challenge particularly in agricultural ecosystems, where excessive plastic use contributes to its accumulation in soils. Microplastic originate from various sources including plastic mulch films, irrigation systems, fertilizers, packaging materials and factories also gradually breaking down into microscopic particles that infiltrate the soil. Their presence disrupts soil structure, alters physicochemical properties and negatively affects water retention, nutrient cycling and microbial diversity ultimately reducing soil fertility and crop productivity. Besides disturbing soil health, microplastic enter the food chain through plant uptake, posing potential health risks to humans and even animals ingestit directly. Long-term exposure to microplastic has been linked to toxic effects including the accumulation of harmful chemicals and heavy metals. To mitigate these impacts, sustainable strategies such as biodegradable plastic alternatives, regulatory frameworks and bioremediation techniques involving plants and microorganisms must be implemented. Additionally, improved waste management practices particularly the 4Rs (Reduce, Reuse, Recycle and Recover) can significantly reduce microplastic contamination. Addressing microplastic pollution in agroecosystems requires a collaborative global effort involving policymakers, industries, researchers and local communities. By promoting sustainable agricultural practices and enforcing stricter regulations on plastic use, we can safeguard environmental health, ensure food security and protect future generations from the long-term consequences of microplastic pollution.

Keywords: microorganisms; microplastic; plasticulture; plant growth; soil health

Introduction

Following industrialization, global plastic production increased significantly and was initially necessary. Over the last twenty years, excessive production and improper disposal of plastic have resulted in significant environmental pollution. The massive production and consumption of plastics serve as a distinctive indicator of human activity. According to Plastic Europe (2024) (1) statistics, worldwide plastic production amounted to 413.8 million metric tons in 2023. It is projected that global plastic production will reach 902 million metric tons by 2050 (2). In 2023, Asia was the leading producer of plastics globally, contributing 33 % of total production. China, produced an average of around nine million metric tons of plastic products per month in recent years. The rest of Asia ranked second in global plastic production, holding a 19 % share in 2023. However, only around 20 % of plastics are recycled, while the remaining 80% accumulate in soil, rivers and oceans (3).

Plastics are long-chain polymeric materials made up of monomers of varying lengths. The most widely used plastics include polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC) and polypropylene (PP). Plastics are extensively used in numerous sectors such as agriculture, packaging, industrial manufacturing, textiles and medicine due to their excellent plasticity, cost-effectiveness and durability as stable compound materials (4). Plastic waste is gradually building up in the environment because of its low recyclability and strong resistance to degradation. These materials can remain for long periods, slowly breaking into tiny plastic particles, a process known as "White pollution" (5). Prolonged exposure of plastics to environmental factors like hydrolysis, ultraviolet (UV) radiation, mechanical wear, soil erosion, animal ingestion (such as earthworms) and microbial activity gradually breaks them down into smaller fragments, including microplastics (6).

Microplastic pollution is emerging as a worldwide issue because of its durability, long-lasting presence and strength across various ecosystems. Microplastics measuring from 1 µm to 5 mm, were first identified in the 1970s and are considered a potential cause of the next global disaster if they continue to accumulate in the environment at this rate. Microplastics are small plastic particles typically 1 µm to 5 mm in size, with a common lower size limit of 1 µm. They originate from the fragmentation of larger plastic items or are manufactured at small sizes for specific applications. Unlike macroplastics (plastic debris larger than 5 mm), microplastics are not always visible to the naked eye. Owing to their small size as well as high surface-area-to-volume ratio, they pose distinct environmental and biological risks. Although the effects of microplastics on aquatic ecosystems and organisms have been extensively researched, their accumulation in agricultural soils has only recently been identified, leaving many aspects of their impact still uncertain. An estimate of mismanaged waste including sewage sludge application, suggests that the amount of microplastics in terrestrial ecosystems is 4 to 23 times greater than the quantity of plastics released into the oceans (7).

Microplastics remain in the environment for extended periods and can endure for centuries (8). It has been detected in a range of polymer compositions, sizes, shapes and concentrations across agro-ecosystems as well as in terrestrial and aquatic environments (9). This review gathers and examines all published literature on microplastic in agroecosystems. It starts with an overview of plastics in agriculture, followed by a discussion on microplastics, their types, sources, transport, impact on soil and plant functions, toxins released and concludes with prevention and control strategies.

Plastics in agriculture

Plastics are extensively utilized in agriculture to enhance productivity and resource use efficiency, a practice referred to as "Plasticulture." They enhance both the quantity and quality of yields while reducing the use of inputs such as water, pesticides and fertilizers. This encompasses materials like bale wraps, mulch and silage films, landscape fabrics, row and tunnel cover, irrigation pipes, drip tape and packaging materials (10) (Table 1). Plasticulture is regarded as a biosecure agricultural system because it helps control insects, pests and soilborne diseases while minimizing weeds and supporting crop intensification. Consequently, it leads to faster and higher crop yields (11). In agriculture, plastic materials are utilized for managing soil fumigation, facilitating irrigation systems (such as drip and sprinkler irrigation), packaging and enhancing the appearance of agricultural products, as well as shielding and safeguarding harvests from precipitation among other applications (12). For instance, plastic mulch film offers several agronomic advantages such as controlling weeds and pests, preserving soil moisture, regulating soil and air temperatures along with improving nutrient absorption (13). At the same time, plastics have become a major environmental concern in recent years, with their pollution having a significant effect on soil, water, and plant life (14). Over the past 70 years, their usage has risen significantly, reaching approximately 12.5 million tons per year. As a result, substantial amounts of macro (>25 mm), micro (1-5 mm) and nano plastics (1-100 mm) have accumulated in soils and other affected environments (15). In March 2022, representatives from 175 nations committed to developing a legally binding global Plastics Treaty (UNEA-5.2) to eliminate plastic pollution (16). This international policy framework seeks to mitigate the environmental and human health risks associated with the entire plastic lifecycle, including its impact on agriculture. It is expected that governments and non-governmental entities will need to provide regular reports on their progress and effectiveness in reducing plastic pollution (17).

Microplastic and its types

Microplastic have recently attracted considerable attention for their environmental impact as they are smaller in size, widely distributed, bioavailable and pose risks to ecosystems (18). Microplastic particles smaller than 5 mm are formed as plastic debris in the environment; breaks down into finer fragments and particles through physical, chemical or biological processes over time (19). They are water-insoluble, persist in the environment and actively interact with their surroundings. These contaminants are considered highly hazardous to the sustainability of ecosystems, as they can alter the physical and chemical properties of soil and plants (20). Microplastics break down into smaller particles which include nanoscale fragments, due to prevailing external environmental factors. Over time, they can break down into carbon dioxide (CO_2), water (H_2O) and methane (21). Microplastic can be categorized as primary or secondary depending on their source of origin (Fig. 1). Primary microplastics are deliberately produced by industries and chemical manufacturers for applications in cosmetics, personal care products, dermal exfoliators and other related items (22). Secondary microplastics are generated when larger plastic materials undergo fragmentation from commercial products. These primarily consist of fibres released during the washing of synthetic fabrics, particles from the wear and tear of plastic coatings and vehicle tires, food packaging and synthetic textiles (23, 24). Microplastics have emerged as ecological toxins that seriously endanger the environment, human health and other life forms; this subject has gained international attention.

Sources of microplastic in agriculture

Plastic film mulching

Plastic mulching is commonly practiced in agriculture, especially in arid and semi-arid regions. Plastic films are extensively utilized, as they aid in modulating the soil temperature and enhance the water use efficiency, ultimately promoting better crop growth and quality. Plastic film mulching is regarded as a major source of microplastics in terrestrial ecosystems because of its extensive

Table 1. Plastic equipment in agriculture (18)

Irrigation & Drainage Pipes	Films for Crop Protection	Nets	Packaging
Irrigation pipes	Mulching sheets	Windbreak	Agrochemical containers
Micro-irrigation	Nursery films	For shading	Liquid storage tanks
Drippers Channel linings Water collection	Greenhouses and tunnels	Anti-bird	Fertilizer storage bags Cages

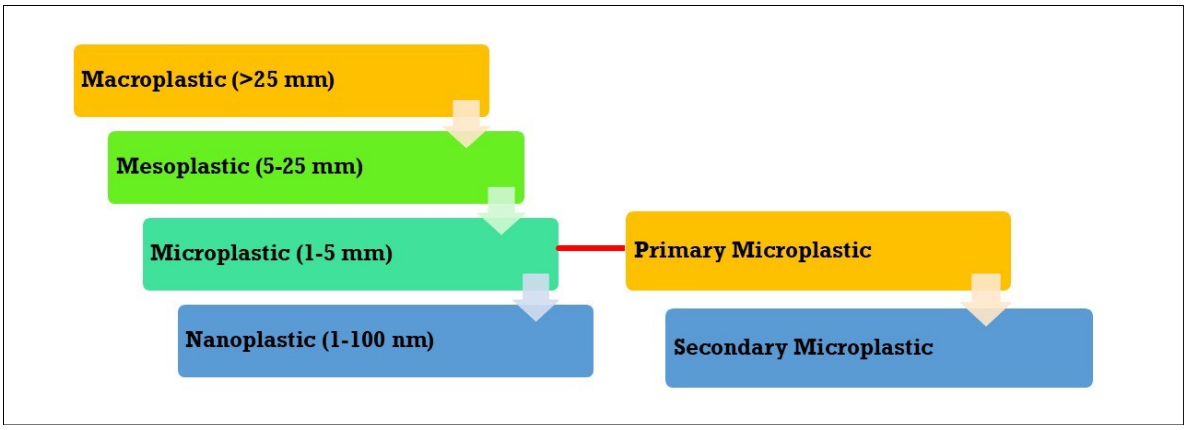

Fig. 1. Classifications of plastics based on size.

use, the presence of plastic residues and improper disposal practices (25). When plastic mulch is incorporated into the soil, it undergoes various processes including physical fragmentation, chemical degradation and biodegradation eventually breaking down into Microplastics (MPs) (26). Along with microplastic, soils also accumulate toxins added during plastic production and organic pollutants absorbed throughout their movement. Soils with mulch contain more plastic film residues than those without mulch (27). Furthermore, the longer the duration of continuous mulching, the higher the concentration of microplastic in the soil. For example, in Shihezi City, the concentration of microplastic rises considerably with prolonged continuous mulching, ranging from 10.10 to 61.05 mg/kg over a period of 5 to 30 years (28). Shearing forces acting on plastic debris in farmland come into play during ploughing and other cultivation activities, causing already fragile plastics to break down further into smaller fragments (29). Simultaneously, plastic fragments buried in the soil are further broken down mechanically by factors such as freezing and thawing cycles, pressure from snow or soil and damage from the interactions with organisms. In recent years, the worldwide use of agricultural films has surged; introducing additional concealed risks for microplastic contamination in the soil (30).

Irrigation

The occurrence of microplastics in water supplies used for agricultural irrigation has been widely confirmed (31). Worldwide, the main sources of irrigation water are rivers, lakes, groundwater and reservoirs. When surface water bodies are contaminated with microplastics, irrigating with such polluted water can transfer these particles to agricultural soils (32). Thus, microplastics present in the water become a source of contamination in the soil through irrigation.

Sewage sludge

The use of sewage sludge and wastewater contributes to microplastic pollution, with the accumulation of microplastics in soil through repeated sludge application. The concentration of microplastic in the soil increases with the duration and amount of sludge application (33). Microbeads from personal care products, polymer fibers shed during the laundering of fabrics, plastic masterbatch discharged from manufacturing facilities and microplastic from vehicle tires end up in sewage. These microplastics travel through and accumulate during wastewater treatment. Although some are released from the sewage system, most are removed through the sedimentation process and eventually end up in the sewage sludge (34).

When waste sludge contaminated with microplastic is used as biosolid fertilizer on farmland, significant amounts of microplastic are reintroduced into the cropland (35). Although the reported increase in microplastics varies, the use of sludge leads to microplastic pollution.

Compost

The use of compost as a soil amendment can also serve as a route for microplastics to enter the soil. Typically, organic waste is composted and fermented before being applied to farmland as a nutrient source, enabling the recycling of nutrients & trace elements. Composts derived from biological waste especially contain plastics, which is caused by improper disposal and inadequate waste sorting (25). A study identified 24 microplastic particles per kilogram ranging from 1 mm to 5 mm in German compost made from green clippings and municipal organic waste (36).

According to Gui et al., 2021 (37), polyether sulfone (PES), Polypropylene (PP) and Polyethylene (PE) were the most prevalent polymers making up 70 - 80 % of the total microplastic detected in compost. This significant number makes compost one of the key pathways through which microplastic enters the soil.

Coated pesticides and fertilizers

The fertilizer and pesticide industry employs plastic polymers as coating materials for slow-release fertilizers and pesticides. Polymer-coated fertilizers (PCF) are formulated with soluble nutrient cores and thermoset polymer coatings, which facilitates the gradual and controlled release of nutrients (38). Once these substances are released, the plastic coating on the fertilizer pellets stays in the soil and acts as a potential source of microplastic in agricultural land (32).

Twine

Plastic twine primarily composed of polypropylene (PP), is widely used for various agricultural purposes (39). During harvest, twine is cut and frequently left unmanaged in the fields; eventually it can break down into microplastics polluting the agricultural soil. So far, no studies have evaluated the impact of plastic twine on soil microplastic accumulation (32).

Urban runoff and floodwaters

In addition to intentional irrigation, urban runoff and flooding serve as significant pathways for transporting and accumulating microplastics in the soil (26). Urban runoff and flooding can transport improperly disposed waste near roads, along with tire abrasion particles (which contain rubber) into the soil (35). Some are microplastics already, while others slowly turn into microplastics through different environmental interactions.

Transport of microplastics into agroecosystem

The movement of microplastics in soil, both horizontally and vertically is influenced by soil properties, soil organisms, soil management practices and climatic factors (40, 41). In agricultural soils containing diverse mineral types, cracks and fissures may form as the soil dries and these cracks act as entry points for particles, enabling their rapid movement into deeper soil layers. Soil organisms including earthworms, mites and springtails aid in the transport of microplastics through their feeding and burrowing behaviours (42). As macroaggregates form in soils with a hierarchical structure, microplastic particles and microaggregates become integrated with organic matter, microbes and primary soil particles (43).

Ploughing is a common practice in agroecosystems and through this process microplastic particles can be effectively transported into the soil to the plough's depth. Furthermore, under conventional tillage, different ploughing techniques may vary in their effectiveness at incorporating microplastic into the layer impacted by the machinery (44). Besides, the bioturbation resulting from plant roots in the soil can impact the movement of microplastic including processes such as root growth, expansion and water uptake. In addition, the characteristics of microplastic may influence their movement. The size, hydrophobicity, charge, density and shape are all likely to exert a considerable effect on the movement of particles. For instance, microplastic containing -COOH functional groups move more readily than those with $-NH_2$, while hydrophilic polystyrene particles are more mobile than their hydrophobic counterparts (45).

Lightweight polymers can be carried by wind erosion across soil environments and ultimately transported to streams and rivers. Plastic transport is likely to occur across the soil surface through runoff and water erosion following hydrological and sediment transport routes shaped by surface morphology, topography and land use. Plastics can indirectly influence runoff formation and erosion by altering soil properties that impact runoff generation and susceptibility to erosion (46).

Impact on soil health and function

Microplastics frequently present in agricultural soils can affect the soil's physicochemical characteristics, reduce fertility and alter the soil microbial community ultimately impacting nutrient cycling and thereby soil health. Microplastic can interact with the soil to create different types of aggregates: loose aggregates form with plastic debris; meanwhile denser aggregates are created with MP fibers (47). Soil aggregates are fundamental components of soil structure and play a vital role in forming habitats for soil organisms, influencing gas and water flow, as well as the activity of associated microbial communities (48). Microplastics can either raise or lower the pH of soil. For instance, Polyamide Microplastic (PA-MPs) and High-density Polyethylene Microplastic (HDPE-MPs) may raise soil pH, whereas Polystyrene Microplastic (PS-MPs) and Polytetrafluoroethylene (PTFE) may decrease it (49).

Microplastics can speed up water evaporation in soil by creating pathways that promote water movement and this effect intensifies with higher microplastic concentrations. Furthermore, microplastics accumulation can weaken the soil's structure, resulting in surface cracks and drying (50).

In addition, microplastics can alter the soil nutrient cycle. While high-concentration PP-MPs (28% w/w) greatly enhanced Soil Organic Matter accumulation and facilitated the release of soil nutrients like Dissolved Organic Carbon (DOC), Dissolved Organic Nitrogen (DON) and Dissolved Organic Phosphorus (DOP). On the other hand, low concentration microplastic (7 % w/w) did not significantly affect DOM solutions in the first 7 days but led to a considerable increase in soil nutrient levels from 14 to 30 days (51).

Soil microorganisms are responsive to shifts in the soil ecosystem that changes in abiotic factors (physicochemical and structural properties) due to microplastic could influence the composition, distribution and functionality of these microorganisms (52). Furthermore, DOM is essential for microbial metabolism and energy supply, changes in carbon levels due to microplastic could influence soil functions and microbial communities with extensive functional redundancy along with high diversity (53). Additionally, influence on soil microorganisms by altering the functional groups responsible for nutrient cycling. These changes in nutrient cycling could affect the availability of nutrients for crops (54).

By examining the impact of soil microplastics on microbial evolution, we can establish an accurate baseline for soil ecology regarding the effects of this varied contaminant group and gain insights into how soil microbiome might respond in the future.

Impact of microplastics on plant growth

Plant growth refers to the expansion in volume or mass of a plant, which can take place with or without the formation of new structures. It involves physical cell differentiation, reproduction and various physiological functions; however, it is highly dependent on growth conditions. Microplastic stress limit plant growth and development via exerting (i) direct effects associated with physical blockage and (ii) indirect effects resulting from the alterations in soil properties (Fig. 2).

Direct effects associated with physical blockage

Seed germination and root development

Due to their small size and high adsorption capacity, microplastics can attach to the surfaces of seeds and roots; thereby preventing seed germination and root growth. Microplastic inhibits seed germination by blocking the pores in the seed capsule, limiting water intake and the imbibition process (55) (Table 2); a decrease in the imbibition process leads to a lower germination rate (56). Microplastics obstruct intercellular connections in roots, hindering nutrient transport and resulting in reduced biomass, lower catalase activity in higher plants, and stunted growth at elevated microplastic concentrations (57). The microplastics that adhere to root hairs and cell wall pores reduce transpiration, hinder nutrient and water absorption as well as impact root respiration. (58).

As microplastics fragments, their particle size decreases while their specific surface area increases, enhancing their potential to adhere to the root surface. However, microplastic can also be absorbed into the root through the endocytosis

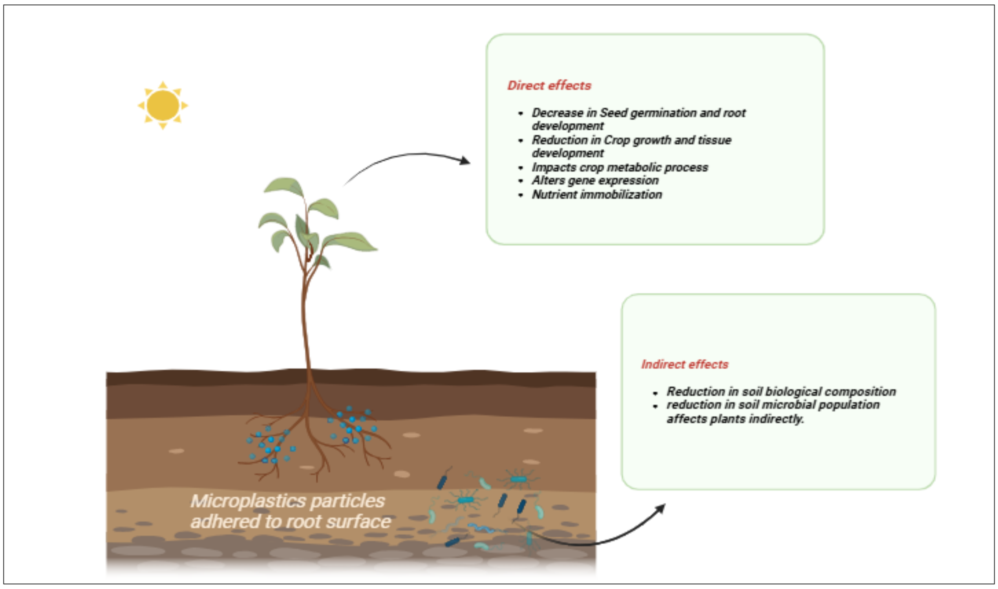

Fig. 2. Impact of microplastics on plant growth.

Table 2. Impacts of microplastics on plant growth and development

Plant species	Microplastic (Polymers)	Impacts	Reference
Hordeum vulgare L.	Polystyrene (PS), Polymethyl Methacrylate (PMMA)	Disruption of metabolic systems and enzyme activity.	(60)
Oryza sativa L.	Polystyrene (PS)	Shoot and root reduction	(68)
Triticum aestivum L.	Polystyrene (PS)	Reduction in micronutrient	(69)
Daucus carota L.	Polystyrene (PS) + Arsenic	Root and leaves reduction, ROS increasement	(70)
Cucumis sativus L.	Polystyrene (PS)	Alteration in Photosynthetic, Biomass and Antioxidant system	(71)
Lolium multiflorum Lam.	High Density Polyethylene (HDPE)	Reduced seed germination and Root shoot length	(72)
Allium cepa L.	Polystyrene (PS)	Decreased root length, Induced cytogenetic toxicity & Increased ROS production	(73)
Zea mays L.	Polyethylene (PE)	Decreased maize growth, Modified bacterial communities in soil & Impacted antioxidants gene expression.	(74)

process (59). Auxin and cytokinin control root system development by directing the growth of root hairs, lateral roots and crown roots. Microplastics decrease rootlet numbers and the levels of three phytohormones- Orthophthalic acid (OPA), Indole-3-butyric acid (IBA) and cis-zeatin riboside in the roots, suggesting that it influences root development by altering cytokinin and auxin concentrations (60).

Furthermore, the influence of microplastics on Reactive Oxygen Species (ROS) generation in crop roots decreases the viability of root cells, which leads to disruptions in the antioxidant defence system and causes damage or modifications to the cellular system (61).

Crop growth and tissue development

Microplastic particles may accumulate on leaves due to atmospheric deposition, which can interfere with stomatal function and in turn influence photosynthesis and transpiration. In addition, microplastic could impair photosynthesis by affecting chlorophyll production in the shoots or leaves of plants (62). Microplastics that accumulate in the stem vascular bundles and leaf veins could block the absorption and transport of water and nutrients, limiting stem growth and tissue development (63). Microplastics lowered the levels of elemental and soluble molecules, as well as organic compounds, total sugar content which could account for the decrease in the crop's stem biomass (64).

Crop metabolic processes

Microplastic could raise Reactive Oxygen Species (ROS) production and enhance antioxidant enzyme activity. Increased ROS production could reduce the synthesis of lipids, amino acids, nucleic acids and other secondary metabolites surpassing the antioxidant system's ability to neutralize them, led to impaired membrane functions (65). As a protective mechanism, crops generate extra antioxidant enzymes to counteract stress caused by excessive ROS. Consequently, microplastic - induced abiotic stress in crops can interfere with energy metabolism by modifying anabolic processes and causing damage to cell lipids, proteins and nucleic acids. These physical damages to cells could undermine their integrity and function, triggering various responses in the crops (54).

Alterations in gene expression

Microplastics exposure expedited root aging or caused root death by altering the expression of CDC2, a gene that controls the cell division cycle and CDK, the gene that encodes cyclin-dependent kinase (65). For example, studies in *Arabidopsis thaliana* and *Lactuca sativa* (lettuce) have demonstrated that microplastics can alter root architecture, reduce biomass accumulation and disrupt hormonal signalling pathways such as auxin transport which is also linked to root development. These gene-level disruptions collectively lead to reduced plant vigour and yield potential under microplastic stress. It particularly limits plant nutrient growth during the vegetative stage, mainly by inhibiting the expression of genes that control nitrate transport within the roots as well as those associated with photosynthesis (66). They also downregulate photosynthesis-related genes including those encoding chlorophyll a/b binding proteins and photosystem components like *psbA* and *rbcL*, thereby reducing photosynthetic efficiency.

Nutrient immobilization

Plastic particles are rich in carbon content, with most of it remains relatively inert due to the material's resistance to decomposition. Over time, the plastic will gradually break down and due to its wide carbon-to-nitrogen (C:N) ratio, this process will lead to microbial immobilization. However, since most plastics decompose extremely slowly; this effect is unlikely to have significant biological implications (62).

Indirect effect in the alterations of soil properties

The growth and productivity of plants are significantly affected by soil properties, the composition of the soil's biological community and its overall diversity. Microplastics impact soil's physical and chemical characteristics as well as microbial populations, potentially resulting in changes in the rhizosphere, plant growth environment and nutrient availability which ultimately affects plants indirectly.

For example, microplastics modify the soil-based bacterial ecosystem and decreases soil organic matter and bulk density. Microplastics greatly influence soil enzymatic activity such as catalase (CAT), peroxidase (PO), fluorescein diacetate esterase (FDAase) and urease leads to temporary alterations in soil health (52). Moreover, microplastic can lower the diversity of soil microbes or reduce the number of rhizosphere fungal partners, which potentially leads to a decline in plant diversity (67).

Toxic leachates from microplastics

Various additives are present in plastic products including plasticizers, antioxidants, flame retardants, light and heat stabilizers, lubricants and pigments. These additives are typically not chemically bound to plastic polymers, making them prone to leaching into the soil. For instance, plasticizers greatly hinder wheat seed sprouting, affect plant antioxidant enzyme functions and initiate programmed cell death in seed cells (75). Plastic additives as well as environmental contaminants like organic pollutants and heavy metals adhered to the surface of microplastic can also impact agricultural soil (76). For example, phthalate (PAE) often called an "environmental hormone", particularly when subjected to prolonged environmental exposure (77, 78). When PAEs are released into the soil from plastic film remnants, it lowers soil microbial biomass activity (SMbA) by disrupting soil respiration and enzyme functions (78). As a result, they may present a hidden threat to the ecological functions of soil.

Risk to human health

The potential risks to both the ecosystem and human well-being from microplastic exposure are key concerns in microplastic research. Microplastics transfer from one trophic level to another, ultimately accumulating at the highest level of the human food chain (79). Research suggests that microplastics can infiltrate the seeds and fruits of crops, eventually entering the human body through dietary intake. Once inside, they may pose health risks due to particle toxicity, chemical toxicity and their potential to carry pathogens as well as parasite vectors (80). Microplastics present in agricultural soil can reach human body through food consumption, inhalation and direct contact. This exposure may lead to asthma, respiratory irritation, obesity, cardiovascular diseases and gastrointestinal disorders posing a significant risk to human health. Once absorbed into the human body, microplastic can accumulate in the intestines; potentially triggering local inflammation, disrupting endocrine regulation and impairing gastrointestinal functions. Furthermore, they may change the composition and diversity of gut microbes, leading to imbalances in the gut microbiome (81).

Prevention and control strategies

Regulatory Measures

Different legal and administrative steps have been taken to tackle the increasing problem of microplastic pollution across various countries. The European Union has actively worked to combat the pervasive issue of microplastics.

In 2018, the EU launched the 'European Strategy for Plastics in a Circular Economy,' aiming to transform the entire plastic lifecycle-from design and production to usage and recycling. The circular economy framework presents a replacement for the traditional linear economy, which operates by "make, use and dispose" pattern. Its aim is to prolong the longevity of resources, derive maximum value from them; subsequently recover and revitalize goods as well as resources after their useful life has ended. This approach includes initiatives to minimize microplastic use in various products and focuses on advancing innovative plastic recycling technologies (82).

India's Plastic Waste Management Rules, 2016 (amended in 2021) and global agreements like the Basel Convention aim to reduce plastic pollution through measures such as Extended Producer Responsibility (EPR) together with bans on certain single-use plastics. However, effective enforcement and local-level implementation are still challenging and need to be strengthened. Raising public awareness is crucial. Many people are still unaware of the environmental impact of plastic waste and proper disposal methods. Awareness campaigns, school programs and community initiatives can help promote responsible plastic use and segregation. Proper plastic management begins with segregation at the source. Use of color-coded bins, regular waste collection and integrating informal waste workers can improve recycling. Technologies such as Material Recovery Facilities (MRFs) and EPR implementation can further improve plastic waste management and support a circular economy. The 2019 Basel Convention Plastic Waste Amendments, which regulate the global transfer of plastic waste, could be expanded to include agricultural products like soil amendments and compost (83). At the government regulatory level, the roles of companies throughout the plastic product life cycle need to be defined. At the public level, initiatives should focus on enhancing awareness and concern regarding microplastic pollution.

Biodegradable alternatives

To address microplastics in soil, it is essential to eliminate plastics at the source as removing them from large agricultural areas is relatively challenging. Therefore, an effective alternative to plastic disposal is to use biodegradable materials. At the end of their life cycle, biodegradable materials can be added to the soil; where they are broken down by microflora into carbon dioxide or methane, water and biomass. Biodegradable plastics have brought fresh insights into waste management strategies, as they are designed to decompose under environmental conditions (84). For instance, biodegradable mulch films break down in the soil after ploughing eliminates the need for film collection and disposal (85).

In addition, possessing properties like those of conventional plastics bioplastics (biopolymers), sourced from microorganisms or genetically engineered plants to produce these polymers are anticipated to substitute the plastics in use today (86).

Various communities in India have embraced creative and eco-friendly alternatives to plastic. In regions like Assam and Meghalaya, where bamboo is plentiful, bamboo-based bottles and utensils are becoming more common. These products are biodegradable, long-lasting and help support local craftsmanship (99).

In the rural regions of Tamil Nadu and Kerala, banana leaves and areca palm leaf plates are commonly utilized during cultural ceremonies, weddings and temple festivals as substitutes for disposable plastic plates. These plates are entirely biodegradable and have cultural significance. One notable example is Kumbalangi village in Kerala, India's first model tourism village where plastic use has been prohibited in favour of sustainable materials like coir, bamboo and leaves. Similarly, Hiware Bazar in Maharashtra renowned for its focus on sustainable development has worked to minimize plastic consumption and embrace eco-friendly practices (100).

4Rs (Reduce, Reuse, Recycle and Recover) Concept

The most effective approach to prevent the creation of microplastic is by reducing the amount of plastic waste. Recycling and processing various forms of plastic waste can transform them into useful raw materials, alleviating the environmental contamination resulting from improper disposal along with facilitating the reuse of materials and energy from plastic waste. Improved solid waste systems and management will reduce plastic litter which contaminates rivers and marine environments, consequently lowering the rate of microplastic buildup. The repeated use of plastic materials can greatly minimize plastic waste and lower microplastics formation. Utilizing plastic waste as an energy resource and converting it into valuable products will also contribute to reducing the emergence of microplastic particles (87).

Need of teaching an environment-based curriculum among the students

This growing environmental issue highlights the urgent need to teach students about the environment from an early age. By introducing an environment-based curriculum in lower classes, children can learn about the importance of protecting nature, reducing plastic use and making eco-friendly choices. Early education helps students build awareness and responsibility encouraging them to care for the planet as they grow. When students understand the impact of pollution like microplastics, they are more likely to adopt sustainable habits and spread awareness. Therefore, including environmental topics in school education from the beginning is not just important-it is essential for building a greener, healthier future.

Bioremediation approach

Bioremediation is a technique that utilizes living organisms like bacteria, fungi or plants to degrade or neutralize environmental contaminants such as chemicals, heavy metals or waste to restore and enhance the ecosystem's health. Phytoremediation is an on-site restoration technique that employs plants and their related soil microorganisms to reduce the pollutant concentrations such as microplastic within soil ecosystems (88). Plant roots trap microplastics, preventing their movement and lowering their accessibility to other parts of the plant thus minimizing the possible threat to other soil organisms. For instance, water plants such as *Lemna minor, Thalassia testudinum* and *Fucus vesiculosus* can adsorb microplastic, thereby reducing their movement and bioavailability in aquatic agroecosystems (89).

Earthworms play a vital part in soil ecosystem stability by accumulating heavy metals and breaking down microplastic. Drilodefensins, a metabolite found in the guts of earthworms, play a protective role by mitigating oxidative stress induced by plant polyphenols (90). When exposed to microplastics, earthworms like *Eisenia fetida* enhance their antioxidant defence mechanisms by secreting enzymes such as, glutathione-related enzymes, acetylcholine esterase, superoxide dismutase, malondialdehyde, catalase and lipid peroxidation enzymes (50).

Microplastics made of synthetic polymers containing carbon and hydrogen are vulnerable to microbial attack (Table 3). The development of biofilms on their surface, formed by microbial communities like bacteria, fungi, algae, archaea, viruses and protozoans is known as the "Plastisphere." The spread of microbial communities as biofilms on microplastic takes place in several stages and follows a sequential pattern over time (91). The process begins with the colonization of microplastic by primary microorganisms that grow and expand across the microplastic surface. As the biofilm develops, there is a shift in the microbial population. The degradation process changes the functional groups, chemical composition, molecular weight and tensile strength of the polymer. The microbial community progressively breaks down microplastic via enzymatic hydrolysis, reducing the polymer into oligomers, dimers and monomers. These simpler compounds act as the main sources of carbon and energy, eventually being fully broken down into carbon dioxide and water (92).

Bacillus cereus, a gram-positive bacterium has been found to degrade low-density polypropylene (LDPP), a plastic widely used in packaging and bags. This microorganism

Table 3. List of microorganisms capable of degrading various types of microplastics

Microorganism	Microplastic degraded	Reference
Bacillus cereus	Low -density polypropylene (LDPP)	(93)
Ideonella sakaiensis	Polyethylene terephthalate (PET)	(94)
Pseudomonas mendocina	Polylactic acid (PLA)	(95)
Thermobifida alba AHK119	Modified polyethylene terephthalate (Modified PET)	(96)
Alcaligenes faecalis LNDR-1	Polyethylene (PE)	(97)
Rhizopus delemer	Polylactic acid (PLA)	(98)

facilitates the breakdown of LDPP by secreting enzymes that break down the polymer chains, converting the plastic into smaller biodegradable substances (93). *Ideonella sakaiensis*, a bacterium discovered in a recycling plant in Japan can break down polyethylene terephthalate (PET) the plastic commonly used in beverage bottles. This bacterium produces two essential enzymes namely PETase and MHETase, which work in tandem to decompose PET into its basic components i.e. terephthalic acid and ethylene glycol. The discovery of *I. sakaiensis* has marked a significant advancement in bioremediation and current research is focused on improving its efficiency for industrial use (94). *Pseudomonas mendocina*, a soil bacterium can degrade polylactic acid (PLA), a biodegradable plastic frequently used in packaging and disposable items. The degradation of PLA by *P. mendocina* occurs through enzyme-driven hydrolysis of the polymer resulting in the release of lactic acid, which the bacterium can further metabolize. This microorganism offers a sustainable alternative to conventional methods of plastic waste disposal (95). *Thermobifida alba* is a thermophilic bacterium that can break down modified polyethylene terephthalate (Modified PET). It generates heat-tolerant enzymes that can decompose polyester-based plastics offering a potential solution for addressing plastic waste from the textile and packaging sectors (96). *Alcaligenes faecalis*, a bacterium found in a variety of environmental samples has demonstrated the ability to degrade polyethylene (PE) a commonly used plastic. It does so by secreting enzymes that break down the long hydrocarbon chains in PE thus contributing to the reduction of plastic waste. *A. faecalis* is especially notable for its ability to thrive in challenging environments making it ideal for large-scale applications (97). *Rhizopus delemer* is a fungus known to degrade PLA. Like *P. mendocina*, it produces enzymes that break down PLA into simpler compounds which can be further processed or metabolized by the organism. This fungus shows promise in bioremediation efforts, especially in composting systems for managing biodegradable plastic waste (98).

Conclusion

This review highlights the prevalence, dispersion and environmental dynamics of microplastics within agroecosystems. The extensive use of plastics in farming has led to their accumulation in soils, where they persist due to their resistance to degradation. Microplastics do affect soil structure, reduce fertility, disrupt microbial communities and ultimately impact crop growth. They also hinder seed germination, nutrient absorption and photosynthesis, whilst introducing toxic additives into the soil. Additionally, microplastic enters the food chain posing health risks to humans through ingestion and inhalation. Effective strategies such as biodegradable alternatives, recycling and bioremediation are crucial in mitigating this issue. Governments and industries must enforce regulations to limit plastic use and promote sustainable practices. Raising public awareness about microplastic pollution is essential for long-term environmental sustainability. A collective global effort is needed to reduce plastic waste and protect soil health. Therefore, careful management and evidence -based policies are essential to effectively safeguard the global ecosystem.

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Authors' contributions

MV and AA conceived the idea for this manuscript. KK conducted the literature review and drafted the initial manuscript. AG, KK and KGS provided critical feedback and revisions to the manuscript. MV and AA prepared the final version of the manuscript. All authors read and approved the final manuscript for submission.

Compliance with ethical standards

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Additional information

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