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Research Progress on the Environmental Behaviors and Ecological Effects of Microplastics in Agricultural Soils

Yunxiang Lu, Shiwei Lu, Lijie Song*

Xinjiang University, College of Civil Engineering and Architecture, Urumqi 830046, China

Abstract. Microplastics (MPs) are an emerging class of pollutants, the accumulation and environmental behaviour of which in soil media may affect the agricultural production process and widespread attention has been paid to ecosystem construction as well as the transport processes and ecological impacts of microplastics in soil ecosystems. This article reviews the sources and distribution of microplastics in agricultural soils and establishes an analysis framework based on standardized units and ecological zoning to enhance the comparability of global data,comprehensively synthesizes their environmental behaviors including adsorption and migration mechanisms within soil ecosystems, and critically examines the interactions among heavy metals, organic pollutants, and antibiotics, along with the ecological impacts of microplastics. Lastly, this paper puts forward the future research direction of microplastics research in agricultural soil, in order to provide relevant information and research ideas for the pollution and management of microplastics in agricultural soil.

1. Introduction

Owing to their low cost, light weight, and ductility, plastic products have become ubiquitous; however, their recycling efficiency remains suboptimal.After entering the environment, they further fragment into smaller particles through long-term physical, chemical, and biological processes. Plastic particles or fragments with a particle size smaller than 5mm are defined as microplastics (MPs). Currently, microplastics have been detected in marine, freshwater, and soil environments. Soil serves as a significant and long-term reservoir for microplastics, with the global median stock of microplastics in soil estimated at approximately 3.6 metric tons, one to two orders of magnitude higher than the estimated stock on the ocean surface. Soil microplastics can not only trigger the emission of greenhouse gases such as N_2O, CO_2 from soil into the atmosphere but also indirectly increase greenhouse gas emissions through adverse effects on underground carbon sinks or reservoirs.

Through the retrieval and filtering of the China National Knowledge Infrastructure (CNKI) and Web of Science Core Collection databases, utilizing search terms pertaining to “soil" and “microplastics”, the keyword co-occurrence network diagram of the retrieved literature was constructed (Figure 1), which reveals that the domestic and international research focuses are generally consistent, encompassing the temporal and spatial distribution characteristics of soil microplastics, their sources and pollution traits, the toxic effects exerted by microplastics on soil properties as well as soil animals, plants and microorganisms along with the corresponding influencing factors, the ecological risks posed by microplastics, The co-contamination of microplastics with heavy metals or organic compounds, and the detection methodologies for microplastics.In recent years, an increasing number of microplastic-related studies have shifted their focus to the soil environment, and the research directions concerning soil microplastics have gradually exhibited a transition from investigating the migration, adsorption, and desorption behaviors of microplastics to exploring the combined pollution involving microplastics and their impacts on soil health.

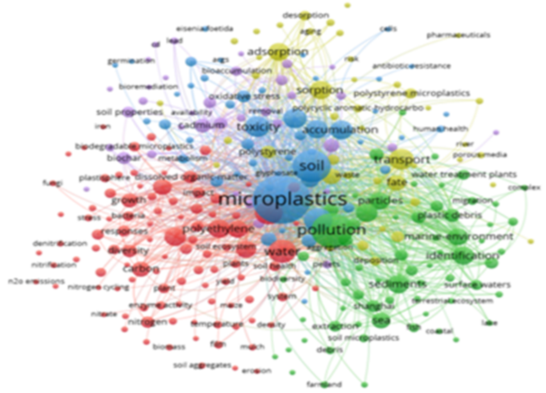

Fig. 1 Co-occurrence network analysis diagrams with microplastic as the keyword.

Microplastics in soil can alter soil structure and physicochemical properties through migration and adsorption, and also affect the soil ecological environment by releasing pollutants or interacting with other environmental contaminants. Given the close connection between agricultural soil and human life, understanding

* Corresponding author: songlijie@xju.edu.cn

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the environmental behavior of microplastics in agricultural soil environments is of great significance for agricultural safety. This article comprehensively reviews the sources and distribution of microplastics in agricultural soil, the mechanisms of their environmental behavior, ecological risks, and provides guidance for scientifically preventing and managing microplastic pollution in agricultural soil.

2. Abundance and Sources of Soil Microplastics

Soil microplastic concentrations exhibit significant spatial heterogeneity, influenced by variables including accumulation duration, soil texture, sampling depth, geographic setting, and the level of agricultural activity. Drawing upon existing research regarding microplastics across diverse soil types—both within the country and abroad—the author outlines the prevalence and distinct features of these particles in various pedological settings, which are enumerated in Table 1.

Due to variations in sampling methods, pretreatment techniques, quantitative units, and classification criteria adopted in different studies, a unified evaluation standard has not yet been established; however, existing research indicates that microplastics have been widely present in various types of agricultural soil environments (Table 1).Table 1 illustrates that polyethylene (PE) and polypropylene (PP) are the most prevalent types of microplastics found in agricultural soil, with their presence being strongly linked to anthropogenic activities—specifically, the abundance of microplastics in industrial zones, long-term plastic film-covered farmlands, and sewage-irrigated areas is generally significantly higher than that in natural or slightly anthropogenically disturbed soils (e.g., farmlands on the Qinghai-Tibet Plateau), while the sources and input pathways of microplastics in soil can be broadly categorized into internal sources from agricultural activities and external inputs from the surrounding environment. Agricultural practices are the main contributors to microplastic pollution in farmland soils. These anthropogenic inputs primarily stem from the breakdown of plastic mulch , the incorporation of organic fertilizers, and the agricultural utilization of sewage sludge. External environmental inputs also constitute significant sources of soil microplastics, encompassing atmospheric deposition from urban dust and traffic-related particulates carrying microplastics, water migration via surface runoff and irrigation water, as well as biological accumulation and food chain transfer.

Table 1 The abundance and characteristics of microplastics in soil environments

Year	Soil Type	Country/Region	Abundance	Component	Size/mm	Shape	References
2017	Garden soil	Campeche, Mexico	870±1900 pcs · kg^{-1}	-	0.01~0.05	-	[2]
2018	Beach soil	Shandong, China	1.3~14712.5 pcs · kg^{-1}	PE, PP, PS, PU	<5	Film, fragments, foam, fibers	[3]
2018	Farmland soil	Southeastern Germany	0.34~0.36 pcs · kg^{-1}	PE, PP, PS	1~5	Fibers, fragments, film	[4]
Year	Soil Type	Country/Region	Abundance	Component	Size/mm	Shape	References
2019	Vegetable garden soil	Wuhan, China	320~12560 pcs · kg^{-1}	PA, PP, PS, PVC, PE	0.02~5	Fibers, fragments, microbeads, foam	[5]
2020	Farmland soil	Qinghai-Tibet Plateau, China	47.94 pcs · kg^{-1}	PE, PP, PA, PS	<5	Film, fibers, fragments, particles	[1]
2020	Farmland soil	Eastern China	571 pcs · kg^{-1}	PE, PP, PES	1~3	Fragments, film, fibers	[6]
2020	Floodplain soil	Germany	1.88±1.49 pcs · kg^{-1}	LDPE, PP, PA, etc.	< 10	Fragments, fibers, film, particles	[7]
2021	Agricultural soil	Jiangxi, China	(16.4±2.7)~(43.8±16.2) pcs · kg^{-1}	PES, PE, PP	-	Fibers, fragments	[8]
2021	Vegetable garden soil	Shandong, China	310~5698 pcs · kg^{-1}1	PE, PP	< 0.5	Film, fragments	[9]
2023	Arid land soil	Central Asia region	182–1784 pcs · kg^{-1}	PU, SR, CPE, PLA, etc.	0.02~0.06	-	[10]
2024	Farmland soil	Loess Plateau of China	56123±82980 pcs · kg^{-1}	PE	0.01~1	Fragments, fibers, microbeads	[11]
2024	Orchard soil	Southern China	8896 ± 5745 pcs · kg^{-1}	PET, PVC, FKM	0.008~0.067	-	[12]

Note: PE stands for polyethylene, PA for polyamide, PP for polypropylene, PS for polystyrene, PVC for polyvinyl chloride, SBR for styrene-butadiene rubber, PES for polyethersulfone, PET for polyethylene terephthalate, FKM for fluororubber, PU for polyurethane, SR for silicone resin, CPE for chlorinated polyethylene, PLA for polylactic acid, LDPE for low density polyethylene.

Residual plastic film is considered a primary source of microplastics in agricultural soils . Agricultural plastic mulching can improve soil hydrothermal conditions, suppress weed growth, and bring economic benefits to agricultural production . According to data from the National Bureau of Statistics, as of 2021, China's plastic film coverage area for crops exceeded 20 million hectares, with annual plastic film usage surpassing 2.35 million tons, accounting for about 90% of global annual plastic film consumption. However, the global recovery rate of used plastic film is less than 66% [13]. The average abundance of microplastics in mulched farmland is 571 $pcs \cdot kg^{-1}$, while in non-mulched farmland it is only 263 $pcs \cdot kg^{-1}$ [14]. Factors such as mulching duration, mulching methods, and usage intensity all influence microplastic abundance in farmland. Huang et al. [15] investigated microplastic abundance in Xinjiang, a typical mulching cultivation area in China, finding microplastics present in the plow layer of the topsoil 40cm (average abundance of 1075.6 ± 346.8 pcs/kg), with a significant increase in microplastic quantity as plastic mulching duration extended. Zhou et al. [16] studied the effects of two types of microplastics—polyester microplastic fibers (PES-MP) and polypropylene microplastic fibers (PP-MP)—on soil environmental factors, plant growth, physiology, biochemistry, crop yield, and quality, finding that PP-MPs had a more negative impact on dicotyledonous plant traits than PES-MPs. These studies indicate that the abundance of various microplastics in agricultural soils increases with mulching duration, and the type of mulching plastic is closely related to agricultural soil environment and plant growth.

The application of agricultural fertilizers is also a significant reason for the high microplastic content in agricultural soils. Organic fertilizers are an important source of plant nutrients in agricultural production, but improper application methods and repeated application processes can introduce microplastics into farmland soils . Research by Wang et al. [17] studied the effects of mulching duration and organic compost application on the distribution of microplastic types in soils at different depths. The results indicated that the surface layer (0-40cm) of soils with long-term mulching and organic compost application had significantly higher microplastic abundance than the control group without mulching and organic compost application ($P<0.05$). Plastic films and organic compost applied in agricultural production can significantly increase soil microplastic abundance under mechanical disturbance and surface runoff, and the growth rate of microplastics further intensifies with increasing duration.

Irrigation is also an important pathway for the accumulation of microplastics in agricultural soils. Salehi et al. [18] detected substantial quantities of microplastics and mesoplastics in agricultural fields irrigated with various water types, including groundwater, surface water, and effluent from wastewater treatment plants, with the greatest concentration of these particles—1188±564 $pcs \cdot kg^{-1}$—observed in farmland irrigated with surface water.In addition to containing microplastics themselves, irrigation water can also promote the migration and transformation of microplastic pollutants in soil caused by agricultural activities and atmospheric deposition. Microplastic particles carried by irrigation water enter the soil with the flow and gradually accumulate. This accumulation process is influenced by factors such as irrigation volume, irrigation frequency, and soil type. In farmlands that have long used water containing microplastics for irrigation, soil microplastic abundance shows a significant increasing trend. Microplastics may also enter the soil through atmospheric deposition, surface runoff, etc. For example, microplastic particles formed from road tire wear may enter roadside environments through dust or stormwater runoff and affect agricultural soils.

3. Environmental Behavior Mechanisms of Microplastics in Soil

Microplastics from diverse sources, after entering the soil, can exert impacts on soil ecology and biodiversity through multiple pathways, and the environmental fate of microplastics constitutes a complex yet crucial process: when exposed to the environment for an extended period, microplastics will slowly release harmful endogenous additives into the soil matrix; furthermore, microplastics can act as carriers for adsorbing other environmental pollutants, thereby prolonging the potential impacts of these pollutants on the ecosystem. Meanwhile, disturbed by a variety of environmental factors, microplastics undergo migration and transportation in the environment, which expands the spatial scope of pollutants that pose potential hazards to the soil environment and crops. It is of great importance to understand and clarify the environmental behaviors of microplastics when investigating approaches to remediate agricultural soils polluted by these particles.

3.1 Migration of Microplastics

Owing to their diminutive dimensions, microplastics exhibit a high propensity for translocation upon entering ecosystems. This movement, driven by diverse environmental forces, is generally classified into two distinct modes: horizontal and vertical transport.The migration process of soil microplastics is affected by multiple factors, including environmental conditions such as temperature, humidity, wind speed, and runoff velocity, as well as the inherent properties of microplastics like density, shape, size, and surface characteristics. Compared to other soil types, microplastic migration in agricultural topsoil (0–30cm) is more susceptible to agricultural activities such as sowing, plowing, irrigation, and fertilization. Laermanns et al. [15] investigated the horizontal migration of polymethyl methacrylate microplastics using fluorescent particle tracking, finding that their horizontal migration rate is influenced by particle size and shape; smaller particles exhibit longer relative migration paths, and migration path length is also related to surface roughness and irrigation levels. Current research on horizontal migration of microplastics is limited, and the actual mechanisms involved require further study. Under various influences such as mechanical disturbance, biological activities (e.g., earthworms, larvae, and vertebrates) [19], and plant roots, microplastics undergo vertical migration in the soil environment, which is affected by soil texture, porosity, physicochemical properties, soil organisms, and other factors. Rillig et al. [19] studied the impact of earthworms (Lumbricus terrestris L.) on the vertical migration of PE microplastic particles of different sizes, finding that earthworm movement in soil can vertically transport PE microplastic particles sized 710 to 2800μm by 10cm within 21 days. Soil wet-dry cycles also cause vertical migration of microplastic particles .

3.2 Transformation Processes of Microplastics in Soil

Environmental plastic debris undergoes aging when exposed to mechanical forces, elevated temperatures, ultraviolet light, chemical oxidation, and microbial activity. These factors cause the long polymer chains in aged microplastics to break down gradually, while also altering their surface structure and physicochemical characteristics. In soil environments, the transformation of microplastics involves physical, chemical, and biological pathways.

The physical transformation of microplastics in soil primarily refers to processes such as mechanical abrasion, friction, and weathering; for instance, plastic films, after long-term exposure to mechanical abrasion and ultraviolet radiation in the soil environment, will gradually decompose into microplastics, a process that further induces the fragmentation of microplastic particles into smaller ones or even nanoplastics.

The chemical transformation of microplastics in soil primarily involves processes such as oxidation, photodegradation, and chemical decomposition. In the soil environment, oxidation on the surface of microplastics can form more functional groups, such as hydroxyl and carboxyl groups, thereby altering their chemical properties. Photodegradation is one of the important pathways for the chemical transformation of microplastics. Studies show that plastics like polyethylene (PE) and polystyrene (PS) undergo significant photodegradation under ultraviolet radiation, forming smaller particles and volatile organic compounds. Lee et al. described two main photodegradation mechanisms: singlet oxygen-induced oxidation and radical-induced oxidation [20]. Furthermore, various photocatalysts such as TiO_2, ZnO–Pt, Fe–ZnO, Mn@NCNTs, and Ag/TiO_2 have been verified to play significant roles in the photodegradation of microplastics .

The biotransformation of microplastics in soil refers to the degradation and transformation of microplastics under the action of microorganisms and soil organisms. Microorganisms can form biofilms on the surface of microplastics, breaking down plastics into smaller molecules through enzymatic action. The microbial degradation of microplastics in soil involves processes including microbial colonization and biofilm formation, deterioration, depolymerization, assimilation, and mineralization (Fig. 2). During the deterioration stage, the physicochemical properties of microplastics change due to external factors such as ultraviolet (UV) radiation or extracellular enzymes secreted by microorganisms, introducing carbonyl groups that are oxidized to form carboxyl groups, providing attachment sites for microorganisms and necessary chemical groups for subsequent enzymatic depolymerization. In the depolymerization process, microplastics are further broken down into oligomers, dimers, and monomers by specific enzymes secreted by microorganisms, such as peroxidases, monooxygenases, and laccases, making these low molecular weight substances more easily absorbed by microorganisms. During assimilation, microorganisms transport these depolymerization products across membranes into cells, incorporating them into metabolic activities as carbon or energy sources. In the final mineralization stage, microorganisms utilize these low molecular weight compounds through aerobic or anaerobic respiration, converting them into CO_2, H_2O and CH_4 and releasing them from the cells.

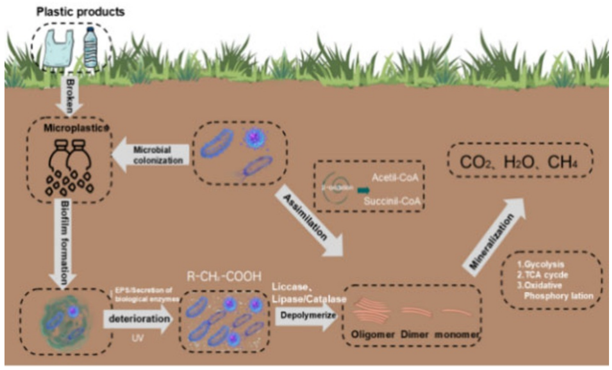

Fig.2 Biodegradation process of microplastics in the soil

3.3 Interaction of Microplastics with Soil Pollutants

Because of their pronounced hydrophobic nature and extensive surface area, microplastics are capable of serving as transport vectors for typical soil contaminants including heavy metals, persistent organic compounds, and antibiotics. They can engage with these substances through multiple mechanisms, which in turn alters the contaminants' movement and toxic effects and ultimately impacts soil biological diversity. Consequently, besides the direct pollution and migration of microplastics, their interactions with other pollutants are equally important for advancing precise ecological risk evaluations.Fang et al. [21] investigated the internal mechanisms and interactions of heavy metals, pesticides, and microplastics in soil, noting that microplastics, as pollutant carriers, primarily bind with other pollutants through mechanisms such as electrostatic adsorption, complexation, partitioning, and surface adsorption, as shown in Figure 3.

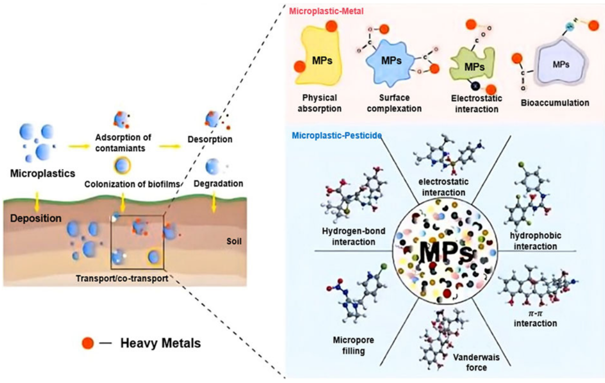

Fig.3 Adsorption mechanisms of microplastics - heavy metals and microplastics - pesticides[21].

3.3.1 Interactions Between Microplastics and Heavy Metals

Microplastics have the capacity to bind heavy metals in soil, thereby altering their bioavailability and mobility. Several investigations suggest that microplastics may serve as vectors that facilitate the transport and transformation of heavy metal ions, promoting their spread and buildup in soil environments and thus exhibiting a distinct pollutant sensitization effect. Zhang et al. [22] investigated the impact of polyethylene microplastics on the adsorption and desorption of Cd in farmland soil under different conditions, finding that adding microplastics increases the mobility of Cd in soil, thereby raising the risk of toxic metals like Cd accumulating in crops and entering groundwater, with this change being more pronounced at higher microplastic concentrations and larger particle sizes. The adsorption efficiency of different microplastics for the same heavy metal ions varies, with microplastic surface area, functional groups, and surface charge all significantly influencing adsorption capacity . Some studies also show that microplastics alter heavy metal forms by affecting the soil environment, promoting the conversion of heavy metals (Cd, Pb, Ni, Cr, Cu) from bioavailable to organically bound states, reducing their bioavailability, thereby diminishing their potential threats to soil ecosystems and human health, exhibiting dilution and inhibitory effects. Overall, the combined effects of microplastics and heavy metals in soil systems lack a universally accepted conclusion. The current prevailing understanding is that interactions between microplastics and heavy metals primarily occur through surface adsorption and chemical bonding; the hydrophobicity and surface characteristics of microplastics enable them to effectively adsorb heavy metal ions, reducing their bioavailability in soil. Additionally, the presence of microplastics can further influence heavy metal toxicity by altering soil redox conditions and microbial activity. Interactions between different types of microplastics and heavy metals may vary, and further research is needed to clarify the specific mechanisms.

3.3.2 Interaction Between Microplastics and Persistent Organic Pollutants

A range of natural and human-related activities—including the use of pesticides, the agricultural application of sewage sludge or compost, and the irrigation of crops with polluted water—lead to the buildup of persistent organic pollutants such as organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), and certain polycyclic aromatic hydrocarbons (PAHs) in environmental matrices, where they come into contact with soil microplastics. Zhang et al. [23] selected hexachlorocyclohexane (HCHs) and dichlorodiphenyltrichloroethane (DDT) as representative organochlorine pesticides to study the adsorption of these pesticides onto polyethylene in soil suspensions, finding that van der Waals forces and hydrophobicity significantly influence the adsorption process. Research by Seidensticker et al. [24] indicates that hydrophobic interactions are a primary factor affecting the adsorption of organic compounds onto microplastics. Various minerals and organic compounds in soil may also adsorb onto the surface of microplastics. The adsorption capacity of microplastics for organic pollutants is closely related to their chemical structure and physical properties. Interactions between microplastics and organic pollutants primarily occur through hydrophobic effects and π-π interactions. Existing research suggests that combined contamination of microplastics and soil organic matter may exacerbate ecological risks in soil. On one hand, the adsorption by microplastics can alter the distribution and forms of organic matter in soil; on the other hand, the presence of microplastics may also affect the degradation and transformation of organic pollutants by changing soil microbial community structure and enzyme activity, leading to accumulation of organic matter in soil and increasing the risk of soil pollution. Additionally, the migration of microplastics in soil may carry adsorbed organic pollutants, thereby expanding the distribution range of contaminants.

3.3.3 Interaction between Microplastics and Antibiotics

The interaction between microplastics and antibiotics is an emerging research field. Prolonged amendment of agricultural soils with animal manure results in the concurrent presence of both antibiotic resistance genes (ARGs) and microplastics.Research by Wang et al. indicates that the presence of microplastics may increase ARG desorption, enhancing the bioavailability of ARGs [25]. Studies by Lu et al. [26] showed that the distribution of ARGs on microplastics in farmland soil is related to microplastic particle size, weathering degree, and the cultivation duration of vegetables in the soil. The interaction mechanisms between microplastics and antibiotics are complex, involving multiple processes such as adsorption, co-precipitation, and microbial degradation. Studies show that microplastics can adsorb antibiotics, reducing their migration and degradation in soil. However, the presence of microplastics may also affect the degradation and transformation of antibiotics by altering soil microbial community structure and enzyme activity. Furthermore, the interaction between microplastics and antibiotics may further influence the spread and enrichment of antibiotic resistance genes (ARGs) in soil ecosystems through biofilm formation and changes in microbial metabolic activities. Based on current research, the impact of microplastics on antibiotic adsorption levels is mainly controlled by polar-polar interactions of microplastics, material properties of microplastics, and other factors such as temperature and pH.

4. Ecological Impacts of Microplastics in Soil

Soil ecosystem health depends on balanced relationships among its non-living and living parts. When microplastics find their way into farmland soils, they not only change the soil's physical and chemical traits but also endanger the well-being of soil microbes, plants, and animals. As a result, microplastics can enter the food chain and affect human health to some extent.

4.1 Effects of Microplastics on Soil Physicochemical Properties

Microplastics embedded in soil aggregates affect the structural composition and stability of soil aggregates, thereby altering physical properties such as soil bulk density, porosity, aeration, and water-holding capacity. Polyethylene microplastics (PE) of different particle sizes increase the distribution of soil organic carbon (SOC) in soil aggregates (>2mm and 0.25~2mm) to varying degrees by enhancing the adsorption of organic matter, thus reducing SOC mineralization . In soils with low organic matter [(10.33±0.04) $g \cdot kg^{-1}$] levels, PE can reduce the stability of soil aggregates and affect soil water and nutrient retention. Research by Zhou et al. [27] found that as PE concentration increases, soil water-holding capacity first rises and then declines, with larger PE particles significantly affecting total soil porosity, water-holding capacity, and available water content.

Microplastics also affect soil adsorption capacity, cation exchange capacity, pH, organic matter (SOM) content, electrical conductivity, etc. Guo et al. [28] evaluated the effects of low-density polyethylene (LDPE) and polyhydroxyalkanoates (PHA) on soil chemical properties, finding that 0.2% LDPE treatment decreased the pH value in acidic soils and increased the pH value in alkaline soils. Some researchers have also observed that adding 1% PE can increase soil organic matter content by 72% to 324% . The influence of microplastics on soil's physical and chemical characteristics is intricate and multifaceted. By modifying soil pore structure and air permeability, microplastics can directly affect the diversity and activity of soil microbes. At the same time, they can also indirectly impact soil carbon, nitrogen, and phosphorus cycling by altering soil organic carbon (SOC) content and the composition of microbial communities.Shi[29] et al. found that, compared to natural organic matter, microplastic-derived dissolved organic matter increased CO_2 emissions by 21–576% and reduced mineral-associated organic carbon formation by 34–83%, with biodegradable microplastics causing higher CO_2 emissions than conventional microplastics. Understanding the effects and mechanisms of microplastic pollution on soil physicochemical properties is crucial for grasping the comprehensive impact of microplastics on the soil environment.

4.2 Effects of Microplastics on Soil Microorganisms

Soil microbiomes regulate critical ecosystem functions, from primary production to soil carbon sequestration. Soil microorganisms are highly sensitive to environmental changes caused by pollutants, including microplastics. The presence of microplastics selectively influences the richness and diversity of microbial communities, depending on factors such as microplastic type, particle size, concentration, polymer composition, surface properties, soil characteristics, microbial composition, and exposure duration.

The impact of microplastics on the richness and diversity of microbial communities is highly complex and varied. Some studies indicate that microplastics can reduce the abundance of Firmicutes, Bacteroidetes, and Bacillus in paddy soil , but Huang et al. assessed the effects of PE on soil microorganisms and found that Acidobacteria, Bacteroidetes, Bacillus, Nitrospirae, and Proteobacteria were significantly enriched in soil amended with microplastics after 90 days, while Actinobacteria were partially depleted. Li et al.[30] found that film-like PE and fiber-like PP increased the alpha diversity of soil microbial communities and enhanced the activities of urease, dehydrogenase, and alkaline phosphatase . However, Chen et al. exposed rice soil to PLA (2% w/w) microplastics and observed no significant effects on the alpha diversity (richness, evenness, and diversity) and community composition of soil bacteria [31]. Compared to bacteria, fungi exhibit a higher degree of resistance to disturbances caused by microplastics, likely because their chitin cell walls provide a protective function, preventing internal damage from osmotic pressure and granting them some resistance to microplastic invasion.

The interplay between microplastics and organic contaminants can exert either synergistic or antagonistic impacts on the diversity of soil microbial communities.For example, when PE and ciprofloxacin (CIP) coexist, they synergistically reduce the diversity of pollutant-degrading bacterial phyla such as Proteobacteria in soil microbes, increase the abundance of Achromobacter and Serratia, leading to greater nitrogen consumption in the soil and resulting in lower overall CIP degradation efficiency. Co-contamination involving polypropylene (PP), polyethylene (PE) microplastics, and phenanthrene (PHE) exerts a pronounced stimulatory effect on the enzymatic activities of fluorescein diacetate hydrolase (FDAse), urease, dehydrogenase, and phosphatase. This synergistic interaction facilitates microbial catabolism of sugars to generate metabolic energy, thereby speeding up the degradation of contaminants and the dynamics of cell membrane transport[32]. Conversely, the co-occurrence of microplastics and organic contaminants can reduce the degradation burden on soil microbiota by exerting antagonistic interactions. A case in point is polystyrene (PS), which effectively lessens the detrimental influence of sulfamethoxazole on the composition and variety of soil microbes while also hindering the spread of associated antibiotic resistance genes (ARGs). Specifically, in environments devoid of heavy metals (HMs), PS acts to suppress the dissemination of the sul resistance gene, thereby significantly mitigating the harmful consequences of sulfamethazine on soil microbial populations.

4.3 Effects of Microplastics on Plants

Microplastics may increase the soil's water evaporation rate, leading to plant water deficiency; they can also block the channels for water and nutrient absorption in plant roots, thereby affecting plant growth and development. Current studies have reported widespread effects of microplastics on agricultural plants, including crops such as wheat, rice, corn, ryegrass, broad beans, onions, lettuce, and cucumbers. Microplastics impact wheat seed germination rate, yield, and roots, stems, and leaves, with the effects correlating with particle size .

Jiang et al. found that 100 nm PS can accumulate in broad bean roots, suggesting it may obstruct cell connections and block cell wall pores that transport nutrients[33]. However, some studies also indicate that appropriate concentrations of dense PS can increase the ratio of chlorophyll a to chlorophyll b in ryegrass, enhance biomass, and promote root growth. Microplastics can also act as carriers for other pollutants in the soil environment, increasing plant uptake of these contaminants and inhibiting plant growth. Beyond entering plants directly and affecting their physiological and metabolic processes, microplastics may release plastic additives such as plasticizers and flame retardants into the environment during aging; these plasticizers may also interfere with plant physiological processes, impacting growth rates. Sun et al. [34] discovered that edible plants like carrots, strawberries, and lettuce can absorb PAEs from their roots, which can then be converted into monoester products (MPEs) within the plants. These metabolites may be more toxic than the parent compounds and more readily absorbed and translocated upward by plants, ultimately accumulating in the food chain.

4.4 Impact of Microplastics on Animals

The impact of microplastics in agricultural soils on animals includes effects on soil fauna and terrestrial organisms. To date, the majority of investigations into the ecotoxicological impacts of microplastics on soil-dwelling invertebrates have centered on species such as earthworms and nematodes. Studies indicate that microplastics within certain concentration ranges have harmful effects on the growth, reproduction, and survival of soil animals. On the other hand, research also shows that the life activities of soil organisms can facilitate the migration of microplastics to deeper soil layers. Li et al. demonstrated that high concentrations of HDPE and PP significantly reduce the activity of enzymes such as SOD, CAT, and GST in earthworms and induce an increase in 8-OHdG (a biomarker of oxidative DNA damage) [35]. Zhu et al. exposed soil springtails to MPs for 56 days and observed significant reductions in growth and reproduction, with an increase of in the isotopes δ15N and δ13C in springtail tissues. Additionally, combined exposure to microplastics and other pollutants such as pesticides (e.g., imidacloprid) produces more pronounced toxic effects on soil animals, potentially leading to reduced body weight, epidermal damage, oxidative stress, and activation of specific cell death pathways .

After microplastic particles spread through wind or hydrological processes, herbivores or omnivores may ingest a certain amount of MPs.As a result of trophic transfer through predation, microplastics are capable of bioaccumulating across multiple trophic levels.Beriot et al. reported that all soil samples from farms covered with plastic film contained MPs, and MPs were detected in 92% of fecal samples from grazing sheep . Bahrani et al. studied the MPs content in edible tissues of cattle and sheep from butcher shops in the Persian Gulf region, finding that beef exhibited higher MPs levels (0.19(±0.13) pcs/g), with 100 to 500μm MPs particles being highest in cattle and sheep tissue samples. Existing research indicates that microplastic exposure may cause damage to animal tissues and organs, impaired growth and development, reduced reproduction rates, etc. However, studies on the behavior and effects of microplastics in terrestrial animals are still in the early stages, and toxicological data on MPs ingestion by large terrestrial animals such as cattle and sheep remain scarce. Despite advancements in understanding how microplastics affect soil-dwelling fauna, the comparability of toxicity assessments remains limited. This is primarily attributed to variations in organism size, habitat tenure, behavioral patterns, and the heterogeneous dispersion of these animals within the soil matrix.

4.5 Impact of Soil MPs on Humans

Microplastics in soil are small in size and easily ingested by various organisms, entering the food chain and accumulating through it, leading to ecotoxicological effects. As microplastics accumulate in the human body, they may impact the respiratory, digestive, endocrine, and circulatory systems (including the cardiovascular and lymphatic systems) (Table 2). The smaller the microplastic particles, the more easily they can enter various organs , increasing human health risks and causing issues such as chronic inflammation, cellular damage, and immune dysfunction. Studies have shown that repeated exposure to PE-MPs can affect human gut microbiota and their metabolites. Microplastic particles not only accumulate in the intestines but can also migrate to the liver, kidneys, and even brain tissues. After migrating from the intestines to the liver, the potential toxic mechanisms of microplastics on the liver include oxidative stress, inflammatory responses, apoptosis, energy metabolism redistribution, autophagy, as well as immune and inflammatory reactions. Research by Zha et al. (2024) indicates that food-derived polylactic acid micro/nanoplastics may affect the "gut microbiota-gut-liver" axis and induce hepatotoxicity, specifically manifested as gut microbiota dysbiosis, alterations in intestinal and serum metabolites, and changes in liver transcriptomics [36]. A study on human alveolar type II epithelial cell line (A549) showed that MPs can induce significant upregulation in the transcription levels of pro-inflammatory cytokines IL-6, IL-8, NF-κB, and TNF-α, as well as significant increases in the expression levels of pro-apoptotic proteins DR5, caspase 3, caspase 8, caspase 9, and Cytochrome C, enhancing reactive oxygen species (ROS) levels. Overall, there is still limited research on soil MPs entering the human body via the food chain, and current detections of MPs in various human tissues/organs lack direct evidence linking them to soil sources. However, as soil is the largest reservoir of microplastics, whether their ongoing accumulation will impact human health warrants further attention.

5. Conclusions and Prospects

Microplastics are widely present in soil, water bodies, and the atmosphere. Microplastic pollution in agricultural soil environments has become a significant environmental issue. As a primary reservoir for microplastics, soil receives plastics from various human activities, and the agricultural soil environment critically impacts crop health. Sources of microplastics in agricultural soils include the use of plastic mulch, agricultural fertilization, sewage irrigation, and atmospheric deposition. Influenced by agricultural activities, soil properties, and environmental pollutants, microplastics migrate and transport through physical and biological means within the soil ecosystem, affecting agricultural soils. This article reviews the sources and distribution of microplastics in agricultural soil environments, summarizing their environmental behavior mechanisms and ecological effects based on soil environmental characteristics.

Research on soil microplastics started relatively late, and understanding of the various risks and impacts of microplastics in agricultural soil environments remains insufficient, with no complete theoretical system yet established. Based on existing studies, current research on the environmental behavior of microplastics primarily uses microplastics cultivated under laboratory conditions with short-term aging characteristics. To better apply research findings in practice, future studies need to investigate the dynamic characteristics of microplastics during long-term aging under field conditions. Additionally, current understanding of the long-term effects and ecological risks of interactions between microplastics and pollutants is not comprehensive. Future research should further explore the interaction mechanisms between microplastics and soil pollutants and assess their impact on ecosystems and human health. Furthermore, effective remediation technologies need to be developed to reduce the accumulation and risks of microplastics and pollutants in soil.

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