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Micro plastics in soil ecosystem – A review of sources, fate, and ecological impact

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Abstract: In recent years, environmental experts and stakeholders have paid increased attention to the pollution of micro plastics in the soil. As persistent pollutants, micro plastics have a significant impact on the soil ecology, agricultural production, and the overall health of the ecological environment. Micro plastics can influence soil bio-physicochemical properties and the mobility of other contaminants in soil, with potentially significant implications on soil ecosystem functionality. Thus, functions including litter decomposition, soil aggregation or those related to nutrient cycling can be altered. Furthermore, micro plastics can influence soil biota at different trophic levels, and even threaten human health through food chains. Despite this potential negative interaction, there is limited research on micro plastics in the soil environment. The primary goals of this review are to summarise the sources, distribution characteristics, migration and degradation laws of micro plastics in the soil ecosystem, to summarise the combined effects of micro plastics and other pollutants in the soil ecosystem, to analyse the effects of micro plastics on soil physical and chemical properties, animals, plants, and microorganisms, and to reveal the effects of micro plastics on soil ecosystem and to according to the distribution characteristics of soil micro plastics, degradation, migration and ecological effects, propose pollution control measures. This current review will provide a comprehensive understanding of soil pollution by micro plastic and offer a scientific basis for the formulation of novel management practices that will protect and improve soils, and contribute to the sustainable development of the ecological environment and highlight important areas for future research.

Keywords: global problem; plastic waste; hydrophobicity; toxicity; source distribution

Plastic is a polymer composed of a variety of synthetic or semi-synthetic organic compound materials, primarily polyethene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethene terephthalate (PET), and polyamide (PA). Plastic materials have been widely used in many fields, including industry, agriculture, medicine, and many others, due to their low cost, good ductility, and durability. Plastic production and consumption increased globally from 1.7×10^6 t in 1950 to 3.22×10^8 t in 2015, for a total output of 7.8×10^9 t (Duis and Coors 2016). According to the Ministry of Environmental Protection in China, the total amount of waste plastics in 2011 was approximately 2×10^8 tons,

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with 1.5×10^7 tons recycled. With a recovery rate of less than 10%, the majority of plastics are buried or discarded in the soil environment, leaving a large amount of plastic waste in the environment, causing pollution and endangering the ecological environment (Geyer et al. 2017).

In 2004, the concept of micro plastic was put forward for the first time, which mainly refers to plastic particles with particle sizes less than 5 mm (Wright and Kelly 2017). Micro plastics exist in the ecosystem as either primary micro plastics (artificial micro plastics) or secondary micro plastics (generated by the decomposition of large plastic wastes). According to research, micro plastics come in a variety of shapes, including fibrous, fragmental, and spherical particles, are small in size, have high hydrophobicity, and have relatively stable properties that allow them to exist in the environment for an extended period (Zhao et al. 2018).

Micro plastic pollution in soil has been identified as the second most serious scientific issue in the field of environment and ecology (Horton et al. 2017). According to relevant studies, the abundance of micro plastics on land may be 4–23 times greater than that in the ocean (Nizzetto et al. 2016). Every year, the amount of micro plastics in cultivated soil exceeds that in the ocean, and soil may be a larger plastic sink than the ocean (Horton et al. 2017). The problem of micro plastic pollution in the soil is extremely serious. Horton et al. (2017) summarised the sources and hazards of micro plastics in the soil environment in recent years. One of the most serious risks is that micro plastics may be ingested by humans and organisms *via* food. Micro plastics can come from a variety of sources, and they are easily transported and transformed by the soil environment, having an impact on the soil ecosystem as shown in Figure 1. Agricultural production activities (the use of agricultural films, and the addition of organic fertilisers), industrial production activities, urban construction, daily life, atmospheric subsidence, automobile tire wear, and so on are all sources of micro plastics in the soil (Bläsing and Amelung 2018).

Rillig (2012) a German scientist was among the first in the world to pay attention to micro plastics in soil. He believes that micro plastics in the soil environment will have an impact on soil physical and chemical properties, soil functions, and biodiversity. According to some researchers, the impact of micro plastics on soil biology is caused not only by the plastic particles themselves, but also by other substances such as plasticisers, stabilisers, flame retardants, and other substances that can adsorb some heavy metals and organic pollutants that can affect soil health (Hodson et al. 2017, de Souza Machado et al. 2018).

Heavy metals, polychlorinated biphenyls (PCBs), organochlorine pesticides, and other pollutants commonly adsorb on the surface of micro plastics, increasing the risk of toxicity to soil organisms (Nizzetto et al. 2016, Hodson et al. 2017). Furthermore, mi-

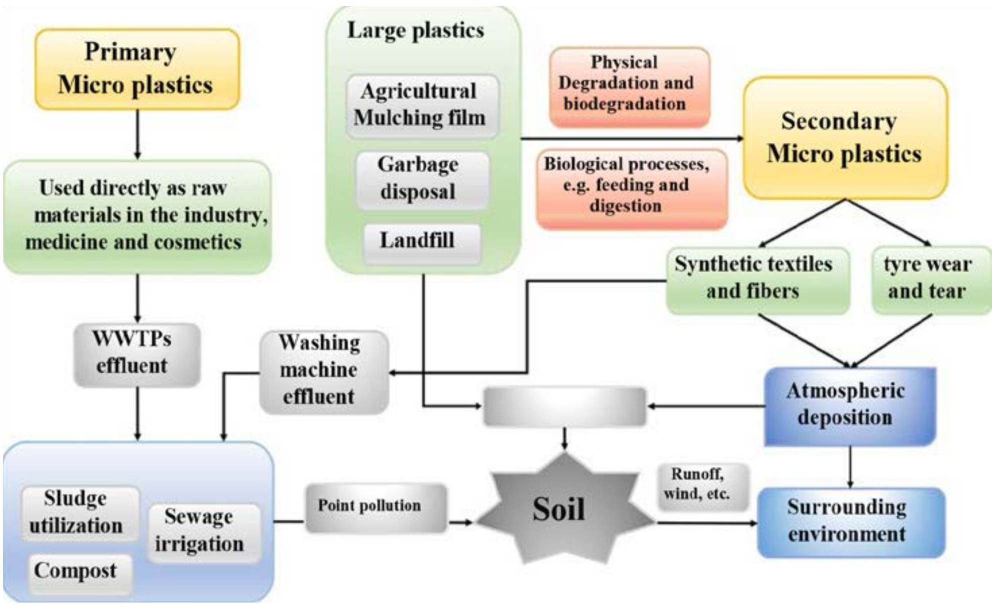

Figure 1. Schematic diagram of the sources of micro plastic in soil ecosystem

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cro plastics that enter the soil can be consumed by animals such as hamsters, moles, earthworms, and nematodes, which are enriched in the organism's body and promote the migration, transformation, and degradation of micro plastics in the soil environment (Rillig et al. 2017b). Researchers have discovered that micro plastics have an impact on soil microorganisms, resulting in a decrease in soil microbial diversity (Rillig et al. 2017b, Kong et al. 2018) in recent years, with the continuous deepening of related research.

The impact of micro plastics on the soil ecosystem is currently a research focus. This review summarises the research progress, source, distribution, migration, and degradation characteristics of micro plastics in the soil, focusing on micro plastics and other pollutants in the soil environment, and analyses the impact mechanism of micro plastics on the ecological effect of soil, to provide a foundation for scientific research.

THE SOURCES AND DISTRIBUTION OF MICRO PLASTICS IN THE SOIL ECOSYSTEM

Source of micro plastics in the soil

The widespread use of agricultural films. The agricultural film is a type of plastic film that is commonly used in agriculture. Polyethene and polyvinyl chloride are used to make agricultural film materials. PE film is light in weight and has good light transmittance, whereas PVC film has good heat preservation but poor light transmittance, and when burned, it emits toxic and harmful substances (Singh et al. 2017). China, as a largely agricultural country, is increasing its use of agricultural films year after year. According to reports, between 1991 and 2004, the use of agricultural film in China increased by 15% at a 30% annual rate (Espí et al. 2006). Between 2006 and 2015, China's total use of agricultural plastic film increased from 1.85×10^6 t to 2.60×10^6 t. (an increase of 41 per cent). With the widespread promotion and application of film-mulching cultivation technology in recent years, global agricultural film coverage is expected to increase at a rate of 5.7 per cent (Brodhagen et al. 2017). The low rate of agricultural film recovery and recycling will result in a large number of waste films accumulating in the environment for an extended period. It becomes an important source of micro plastic in farmland soil because it is difficult to degrade in farmland soil and easy to cause plastic pollution.

Soil amendments and compost products

Because compost products and sludge are high in plant nutrients and organic carbon, they are commonly used as soil amendments to improve soil physical and chemical properties, increase soil nutrient content, and boost crop yields (Naeini and Cook 2000, Slater and Frederickson 2001, Cherif et al. 2009). Most sludge treatment and composting technologies are currently incapable of removing micro plastics (Zubris and Richards 2005). As a result, agricultural sludge and compost products are a significant source of micro plastics in farmland soil.

China is a large country in terms of compost product production and use, with an annual production output of more than 2.5×10^7 t and an application rate of about 2.0×10^7 t. In the EU, approximately 1.8×10^7 t of compost products were produced in 2008, with a 37% increase expected by 2020 (Franckx 2010). Around the world, there are various levels of regulations governing the quality and application rate of compost products. Compost products are typically applied at a rate of 30–35 t/ha per year (Hopkins et al. 2017). Plastic has been found in livestock and poultry manure, according to studies. The majority of the plastic can be removed through screening and sorting methods before and after composting, but there are still micro plastics in the compost product, with a concentration of 2.38–180 mg/kg (Bläsing and Amelung 2018). According to the amount of compost applied, the use of dry compost products is estimated to result in an annual plastic dosage of 0.016–1.2 kg/ha (annual application rate: 7 t/ha) and 0.08–6.3 kg/ha (annual application rate: 35 t/ha) (Bläsing and Amelung 2018). In a study in farmlands, the average concentration of plastics in composted products reached 1.2 g/kg, with individual areas having higher concentrations of micro plastics (Gao et al. 2019). As a result, the use of a large number of composted products has resulted in the accumulation of micro plastics in farmland soil and has become a significant source of micro plastic pollution in soil.

Sewage sludge

The concentration of micro plastics in the influent of sewage treatment facilities on the Clyde River was found to be 15.7 ± 5.23 pcs/L during an investigation of sewage treatment facilities on the Clyde River. The concentration of micro plastics in the effluent was reduced to 0.25 ± 0.04 pcs/L after the sewage treat-

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ment facilities, and the removal rate reached more than 98 per cent, but the removed micro plastics did not undergo any serious degradation and remained in the sludge (Murphy et al. 2016, Mintenig et al. 2017). Because sludge is high in N, P and other nutrients that can alter soil structure and increase soil fertility, it can be used as a raw material in the composting process and applied to farmland soil. According to available data, China's annual sludge production is 3–4 × 10^7 t. Sludge utilisation is increasing year after year. Every year, approximately 4–5 × 10^6 (dry weight) of sludge is used for composting of cultivated land in the European Union, and approximately 40 × 10^4 t of micro plastics enter the soil (Zubris and Richards 2005, Nizzetto et al. 2016, Willén et al. 2017). In terms of sludge application, a load of micro plastics in sludge in Europe and North America reached 6.3 × 10^4 t and 43 × 10^4 t, respectively. The total amount of micro plastics produced by sludge application in Australia can reach 2.8 × 10^3 t – 1.9 × 10^4 t (Ng et al. 2018). In Finland and Ireland, up to 72% of sludge is used for agricultural purposes (Hall 1995). As a result, using sludge as fertiliser will cause micro plastics to accumulate in the soil. Furthermore, studies have revealed that sludge contains toxic and harmful substances such as heavy metals, persistent organic compounds, antibiotics, pathogenic bacteria, and parasite eggs. Worm eggs and other toxic and harmful substances will be loaded on the surface of micro plastics when they coexist, exacerbating the problem of soil pollution. There are few relevant research results at the moment, and there is still a lack of a unified understanding of micro plastic pollution in soil (Rillig et al. 2017a).

Irrigation water

Irrigation water is primarily purified sewage, surface water, or groundwater in many developing countries where water resources are scarce. Water scarcity is becoming more severe as a result of climate change, population growth, and urbanisation, and the direct or partial use of untreated sewage to irrigate farmland is increasing. According to Mintenig et al. (2017), about 20 million hectares of arable land worldwide are reported to be irrigated with untreated or partially treated sewage and an estimated 10% of the world's population depends on food grown with contaminated wastewater (Corcoran et al. 2010). The main sources of micro plastics in domestic sewage are personal care products and detergents. According to the findings of Lei et al. (2017), micro plastics are found in a variety of facial cleansers and shower gels on the market, with the main component being polyethene. According to preliminary estimates in China, personal care products can introduce approximately 39 t of micro plastics into the natural environment (Lei et al. 2017). According to Majewsky et al. (2016), sewage contains 80–260 mg/m^3 polyethene and polypropylene. Numerous studies are being conducted on micro plastics in the water environment at the moment. Surface water, which is a common source of water for agricultural irrigation, contains a small number of micro plastics. Micro plastic abundance varies greatly in surface waters. According to Dris et al. (2015) and Eerkes-Medrano et al. (2015), the concentration of micro plastics in lakes and rivers varies greatly, ranging from 10^3 to 10^9 times. Su et al. (2016) conducted a survey and discovered that the majority of the micro plastics in Taihu Lake are fibrous, and their abundance is approximately 1 × 10^4–6.8 × 10^6 pcs/km^2. Mintenig et al. (2019) used infrared spectroscopy imaging technology to study groundwater and plastic particles in drinking water (> 20 µm). The results showed that the concentration of micro plastics in groundwater could range from 0–7 pcs/m^3, with an average value of 0.7 pcs/m^3. The main components were polyethene, polyamide, polyethene terephthalate, and polyvinyl chloride, with particle sizes ranging from 50–150 µm. Several studies have found that surface water has become a significant source of micro plastic pollution in the soil. Kim et al. (2004, 2006) discovered that rubber particles from road tire wear could enter the roadside soil environment *via* atmospheric deposition or surface runoff. According to their research, annual tire dust emissions in Sweden and Germany are approximately 1.0 × 10^4 t and 1.1 × 10^4 t, respectively. The plastic waste calculated based on the amount of waste plastic in the world differs from the actual experimental results. Researchers have paid close attention to the distribution of plastics in the environment. Preventing plastic waste from entering the soil environment is a major challenge that all countries must address.

Atmospheric deposition

As illustrated in Figure 1, atmospheric deposition is another method by which micro plastics enter the soil environment. Dris et al. (2016) studied the atmosphere near Paris and discovered that

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29 280 pcs/m^2 of micro plastics were deposited every day in the atmospheric environment, and 3–10 t of fibrous micro plastics were deposited in the area every year through the atmosphere, the majority of which were fibrous, accounting for 90% of the total amount, and 50% of which had a particle size of > 1 000 m. Simultaneously, some researchers focused on fibre micro plastics constituents in atmospheric deposition, and the results revealed that 50% are natural fibres, 21% are processed natural fibres, 17% are man-made plastic fibres, and 12% are man-made mixed fibres (Dris et al. 2016). As a result, to better study the atmosphere for micro plastics, it is also necessary to better understand the temporal and spatial distribution of micro plastics in the atmosphere, as well as the characteristics of atmospheric migration and influencing factors.

DISTRIBUTION CHARACTERISTICS OF MICRO PLASTICS IN SOIL

There have been few studies on the distribution and concentration of micro plastics in soil. Table 1 depicts the distribution characteristics of micro plastics in some soils around the world, indicating that the soil has been contaminated to varying degrees by micro plastics. Because of the various units used to describe the abundance of micro plastics, there are also differences in quantity and quality when counting, making it difficult to compare different results. However, in the countries listed in Table 1, micro plastics have varying abundances, sizes, and compositions, with PE and PP being the main components. Among the selected regions in China, the Loess Plateau may have the lowest abundance of micro plastics (0.54 mg/kg). This region is the lowest in China. As a province rich in tourism resources, Yunnan province of China has a micro plastic content of 7 100–42 960 pcs/kg of micro plastics, which is significantly higher than that of other regions in China (Table 1). Previous research has shown that micro plastics are unevenly distributed in space, which may be related to the country or region's natural geographic characteristics, development level, and population density, among other things. The precise influencing factors must be investigated further. At the moment, research on the distribution of micro plastics in China is in its early stages, and the distribution area and abundance of micro plastics remain unknown. As a result, it is critical to establish a standardised measurement system.

MIGRATION AND DEGRADATION OF MICRO PLASTICS IN SOIL

Figure 2 shows the various factors that contribute to the migration of micro plastics through the soil profile. The characteristics of micro plastics (size, density, and shape), external climate (wind, rain), soil animals (earthworms, *Orchesella cincta*), and the influence of other external forces all influence the migration process of micro plastics in soil (mechanical disturbance) (Free et al. 2014, Driedger et al. 2015, Dris et al. 2016). There are few reports on the migration and degradation of micro plastics in the soil environment at the moment. O'Connor et al. (2019) discovered that the migration depth of micro

Table 1. Distribution characteristics of micro plastics in some parts of the world (pieces of micro plastics determined per kilogram of dry weight of soil)

Country/region	Abundance	Composition	Size range	Literature
Mexico	2 770 pcs/kg	PE, PS	5–150 mm	Huerta Lwanga et al. (2017)
Switzerland	593 pcs/kg	PE, PS, PVC	12.5–500 μm	Scheurer and Bigalke (2018)
Australia	300–67 500 mg/kg	PVC, PE, PS	< 5 mm	Fuller and Gautam (2016)
Hebei China	317 pcs/500 g	PE, PP, PVC	1.56 ± 0.63 mm	Zhou et al. (2016)
Shandong China	1.3–14.7125 pcs/kg	PE, PP, PS	1 mm (60%)	Zhou et al. (2018)
China's Loess Plateau	< 0.54 mg/kg	PE	> 100 μm	Zhang et al. (2018)
Yun Nan China	7 100–42 960 pcs/kg	PE, PP	10–0.05 mm	Zhang and Liu (2018)
Shanghai, China	62.59 ± 12.97 pcs/kg	PE, PP, PVC	0.03–16 mm	Liu et al. (2018)

PE – polyethene; PS – polystyrene; PVC – polyvinyl chloride; PP – polypropylene

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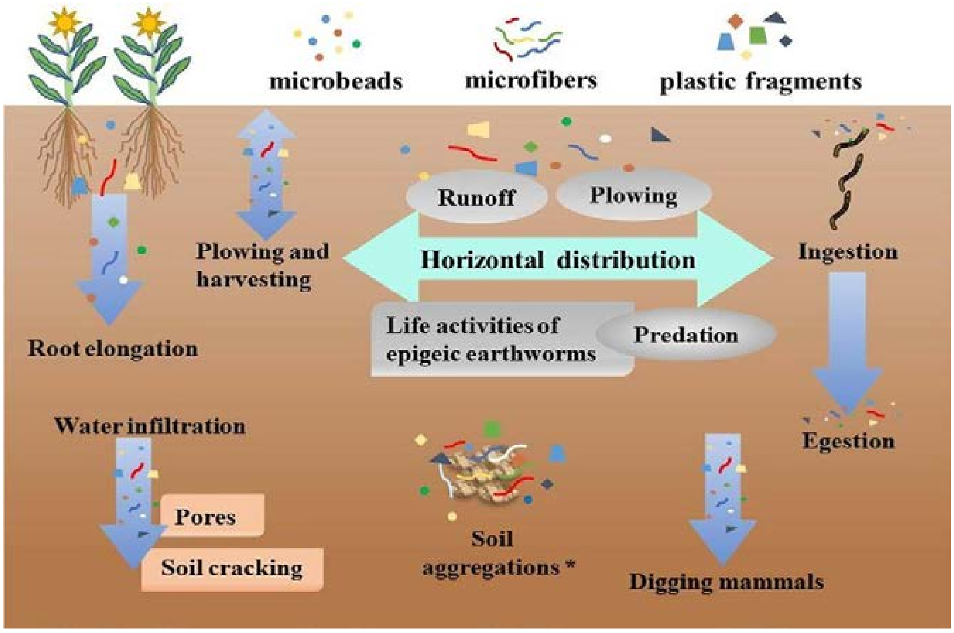

Figure 2. Schematic diagram showing factors that affect micro plastic distribution and migration through the soil profile

plastics increased significantly with the number of dry-wet cycles, whereas the single applied precipitation and the surface micro plastic concentration had little effect on the migration depth through infiltration and migration simulation experiments of micro plastics in sand columns. Furthermore, earthworms can move micro plastics from the soil's surface into their burrows and deeper into the soil (Figure 2). According to the data presented above, one of the sources of groundwater pollution is the migration and transformation of micro plastics by soil organisms (Huerta Lwanga et al. 2017).

There are currently many studies on the migration of micro plastics in soil driven by earthworms and *Collembola* (Eckmeier et al. 2007, Huerta Lwanga et al. 2016, Maaß et al. 2017, Rillig et al. 2017a). Rillig et al. (2017a) added PE of various particle sizes to the surface soil and found PE in the middle and lower soil layers after 21 days of culture. The findings revealed that earthworms promote the migration of micro plastic particles along with the soil profile and that the smaller the particle size of the micro plastics, the easier it is for them to migrate.

Simultaneously, Huerta Lwanga et al. (2016) discovered that earthworms migrate micro plastic particles from the surface soil to the deep soil, potentially affecting other soil organisms and entering groundwater. Maaß et al. (2017) investigated the migration of two species of *Collembola* to micro plastics with varying particle sizes. The particle size was related to low density polyethylene (LDPE) migration, and the smaller the particle size, the greater the biological disturbance (Huerta Lwanga et al. 2017). At the moment, the migration mechanism of micro plastics in the soil environment has not been thoroughly discussed, and changes in soil environmental quality caused by micro plastic migration are hardly involved. Researchers must uncover this information through theoretical studies and experimental tests. Furthermore, several studies have confirmed the process of micro plastics migration through the food chain. Significantly alter the biological community of soil faunas, and as the particle size of micro plastics continues to decrease, micro plastics accumulate and are transferred in different food chains, and are likely to enter the human body *via* the food chain (Setälä et al. 2014, Huerta Lwanga et al. 2017). As a result, the movement of micro plastics through the food chain is gradually becoming a topic of study in the scientific community.

Micro plastics in soil undergo chemical changes in the chemical structure of polymer molecules, including molecular bond breakage and disproportionation, as a result of mechanical wear, high-temperature oxidation, ultraviolet radiation, and biodegradation, and eventually become micro plastics with smaller particle diameters or even nanoplastics. There are currently few studies on the degradation of micro

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plastics in soil. The main mode of degradation of micro plastics in the soil is biodegradation, but the effects of soil environment, mechanical crushing, high-temperature oxidation, and ultraviolet radiation are limited. Micro plastics degrade at a very slow rate in soil (Cooper and Corcoran 2010, Krueger et al. 2015). For example, fragments of the agricultural plastic film, PE are difficult to degrade in farmland soil and can be retained for several years or even decades, eventually forming small micro plastic residues and a relatively stable environment (Briassoulis et al. 2015). Arkatkar et al. (2009) reported a 0.4 per cent weight loss after one year of soil culture with PP. Furthermore, there is no comprehensive report on the detection and analysis of micro plastic degradation products. Several studies have shown that earthworm intestines can decompose micro plastics in the soil (Huerta Lwanga et al. 2018), but the specific mechanism needs to be confirmed through experiments.

INTERACTION BETWEEN MICRO PLASTICS AND OTHER POLLUTANTS IN SOIL

When exposed to the soil environment, micro plastics inevitably interact with other pollutants due to their small particle size, large specific surface area, and strong hydrophobicity. Micro plastics play an important role in pollutant transport and transformation in the soil environment. Persistent organic pollutants (POP), heavy metals, and antibiotics have been found on the surfaces of micro plastics. Micro plastics, as a good carrier of these substances, have a certain combined effect on the soil environment and organisms, which has piqued the interest of academics. Relevant academics have researched the combined impact of micro plastics and other pollutants. Table 2 summarises research on the combined effects of micro plastics and other pollutants in various soil environments. At the moment, research on the combined effect of pollutants is quite contentious. Researchers have conducted fewer studies on the migration and degradation of micro plastics and pollutants when compared to other exposure pathways (Ziccardi et al. 2016). A wide range of clay minerals, metal oxides and hydroxides, humus, and microorganisms can react with pollutants in the environment. Because of the low abundance of micro plastics in the soil environment, researchers believe that micro plastics may play a less important role as pollutant carriers (Hartmann et al. 2017).

Interaction between micro plastics and persistent organic pollutants

Plastics are excellent carriers for hydrophobic organic compounds like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and herbicides. They can have a direct impact on the distribution of persistent organic pollutants (POS) in the soil environment, as well as the ecosystem. Pollutants in the environment do not exist in isolation, and the majority of compounds have antagonistic or synergistic effects. When they are absorbed by micro plastics, their adsorption capacity varies, and competitive adsorption may occur. Hüffer and Hofmann (2016) investigated the adsorption behaviour of four types of micro plastics and seven types of aliphatic substances to investigate their relationship, and discovered that the adsorption coefficient of micro plastics is closely related to its hydrophobicity. Seidensticker et al. (2018) investigated the adsorption of two micro plastics and various pollutants under three different pH conditions and discovered that hydrophobic compounds adsorb more strongly to micro plastics than natural substances such as caffeine and phenanthrene. Teuten et al. (2007) discovered that the concentration of organic pollutants on plastics in sediment was much higher than that in the soil environment, indicating that micro plastics and persistent organic pollutants pose a synergistic threat to the soil system. The polarity of persistent organic molecules influences the recombination effect. Hydrophobic organic compounds are typically the source of more serious composite pollution. According to current research, the specific surface area, van der Waals force, and affinity of the hydrophobic surface of micro plastics are the most important factors influencing physical and chemical adsorptions (Mato et al. 2001). Hydrophobicity, crystallinity, functional groups, and electrostatic attraction between micro plastics and organic matter are all physicochemical properties of micro plastics. At the same time, external environmental factors that influence micro plastic adsorption include hydrodynamics, temperature, moisture content, and pH (Bakir et al. 2014, Zhan et al. 2016, Lambert et al. 2017).

Interaction between micro plastics and heavy metals

The effects of micro plastics and heavy metals have been studied, and it has been discovered that when

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Table 2. The combined effect of micro plastics and other pollutants

Contaminant type	Classification	Microplastic type	Particle size	Influences	Literature
Phthalic acid esters	POP	PVC, PE, PS	< 75 μm	adsorption is highly linear	Liu et al. (2019)
Polybrominated biphenyls	POP	PET	< 75 μm	alter soil physico-chemical properties	Gaylor et al. (2013)
Chloroacetate	POP	LDPE	25 μm	absorb more pesticides alter soil water content	Rochman (2018)
4 (2,4-dichlorophenoxy) butyrate (atrazine)	POP	PE	250 μm	reduce soil adsorption capacity	Hüffer et al. (2019)
Polycyclic aromatic hydrocarbons, polychlorinated biphenyls	POP	PE, PS	250 μm, 300 μm	when micro plastics are added, the tissue concentration of PAHs and PCBs decreases	Wang et al. (2019)
Chlorpyrifos.	POP	LDPE	5 mm	micro plastics can transfer more chlorpyrifos into the soil matrix	Rodríguez-Seijo et al. (2017), Wang et al. (2019)
As	heavy metals	PVC	0.25–1 mm	low toxicity to earthworms	Wang et al. (2019)
Cu	heavy metals	PA, PE, PS, PET, PVC, PMMA	70–350 μm	the adsorption of copper ions is affected by the type of micro plastics	Yang et al. (2019)
Zn	heavy metals	HDPE	< 5 mm	increase the bioavailability of zinc	Hodson et al. (2017)
Sulfadiazine, amoxicillin, tetracycline, ciprofloxacin, Star, Methoxybenzidine	antibiotics	PE, PS, PP, PA, PVC	75–180 μm	adsorption capacity varies by antibiotic, micro plastics type, and environmental conditions	Li et al. (2018)
Tetracycline	antibiotics	PE	< 1 mm	inhibit the degradation and spread of tetracycline	Sun et al. (2018)

POP – persistent organic pollutants; PVC – polyvinyl chloride; PE – polyethene; PS – polystyrene; PET – polyethene terephthalate; LDPE – low density polyethylene; PA – polyamide; PMMA – polymethyl methacrylate; HDPE – high-density polyethylene

heavy metals and micro plastics are released into the soil environment, geochemical processes occur, which may lead to soil degradation (Guo et al. 2020, Jiang and Li 2020, Liu et al. 2021). Relevant researchers have also investigated the interaction of micro plastics and heavy metals (Hodson et al. 2017) discovered that the surface of micro plastics in the soil environment becomes charged during abrasion and is capable of adsorbing metal cations. The adsorption kinetics follows the nonlinear adsorption equation, and micro plastics can increase heavy metal adsorption potential in the terrestrial environment. Studies conducted in aqueous media to determine the adsorption rates of heavy metals such as Cd, Zn, Ni, and Pb on micro plastics vary greatly due to the different chemical and physical properties of micro plastics (Mato et al. 2001, Teuten et al. 2007, Bakir et al. 2014, Zhan et al. 2016, Lambert et al. 2017). According to Massos and Turner (2017), the adsorption rates of micro plastics to Cd and Pb are 6.9 per cent and 7.5 per cent, respectively. Furthermore, the researchers concluded that the surface structure of micro plastics changed as a result of

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sunlight oxidation and weathering, allowing them to easily obtain electrical charges and adsorb metal ions to achieve charge balance. Simultaneously, it was discovered that the pH of the soil and the residence time of micro plastics in the environment were important factors influencing the adsorption capacity of micro plastics for metal ions. When micro plastics are exposed to UV light for 2 000 h, they increase the content of copper and zinc adsorption capacity (Bandow et al. 2017). Furthermore, metal cations are adsorbed by forming complexes with organic compounds by combining with the polar regions or oxygen anions on the surface of the plastic (Holmes et al. 2012). Although studies on the interaction of micro plastics and heavy metals have been conducted, the mechanism by which micro plastics adsorb heavy metals warrants further investigation.

Interaction between micro plastics and antibiotics

Antibiotics are widely used in veterinary medicine. Antibiotics and micro plastics can coexist in the natural environment to some extent. The interaction of micro plastics with antibiotics has also been investigated (Sun et al. 2018). Li et al. (2018) investigated the adsorption of 5 different antibiotics on five different micro plastics (PE, PS, PP, PA, and PVC) (sulfadiazine, amoxicillin, tetracycline, ciprofloxacin, trimethoprim). It was discovered that PA has the greatest antibiotic adsorption capacity, and the two main mechanisms are the formation of pore structures and the formation of hydrogen bonds. The polarity-polarity interaction of micro plastics (Wang et al. 2015), rubbery state (Teuten et al. 2009), and crystallinity (Guo et al. 2012) have been reported to influence antibiotic adsorption on micro plastics, whereas environmental factors such as pH, ionic strength, and temperature do not affect the ability of micro plastics to adsorb tetracycline (Shen et al. 2018). The adsorption behaviour of micro plastics on antibiotics may result in a combined effect of the two, i.e., they may interact and cause greater harm to the soil ecosystem. For example, in a study to examine the changes in soil microbiome and antibiotic resistance genes, Ma et al. (2010) reported a significant increase in the diversity and abundance of antibiotic resistance genes (ARGs) in *Enchytraeus crypticus* due to the influence of the combined effect of micro plastics and antibiotics. In addition, the combined effect of micro plastic and antibiotics on the abundance of ARG's in *E. crypticus* was greater than single treatment with single micro plastic treatment. Furthermore, antibiotics in the soil can alter the degradation process of micro plastics. As a result, the relationship between micro plastics and antibiotics should not be overlooked; their potential ecological risks should be investigated.

EFFECT OF MICRO PLASTICS ON THE SOIL ECOSYSTEM

Effect of micro plastics on soil physical and chemical properties

Micro plastics have a direct impact on the physical and chemical properties of the soil as well as the material cycle (Figure 3). When micro plastics enter the soil environment and combine with other organic pollutants, their adsorption capacity is significantly increased due to their small particle size and large surface area, which changes the physical and chemical properties of the soil and affects the health of the soil ecosystem (Li et al. 2020). Liu et al. (2017) investigated the impact of micro plastics (PP particle size 180 μm) on soil soluble organic carbon (DOC), organic nitrogen (DON), organic phosphorus (DOP), PO_4^{3-} concentration, fluorescein diacetate (FDA) hydrolase, and phenoloxidase activities. High concentrations of micro plastics had a significant effect on DOC, DON, DOS, humus, and fulvic acid concentrations after 30 days of incubation. De Souza Machado et al. (2019) investigated the effects of four commonly used micro plastics on soil structure and microbial function. They measured the influence of micro plastics on microbial bulk density, water-holding capacity, and the functional relationship between microbial activity and water stabile aggregate in a 5-week soil culture experiment. The findings revealed that different types of micro plastics have varying effects. Polyester, for example, can reduce the amount of soil water-stable aggregates, whereas polyethene significantly increases the amount of soil water-stable aggregates. The reduction of water-stable aggregates reduces the diversity of the soil microenvironment significantly. At the moment, research on the interaction of micro plastics and soil aggregates is limited, and research on the potential changes in soil physical and chemical properties caused by microplate pollution is still in its early stages, making it impossible to conclude the impact of plastic pollution on soil water movement and soil water conservation.

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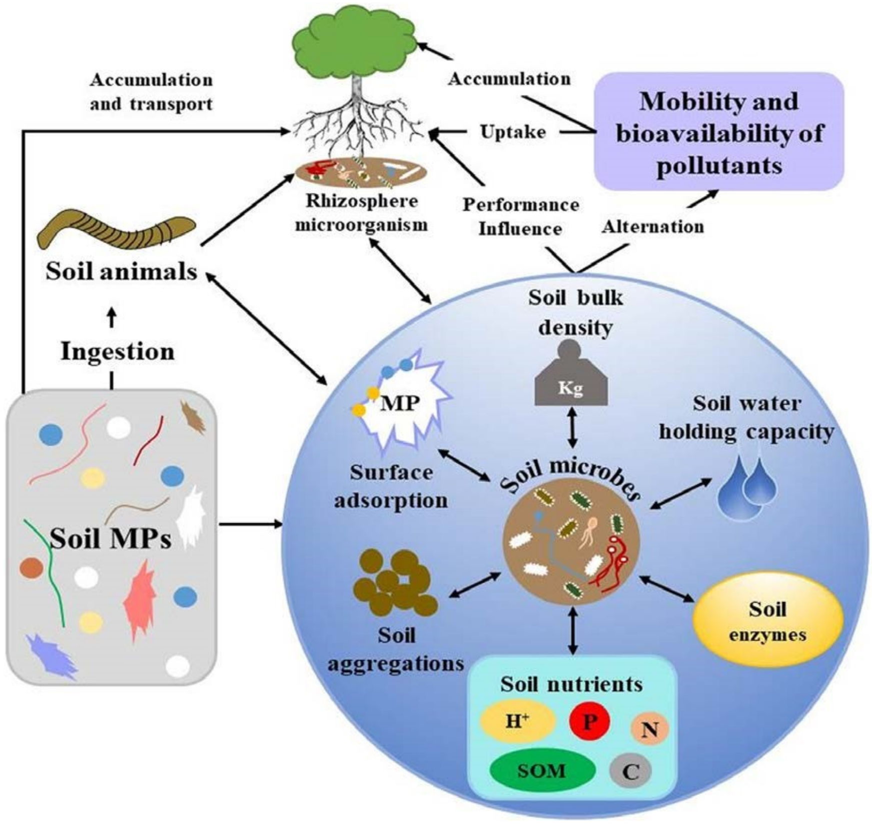

Figure 3. Schematic diagram showing the effect of micro plastics on soil parameters, soil organisms, plants, and microorganisms, and adsorption of ions

Effects of micro plastics on soil animals

Micro plastics primarily have an impact on soil animals *via* feeding pathways (Figure 3). At the moment, research into the effects of micro plastics on soil animals is making some headway. However, the complexity of the soil animal system, diversity of functions, and differences in individual size, habitat, and lifestyle of soil fauna, makes a further study on the effects of micro plastics on soil fauna groups extremely difficult.

Earthworms are currently the most studied in the soil (Rodriguez-Seijo et al. 2017, Rillig and Bonkowski 2018). Earthworms can transport micro plastics from the surface soil to the deeper layers, increasing their distribution. However, there has been very little research into the molecular and biochemical effects of micro plastics on soil fauna. Cao et al. (2017) in their studies suggested that micro plastics significantly inhibit the growth of earthworms and that at different concentrations of 1% and 2%, it poses a very toxic effect to them. Micro plastics enter the earthworm's body after being ingested, causing intestinal damage, easily agglomerating in the body, affecting eating and excretion, and seriously affecting the earthworm's growth and survival (Figure 3). PE micro plastics have a clear effect on the histopathological damage and immune system of earthworms, increasing their protein, lipid, and polysaccharide content by 10% (Rodriguez-Seijo et al. 2017). It was discovered in a study to determine the combined effect of polyurethane foam micro plastics and PBDEs on earthworms that PBDEs could accumulate in earthworms and then affect other organisms through the food chain (Rodriguez-Seijo et al. 2017). Micro plastics have been shown in studies on earthworms to affect their reproduction rate, growth rate, and survival rate, but little is known about the molecular and biochemical effects.

According to a study by Lu et al. (2018), hepatic lipid metabolism disorder, and reduced secretion of mucin are induced when mice are exposed to micro plastics. In addition, there is a disruption in the microbial community structure and significant change in the abundance and biodiversity of intestinal microbiota with sufficient consumption of micro plastics (Lu et

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al. 2018). Furthermore, exposure to micro plastics may alter the microbial diversity and community structure of Collembola and Nematodes (Zhu et al. 2018). Nematodes can also effectively consume micro plastics (Liu et al. 2018). The main negative effects of micro plastics on nematodes are intestinal damage and oxidative damage, which result in a decrease in intestinal calcium levels and an increase in the oxidative stress gene *gst-4* in nematodes. Nematode survival, body length, and reproductive ability all decrease significantly. Based on the findings of the earthworm and nematode studies, related research into the impact of micro plastics on other soil animals, such as pods, has been expanded. Because of the limited detection methods for micro plastics, in-depth research on the effects of micro plastics on soil animals is limited, and whether the toxic and harmful substances adsorbed by the micro plastics, themselves will be toxic to soil animals and the soil ecosystem requires further investigation.

Effects of micro plastics on plants

There has been little research into the impact of micro plastics on terrestrial ecosystems, particularly agricultural ecosystems. Micro plastics in agricultural ecosystems can affect not only soil microbial biomass, microbial activity, and functional diversity, but also the cycling process of plant nutrient elements in the soil (Horton et al. 2017, de Souza Machado et al. 2018) (Figure 3), which may have an indirect effect on plant seed germination and growth. Micro plastics that remain in the soil for an extended period are likely to form nano plastics (Ng et al. 2018) which migrate and accumulate in plants before being ingested into the body *via* the food chain, eventually leading to human exposure, which is harmful to the ecological environment (Rico et al. 2011).

Soil plants are an essential component of the soil ecosystem, and their growth is influenced by the soil environment. However, there have been few studies on the effects of micro plastics on plants. Micro plastics can have an impact on the growth of soil plants. The growth of wheat seeds and seedlings is significantly inhibited by LDPE and biodegradable plastic mulch film fragments (Qi et al. 2018). Furthermore, soil plants can absorb and accumulate micro plastics (Figure 3). The study of tobacco cell structure revealed that nano-sized plastic beads can enter tobacco cells *via* endocytosis (Bandmann et al. 2012), implying that small-sized plastics may be absorbed into the plant body *via* the plant's rhizosphere. According to Asli and Neumann (2009) and Ma et al. (2010), the accumulation of micro plastics in plants may affect the absorption and transport of nutrients and other important soluble products by blocking the pores of the cell wall or cell connections. Qi et al. (2018) conducted a pot experiment using LDPE and a starch-based biodegradable plastic film as research materials, mixing 1 per cent of the plastic residue with sand during wheat growth. The plastic residue was discovered to have an impact on both above and below-ground parts. When *Oenanthe javanica* was exposed to different particle sizes (50, 500, and 4 800 nm) and concentrations (103–105 pieces/mL), the germination rate of seeds was significantly inhibited, with the impact of micro plastics with large particle size being greater (Bosker et al. 2019). Judy et al. (2019) however, reported an insignificant influence of micro plastics on germination as well as wheat biomass. More research is, therefore, necessary to address the knowledge gap on the influence of micro plastics on plants.

The current research focuses primarily on the external effects of micro plastics on soil plants, and it is limited to a few species. The toxicological effects of micro plastics on soil plants, as well as their interaction mechanisms, are yet to be revealed. The research on how micro plastics enter plants, as well as the analysis and detection, are still being optimised. As a result, the corresponding results do not apply to all plant types. The physical and chemical properties of the soil used in the experiment, as well as the concentration, type, and particle size of the micro plastics, all affect the plants. The concentration of micro plastics in the experiment far exceeds the real-world situation. Such experimental conditions are favourable for the accumulation of micro plastics in plants, which differs from the real-world growth environment of plants. These issues must be addressed in future research.

Effect of micro plastics on soil microorganisms

Soil microorganisms play an important role in the soil ecosystem. According to research, increasing microbial activity promotes the release of soil C, N, P, and other nutrient elements, thereby promoting nutrient element migration between plant and soil (Burns et al. 2013, Huerta Lwanga et al. 2018). Several studies have revealed that soil physicochemical properties and nutrients are related to the activities of

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soil microbes (Girvan et al. 2003, Arthur et al. 2012, Naveed et al. 2016, Rillig et al. 2017a). Any alteration, such as changes in soil aggregation in the soil environment, which has been found to incorporate linear microfibers (de Souza Machado et al. 2018); will result in changes in the microbial diversity compared to soil without microfibers (Rillig et al. 2017a). The presence of soil micro plastics, on the other hand, may act as a carrier of other toxic and harmful substances. The migration of micro plastics will have an impact on soil microorganisms, changing the microbial community and biodiversity of the soil ecosystem, thereby affecting the soil ecosystem's health. In addition, changes in porosity of soil due to the presence of micro plastics can influence oxygen flow through the soil, which in turn would determine the abundance and distribution of both aerobic and anaerobic microorganisms in the soil profile. In addition, micro plastics can cause changes in the pore spaces of soil, which may result in loss of habitat and extinction of indigenous soil microbes.

Judy et al. (2019) reported significant interference in the microbial structure and a reduction in substrate-induced respiration after adding micro plastics to the soil. The outcome of their study reveals that soil microbial function is induced by micro plastics. DOM has been reported to be related to the eutrophication of water and serves as a substrate and a very important carbon source for microorganisms (Marschner and Kalbitz 2003, DeForest et al. 2004), and therefore, microbial soil function may be affected if there are changes to DOM under the influence of micro plastics. Soil enzyme activities are a reflection of microbial activity and substrate availability for uptake and use by microbes. Consequently, alteration to enzymes of the soil can indicate possible detrimental effects of micro plastics on soil microbes. De Souza Machado et al. (2018) reported significant changes in the root colonisation rate of arbuscular mycorrhizal fungi (AMF) (soil fungus) due to the influence of micro plastics. Largely, a wide range of effects is exerted on the properties of soil by micro plastics. They also cause changes in the diversity and structure of the soil microbial community (Rillig 2018) (Figure 3).

Studies on the effects of micro plastics on soil microorganisms focus primarily on the effect on the soil microbial community and the degradation of micro plastics by microorganisms (Bandopadhyay et al. 2018, Jin et al. 2018, Wang et al. 2019). When micro plastics enter the soil, the newly added carbon sources, additives, and chemical substances have an impact on the soil microbial community. The additives found in micro plastics, such as phthalates, bisphenol, heavy metals, and others, have an inhibitory effect on soil microbial activity, affecting microorganism reproduction (Teuten et al. 2009, Hämer et al. 2014). Certain pathogenic bacteria found in *Campylobacter* can attach to micro plastics and pose a threat to biological and human health (Lu and Lu 2014). The structure of the microbial community in the intestines changed after *Combella* was exposed to PVC for 56 days, and the worm's growth and reproduction were significantly inhibited (Chen et al. 2018).

Currently, research on the impact of micro plastics on soil microorganisms is limited. Future research on the impact of micro plastics on soil microorganisms should focus on how to apply existing microbial testing methods to the microbial communities attached to the surface of micro plastics in soil, revealing the mechanism of micro plastics on soil microbes and the biodegradation mechanism of micro plastics themselves.

MICRO PLASTIC POLLUTION IN THE SOIL ENVIRONMENT: PREVENTION AND CONTROL

Reduced use and discharge of plastic products from the source is an important way to control the accumulation of micro plastics in the soil environment. European and American countries have enacted legislation and regulations to control the origin of plastic products. In 2015, the United Nations Environmental Programme recommended that plastic microbeads be phased out and banned in personal care products and cosmetics in countries and regions around the world. Plastic microbeads were listed as toxic substances by the Canadian Federal Government in 2016, and the "Regulations on Plastic Microbeads in Cosmetics" were issued. Italy proposed a ban on the use of non-biodegradable and non-compostable cotton swabs beginning in 2019; since 2020, all cosmetics containing plastic beads (including over-the-counter medicines and natural health products) containing plastic microbeads have been banned. China issued the "Plastic Restriction Order" in 2000, referring to the "Emergency Notice on Immediately Stopping the Production of Disposable Foamed Plastic Tableware"; on December 31, 2007, the "Notice on Restricting the Production and Sale of Plastic Shopping Bags" was issued (from the "Plastic Restriction Order"). The State Council's "Soil Pollution Prevention and

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Control Action Plan" issued on May 28, 2016, and the "People's Republic of China's Soil Pollution Prevention and Control Law" promulgated on August 31, 2018, proposed to strengthen recycling and utilisation of waste agricultural film and encourage the use of biodegradable films. China is currently implementing urban waste classification and management. All of these plastic waste control measures are geared toward lowering the amount of plastic waste that is released into the environment.

However, current laws and regulations for preventing and controlling soil micro plastic pollution are not perfect. The relevant regulations are overly broad and difficult to implement. The rights and responsibilities are ambiguous and difficult to apply. There is a lack of methods for collecting and analysing plastic waste and micro plastics in the soil environment to guide soil micro plastic prevention and control strategies. Furthermore, there is a lack of efficient plastic waste and micro plastics collection and removal technology in the soil to address the problem of plastic waste and micro plastics pollution in the soil ecosystem.

CONCLUSION AND PROSPECTS FOR FUTURE RESEARCH

Plastic pollution is a global problem, but current research is still relatively scattered, and some systematic thinking is needed for the future. According to some studies, micro plastics can affect soil animals, plants, microorganisms, and even the food chain *via* physical, chemical, and biological processes. It will eventually affect human health. However, due to the late start of related research, it is still in the exploratory stage, and no comprehensive theoretical and methodological system has been developed. In the future, in-depth research can be conducted on the following topics:

(1) Investigate and standardise methods for separating and detecting micro plastics in soil. At the moment, detection methods for micro plastics in soil are limited and insufficient for analysing the distribution and source of micro plastics in soil. It is critical to establish a system for standardised micro plastic separation and detection methods.

(2) Investigate the toxicological effects of micro plastics on soil animals. Soil animals have an impact on the migration and decomposition of micro plastics. Laboratory simulation methods are currently used, which are primarily based on index tests such as reproduction rate, growth rate, and survival rate. Clinical trials should be conducted in the future to investigate the toxicological effects of micro plastics on soil animals as well as the migration mechanism *in vivo*.

(3) Investigate the effects of micro plastics on terrestrial ecosystems, particularly agricultural ecosystems. Micro plastics in agricultural ecosystems can affect not only soil microbial biomass, microbial activity, and functional diversity, but also the cycling of plant nutrient elements in the soil. This may have an indirect effect on seed germination and seedling growth. The risk analysis of the soil and groundwater environment, as well as the health risk of agricultural products, must be investigated as soon as possible.

(4) Investigate the mechanism of micro plastics' influence on soil microorganisms. The nature of micro plastics in soil influences the ease with which microorganisms adhere to its surface. It is necessary to uncover the mechanism by which micro plastics affect the microbial community as well as the mechanism by which micro plastics themselves degrade.

(5) Develop laws, regulations, and standards for the control of micro plastic pollution. To provide more theoretical and data support for plastic waste control and treatment, micro plastic discharge, and dissemination, it is necessary to raise public awareness of domestic waste classification implementation and strengthen research and development of efficient plastic waste treatment technologies.

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