Microplastic Pollution in the Soil Environment: Characteristics, Influencing Factors, and Risks

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Abstract: As plastic products are widely used in all walks of life, plastic waste is also accumulating in the environment. Today, microplastic pollution in the soil environment has become an environmental issue of global concern. Compared with the water environment, the research on microplastics in the soil environment is relatively lacking. Based on the above situation, this paper systematically reviews the distribution characteristics, influencing factors, and environmental and ecological risks of microplastics in the soil environment. The abundance, distribution characteristics, and impacts of microplastics in soils globally in recent years are reviewed in detail. Our review suggests that most scholars only focus on the surface soil, and the determination of the accumulation of microplastics in the soil as a whole is still lacking, and there is still no uniform standard for sampling techniques, extraction methods, analytical procedures, and even expression units for soil microplastics. The distribution of microplastics in soil is affected by human factors, natural factors, and the physical and chemical properties of the plastics themselves. We also focused on the analysis of the environmental risks arising from the accumulation of microplastics in soil interacting with metals and organic pollutants, and found that large research gaps exist in the interaction between microplastics and pollutants in the soil and the mechanism of compound pollution. The impact and ecological risks of microplastics on animals, microorganisms, and plants in the soil are explained. Moreover, key suggestions for future research are presented based on the current research status, and we call for more efforts focusing on the occurrence and fate of microplastics in the soil environment.

Keywords: microplastics; soil; abundance; ecological risk; environmental risk

1. Introduction

Plastics are widely used in all walks of life because of their low price, durability, light weight, and good ductility [1]. It is estimated that plastic production will reach 33 billion tons by 2050 [2]. However, due to the poor natural degradability of plastics, the low recycling rate, and the existence of possible health and ecological risks, the environmental problems caused by its accumulation in terrestrial and marine environments have attracted extensive attention around the world [3–6]. Moreover, the current levels of plastic production, usage/disposal patterns, recycling rates, and demographics all point to an increasing amount of plastic waste [7–9]. Plastics accumulated in different environmental media will be degraded under the action of a series of physical, chemical, or biological processes, thereby gradually reducing their particle size [10,11]. They are generally excreted directly or indirectly into the environment [12]. The degradation cycle of plastic waste can
cause serious environmental problems as surface embrittled plastics are microcracked due
to weathering including ultraviolet light and hydrolysis, and then progressively broken
down into the small fragments or particles known as microplastics [13,14]. In 2014, marine
ecologist Richard Thompson first reported on the distribution of microplastics in the ocean
in a groundbreaking study [15,16]. Since then, environmental microplastics have been
widely reported around the world.

Microplastics are any synthetic solid plastic particle or polymeric matrix, their size
ranges from 1 µm to 5 mm [17], and they are an emerging pollution of concern in the
global environment because of their widespread and potential risks. Microplastics can
be divided into primary microplastics and secondary microplastics according to their
sources [12]. Primary microplastics are the direct production of tiny-sized plastic particles
due to industrial needs such as cosmetics, toothpaste, detergents, and some polishing
agents with abrasive functions, all of which contain a certain amount of plastic particles,
while secondary microplastics are plastic wastes that break into smaller pieces due to the
mechanical wear of wind and water and the chemical and biological degradation of light,
heat, and microorganisms after plastic waste enters the environment [18,19]. Numerous
studies have reported the detection of different types of microplastics in the environment
as well as in food and drinking water and even in humans [20–22]. At present, most
of the research on microplastics focuses on the aquatic environment. Moreover, there is
plenty of evidence that microplastics are also present in terrestrial ecosystems, and that
~80% of global plastic waste is accumulated in landfills, meaning that soil is likely a large
microplastics sink. Although more and more scholars have begun to pay attention to the
terrestrial environment in recent years, the research on microplastics in soil is still limited
and needs more attention.

Soil is a loose surface layer on the Earth’s surface that can grow plants. It plays an
irreplaceable role in ensuring environmental and energy security as well as protecting
biodiversity. However, soil is also an important reservoir for microplastics in the terres-
trial environment [23,24]. It has been reported that nearly 90% of the plastic waste on
land enters the soil environment directly or indirectly [25]. Many previous studies have
indicated that large amounts of microplastic fibers or debris are present in sewage sludge
and compost [26–28]. Since sewage sludge is used in agricultural production activities, a
large amount of microplastics enters the soil environment [29]. In addition, the weathering
and decomposition of mulch film in farmland, crushing of plastic waste in landfills, and
atmospheric deposition are all important ways for microplastics to enter the soil environ-
ment [30–32]. The main sources of soil microplastics are shown in Figure 1. Once in the
soil environment, microplastics will persist and accumulate for a long time, eventually
affecting soil organisms [33]. Moreover, since microplastics can act as carriers of various
toxic contaminants, if these contaminants are transferred into the soil environment, they
may also cause damage to the soil ecosystem [34,35], which will have detrimental effects
on soil health and function. However, most of the current research on environmental
microplastics focuses on the water environment, while the research on microplastics in
soil, especially their spatial distribution patterns and influencing factors, is very limited.
Therefore, it is necessary to understand the recent progress in order to serve future research
on this issue.

Currently, more and more evidence has shown that microplastics are ubiquitous in
soil, and some reviews have focused on the microplastics in a soil environment [24,35–50].
These reviews mainly focused on the detection methods of microplastics in soil as well
as their occurrence and effects on soil ecosystems. However, our current understanding
of microplastics in soil is still fragmented [51]. Moreover, the research on microplastics is
changing with each passing day, the number of publications is increasing exponentially
every year, new research discoveries are constantly emerging, and new cognitions are
constantly iterating. Therefore, it is necessary to constantly summarize the latest research
progress. In this review, we collected and screened the recent available literature from the
database of ScienceDirect (https://www.sciencedirect.com) (accessed on 15 August 2022)
and Google Scholar (https://scholar.google.com) (accessed on 15 August 2022) by using the keywords “microplastics” or “plastic debris” or “plastic”, and the articles were grouped with different categories including “soil”, “terrestrial”, or “land” to summarize the research on (1) the distribution characteristics of microplastics; (2) the influencing factors of microplastic distribution in the soil environment; and (3) the environmental and ecological risks from the distribution of microplastics in polluted soil. In addition, current existing problems, knowledge gaps, and proposed suggestions for future research are included.

Figure 1. Main sources of soil microplastics.

2. Distribution Characteristics of Microplastic in the Soil Environment

In recent years, more scholars have begun to pay attention to microplastics in the soil environment. However, since there is no corresponding analytical test standard, many scholars have mainly focused on the extraction, identification, and distribution of microplastics [52–58], mostly located in farmland soils. As shown in Table 1, there were large differences in the abundance of soil microplastics in various locations. For example, the average abundance of microplastics in traditional farmland soil in southeastern Germany was only 0.34 ind·kg$^{-1}$ [53], while the microplastics in the soil of a traditional home garden in southeastern Mexico were as high as 870 ind·kg$^{-1}$ [59]; the average abundance difference between the two locations was about 2500 times. Even within the same city, the abundance of soil microplastics in different land types varies greatly [60,61]. In addition, the estuarine intertidal zone is located in the transition area between land and ocean and is susceptible to microplastic pollution; thus, the tidal flat soil of the coastal zone has become one of the first areas of concern [62,63]. These studies have confirmed the prevalence and overall abundance of microplastics and showed a trend of increasing with the decrease in particle size; the proportion of microplastics with a small particle size (<1 mm) was higher. In Wuhan, China, the abundance of microplastics even reached $2.2 \times 10^4$–6.9 $\times 10^5$ ind·kg$^{-1}$ [61], which was significantly higher than in other regions, which might be strongly related to human activities in the study area. Film plastic is widely used in farmland because it can improve the ground temperature, maintain soil moisture, and promote seed germination and the rapid growth of seedlings. Therefore, film-covered farmland is also a key area of focus for research on soil microplastics [51,64]. These studies have shown that the longer the farmland was covered with film, the higher the abundance of microplastics in the soil, which was related to the fact that the plastic film does not easily degrade and accumulates over time. In addition, a higher abundance of microplastics has also been found in some farmland or non-agricultural soils in other regions [52,56,65,66]. The abundance of microplastics in soils reported by countries varies considerably. This is
not only related to different land use patterns, but also to the nonuniform methods used for
the extraction, isolation, and analysis of microplastics in the soil. It is worth noting that in
the current research on soil microplastics, most scholars have only focused on the surface
soil, and the determination of the accumulation of microplastics in the soil as a whole is
still lacking. In the future, unified and comparable research methods need to be established
to standardize the expression of microplastic abundance.

**Table 1. Occurrence of microplastics detected in the soil compartment.**

| Region               | Soil Type/Depth                          | Size (mm) | Polymer Shape               | Polymer Composition                  | Abundance (Ind·kg⁻¹ Dry Soil) | Reference |
|----------------------|-----------------------------------------|-----------|-----------------------------|--------------------------------------|--------------------------------|-----------|
| Oceania              | Sydney, Australia                        | Industrial soil/0–25 cm | <10 | Fibers (97%), fragments, films, pellets | PE, PS, PVC, AC, LDPE, nylon, PVC, PE | 300 to 67,500 (mg·kg⁻¹) | [52]     |
| America              | Mellipilla, Chile                        | Agricultural soil/0–10 cm, 10–20 cm | <5 | —                          | PE, fiber, PS                  | 600 to 10,400 | [56]     |
| Pacific              | Pucnachen, Mexico                       | Home garden soil/0–10 cm, 10–20 cm | 0.05 to 5 | Fragments, fibers, films | LDPE, PMMA, PVC, PP, PET, HDPE, POM, PS, PE | 1.88 | [55]     |
| Europe               | Floodplain areas, Lahn River, Germany    | Agricultural/grassland soil/2 m | 2 to 5 | —                          | PS, PET, PMMA, PVC, PP, PE     | 0.34 | [53]     |
| Asia                 | Dian Lake, China                        | Agricultural soil/0–5 cm, 5–10 cm | 0.03 to 10 | Fibers (92%), fragments, films | PE, PP, PET, PAN, CL, PE (61.4%), PP (35.1%), PVC, PE (3.5%) | 7100 to 42,960 | [65]     |
| Jiangsu province, China | Agricultural soil/surface soils         | Agricultural soil/0–10 cm | 1 to 5 | Bulks, fibers, fragments, Fibers, | PE, PP, PET, PAN, CL, PE (61.4%), PP (35.1%), PVC, PE (3.5%) | 420 to 1290 | [67]     |
| Shanghai, China      | Agricultural soil/0–10 cm                | Agricultural soil/0–5 cm | 0.02 to 5 | Fibers, fragments, films, | PA, PP, PVC, PE (35.1%), PVC, PE (3.5%) | 10.3 | [68]     |
| Wuhan, China         | Agricultural soil/0–10 cm                | Agricultural soil/0–5 cm | 0.02 to 5 | Fibers, pellets, fragments, foams, Films, fragments, fibers | PE, PP, PET, RY, AC, PA | 320 to 12,560 | [60]     |
| Hangzhou Bay, China  | Agricultural soil/0–10 cm                | Agricultural soil/0–10 cm, Agricultural, orchard, greenhouse soil | <5 | —                          | PE, PP                          | 571.2 (with films), 262.7 (without films) | [64]     |
| North-western China  |                                        |                                        |                                        |                                      |                                |           |
| Shanxi, China        | Agricultural soil/0–10 cm                | <5 mm                    | Fibers, fragments, films, pellets | PE, PP, PS, PVC | 1430 to 3410 | [66]     |
| Shihezi, China       | Agricultural soil/0–10 cm                | <5 mm                    | Films                          | PE                                     | 80.3 (with films 5 years), 308 (with films 15 years), 1075 (with films 24 years) | [51]     |
| Yunnan-Guizhou Plateau, China | Agricultural soil/0–10 cm | <5 mm                    | Fragments (80.6%), fibers (19.4%) | —                                     | 900 to 40,800 | [70]     |
| Shenyang, China      | Agricultural soil/0–100 cm               | <5 mm                    | Films, fibers, granules         | PE                                     | 3,700,000 (fertilized plot), 2,200,000 (non-fertilized plots), 8885 (topsoil), 2899 (deep subsoil) | [71]     |
| Region                          | Soil Type/Depth                  | Size (mm) | Polymer Shape             | Polymer Composition            | Abundance (Ind kg⁻¹ Dry Soil) | Reference |
|--------------------------------|----------------------------------|-----------|---------------------------|-------------------------------|--------------------------------|-----------|
| Shanghai, China                | Farmland soil/0–3 cm, 3–6 cm     | 0.02 to 5 | Shallow: fibers (53.33%), fragments (37.58%), deep: films (6.67%), particles (2.12%) | PP (50.5%), PE (43.43%), PET (6.1%) | 78 (shallow), 62.5 (deep)     | [72]      |
| Southwestern, China            | Forest and plantation soil/0–10 cm | <5 mm     | Fragments, fibers         | PE (59.6%), RY (12%), PP (10.9%) | 10.975 (banana plantations), 1112.5 (rubber plantations), 612.5 (forests) | [73]      |
| Guilin, China                  | Citrus orchard soil/0–5 cm, 5–15 cm, 15–25 cm | <5 mm     | Films (50.3%), fibers (31.2%), fragments (18.5%) (B) Fibers (71%), fragments (29%) | PP (59%), PP/PE, PET, PE | 545.9 (A), 87.6(B), 5.0 (C) | [28]      |
| Wuhan, China                   | vacant land, woodland, vegetable soil/0–5 cm | 0.01 to 5 | Fragments (52%), pellets (14%), fibers (13.8) | PE, PA, PP, PS, PVC | 22,000 to 690,000 | [61]      |
| Tangshan, China                | Tidal soil/0–2 cm                | 0.12 to 4.67 | Pellets (76.3%), fragments (20.5%), fibers (2.2%), filaments (1%) | — | 634 | [62]      |
| Shandong province, China       | Coastal soil/0–2 cm              | <5        | flakes (69%), foams (27.8%), fragments and fibers (2.1%) | PE, PP, PS, PUR | 1.3 to 14,712.5 | [63]      |
| Southeast coastal area, China  | Mangrove soil/0–2 cm             | <5 mm     | Foams (74.6%), fibers (14%) | PS (75.2%), PP (11.7%), rayon, PES PP | 8.3 to 5738.3 | [74]      |
| Tianjin, China                 | Campus soil                      | 0.1 to 3.2 | Fragments (43.54%), fibers (32.2%), films (23.78%) | PVC, PE, PP, PS | 47.12 | [76]      |

Note: PET = polyethylene terephthalate, HDPE = high-density polyethylene, LDPE = low-density polyethylene, PA = polyamide, PP = polypropylene, PS = polystyrene, PUR = polyurethane, PAN = polyacrylonitrile, PES = polyester, PVC = polyvinyl chloride, RY = rayon, CL = cellophane, AC = acrylic, SBR = styrene butadiene, PMMA = polymethyl methacrylate.

3. Influencing Factors of Microplastic Distribution in the Soil Environment

Soil is a complex organic–inorganic complex consisting of minerals, organic matter, moisture, and air [77]. The distribution of microplastics in soil is affected by human factors (exogenous input), natural factors (soil properties), and the physical and chemical properties of the plastics themselves.

3.1. Human Activities

There are various sources of microplastics in soil including agricultural film residues, sludge reuse, sewage irrigation, and fertilizer use, etc. [50]. The exogenous input caused by human activities is an important factor affecting the distribution of microplastics in the soil, and thus the distribution of microplastics from different sources in the soil environment is often dominated by specific external environmental factors. For example, the length of film mulching time significantly affected the abundance of microplastics in the soil of film-covered farmland. Zhou et al. [64] found that the abundance of microplastics in the soil of mulched farmland near Hangzhou Bay was higher than that of unmulched farmland.
In the long-term film-covered cotton fields in Shihezi, Xinjiang, the mean abundance of microplastics in the soil of the cotton fields covered with film for 5 years was 80.3 ind·kg⁻¹, the mean abundance of microplastics in the soil of a cotton field covered with film for 15 years was 308 ind·kg⁻¹, and the mean abundance of microplastics in the soil of cotton fields covered for 24 years was as high as 1075.6 ind·kg⁻¹ [51]. The longer the farmland was covered with film, the higher the abundance of microplastics in the soil, which also showed that the residue of agricultural film was an important method for the accumulation of microplastics in the soil.

The sludge reuse also brings a large amount of microplastics into the soil environment. It is estimated that 0.63 to 4.30 and 0.44 to 3.00 million tons of microplastics enter the soil through sludge application in Europe and North America, respectively [78]. In China, up to $1.56 \times 10^{14}$ microplastics enter the environment through sludge each year [26]. Therefore, the amount of sludge used greatly affects the accumulation of microplastics in the soil. The long-term use of farmland organic fertilizer is also one of the important exogenous inputs of microplastics into the soil. One study found that the abundance of plastic debris with a particle size greater than 1 mm in organic fertilizers reached 14 to 895 ind·kg⁻¹ [79]. In sewage irrigation areas, the irrigation water is filtered, and the removal efficiency of microplastic particles during processing may determine the abundance of microplastics discharged into farmland soil. For instance, even if the wastewater from a sewage treatment plant in Vancouver, Canada is treated, about 30 billion microplastics are released into the environment through sewage every year. In coastal tidal flat soils, high-intensity human activities such as mariculture, tourism, and port construction are the main factors affecting the composition and distribution of microplastics in the intertidal zone [63].

3.2. Soil and Plastic Physicochemical Properties

After microplastics enter the soil environment, soil factors significantly affect the distribution of microplastics such as the pH, texture, organic matter, and soil animals [46,80–83]. The soil pH affects the soil adsorption capacity through H⁺ competition, changing the soil surface potential, and specific adsorption sites; a recent study indicated that the abundance of microplastics in acidic soil was significantly lower than that in neutral soil [81]. Soil texture affects the distribution of microplastics through the ease with which they move through the soil layers [49,84]. Microplastics are more likely to move to deeper layers in sandy soils, while the stickiness of the clay particles may prevent microplastics from moving into the deeper layer of clay soils [81]. A recent study also found that the abundance of microplastics in sandy loam soils was significantly higher than in other textures of soil [80]. Guo et al. [84] indicated that soil texture is an important factor determining how microplastics affect the soil hydraulic characteristics, and found adverse effects of microplastics on the infiltration properties of the three studied soils (loam, clay, and sand) were influenced by particle size, with larger particles having the weakest effect. Soil fauna can also affect the distribution of microplastics in the soil layers by ingesting or excreting microplastics, and their movement or disturbance may also cause microplastics to migrate back and forth between different soil layers [85,86]. Yu et al. [87] found that earthworms can ingest topsoil microplastics and transport them to deeper soil layers. Zhu et al. [88] also found that small soil fauna (e.g., collembolans and mites) could also facilitate the migration of microplastics in soil through surface attachment, grasping and pushing. Collembola accelerated the migration of MPs in soil, but there were also significant differences in the migratory ability between different collembola, the mode of action was that microplastics can attach to the cuticle of these micro-arthropods, and then with additional movement, be transported further [89]. In addition to the above factors, the physical and chemical properties of different microplastic types will also affect their distribution in the soil environment. For example, polyethylene is a long-chain polymer composed of thousands of ethylene (–CH₂–) monomers, and the high molecular weight and hydrophobicity of this polymer make it particularly difficult to degrade [90,91]. Polyethylene terephthalate is also not easily degradable due to its chemical inertness, so the mass production and use
of this material has also led to its massive accumulation in the soil environment [92]. In addition, other factors such as ultraviolet rays, temperature, and microfauna communities will also affect the distribution of soil microplastics [10,93]. However, due to the refractory properties of each polymer, its impact may not be significant in a short period of time.

4. Environmental and Ecological Risk Research on the Distribution of Microplastics in Polluted Soil

4.1. Release of Additives and Adsorption of Toxic Pollutants

Plastics usually have chemical additives (e.g., bisphenol A, bis (2-ethylhexyl) phthalate) [94–96]. Therefore, when microplastics accumulate in the soil environment, these chemical additives may be released into the soil under the influence of external factors [97,98], thereby threatening the soil ecosystem and affecting the quality and safety of the soil in the long-term. Zhang et al. [99] found that organophosphates (OPEs) and phthalates (PAEs) were prevalent in microplastics in the Bohai Sea and Yellow River beaches. Another study showed that microplastics can release phthalates, which can affect the diversity of soil microorganisms [100]. In addition, the surface of microplastics can adsorb hydrophobic organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) [101–103], polychlorinated biphenyls (PCBs) [104–106], and organochlorine pesticides (OCPs) [102,107]. When hydrophobic organic pollutants are adsorbed by microplastics, different adsorption sequences may occur, which may lead to competitive adsorption [108]. Lee et al. [109] conducted adsorption experiments on 14 different hydrophobic organic pollutants using polyethylene, polypropylene, and polystyrene microplastics, and showed that there was a significant correlation between the adsorption capacity of microplastics and their hydrophobicity. In addition, microplastic surfaces can also adsorb Cd, Zn, Ni, Pb, and other heavy metals [41,110–112]. Zhou et al. [61] found that plastic particles in the soil environment contained different levels of heavy metals including Cd, Cr, Pb, Ag, Cu, Sb, Hg, Fe, and Mn. However, due to the different chemical and physical properties (e.g., the specific surface area and molecular polarity) of each plastic, the adsorption rate of various heavy metals on microplastics may also vary greatly [113]. It is worth noting that their adsorption capacity for heavy metals and organic pollutants may further increase as microplastics age, thereby increasing their environmental risk [41]. For example, Ding et al. (2020) indicated that the adsorption capacities of polystyrene were enhanced with the increase in the aging degree [66]. Since microplastics enter the soil, they will interact with other pollutants. Under certain conditions, the slow degradation process of microplastics may also diffuse or release these adsorbed toxic chemicals into the surrounding environment or even into the underlying soil adjacent to groundwater [114,115]. Therefore, microplastics with attached pollutants have a greater environmental risk.

4.2. Ecological Risk

The accumulation of microplastics in the soil will not only affect the physicochemical properties of soil but also harm the development and reproduction of fauna, affect the plant growth, and even change the microbial community and enzyme activity [116–118]. Microplastics attached to the outer surface of some soil organisms (e.g., earthworms and springtails) may directly hinder their free movement in the soil layer [119]. In addition, incidental ingestion of microplastics can also cause mechanical damage to the esophagus of soil animals (e.g., earthworms, snails, and mice), intestinal obstruction, decreased fecundity, and biochemical reactions (e.g., decreased immune response and metabolic disturbance) [35,120,121]. It can also cause soil animals to produce false satiety, thereby reducing the carbon biomass intake, further leading to energy consumption, and ultimately resulting in reduced growth and even death [122]. In addition to particle toxicity, the impact of microplastics on soil organisms also includes the toxic effects of the various environmental pollutants attached to their surface, as discussed above [123,124]. At present, the research on the impact of microplastic distribution on soil microbial ecology mainly focuses on the assessment of changes in soil enzyme activities [45]. Previous studies have
indicated that changes in the soil microbial activity were mainly dependent on the particle characteristics of microplastics, exposure concentrations, enzyme types, and the presence of plants [125,126]. The presence of microplastics may also affect the migration and sedimentation of bacteria in the soil as well as the loss of antibiotic resistance genes [38,127]. A recent study found that the distribution of microplastics significantly affected the community structure of soil microorganisms, which may also have an impact on the global carbon and nitrogen cycle [128]. However, there is still a lack of systematic research on the environmental and ecological risks caused by the distribution of soil microplastics.

The accumulation of microplastics in soil can also affect plant growth. A study found that the accumulation of plastic film residues in the soil led to a decrease in the fertilizer use efficiency of crops such as wheat and corn, a decrease in yield and the inhibition of root growth [129]. In addition, microplastics can also affect the photosynthesis and antioxidant defense systems of lettuce, thereby inhibiting its growth [130]; they can block cress seed pores and inhibit water absorption, thus delaying germination and root growth [131]. A study indicated that microplastics and synthetic fibers made from high-density polyethylene and polylactic acid affect ryegrass development, Rhodiola health, and soil properties, and may have further impacts on soil ecosystem function [132]. The high dose of polylactic acid produced stronger phytotoxicity than polyethylene [133]. In addition, microplastics of different sizes have different effects on plants, and generally, microplastics with small particle sizes are more toxic. A study found that 100 nm microplastics (100 mg·L$^{-1}$) had an inhibitory effect on the growth of faba bean, and its genotoxicity was stronger than that of 5 µm microplastics [134]. Another study showed that 100 nm polystyrene microplastics could enter the roots of the legume plant, faba bean, blocking cell wall stomata and intercellular connections and affecting nutrient transport [134].

5. Conclusions and Future Research on Microplastics in the Soil Environment

To summarize, there are various sources of environmental microplastics. At present, the research on soil microplastics has mainly focused on their abundance, types, or testing and analysis methods. Microplastic pollution is a relatively new research topic in soil science, and there is still no uniform standard for sampling techniques, extraction methods, analytical procedures, and even expression units for soil microplastics. The following research should be strengthened in the future:

(i) Establish a unified standard method for rapid extraction, convenient identification, and efficient monitoring of microplastics in soil, since there is still no unified standard for the testing and analysis methods of soil microplastics, which will inevitably reduce the comparability of data between different studies. At present, the separation methods of soil microplastics mainly include density separation, froth flotation, magnetic extraction, electrostatic separation, oil separation, and solvent extraction separation. However, these methods have their own advantages and disadvantages. For instance, the froth flotation method is low-cost, green, and non-polluting, but it is not effective for extraction, and the flotation results vary considerably between polymers. Therefore, there is an urgent need to develop a fast, convenient, and standard quantitative analysis method for soil microplastics, especially detection technology that can meet the needs of the content, size, and type of nanoscale plastics.

(ii) Systematically explore the influencing factors of the distribution of microplastics in soil, and introduce a new method to screen these factors to achieve an ideal quantitative characterization of the spatial distribution of soil microplastics. At present, there is no report on the quantitative characterization of soil distribution of microplastics. Previous studies on the quantification or prediction of the spatial distribution of soil pollutants have mostly used mathematical statistics and geostatistics. The application of geostatistical methods (e.g., Kriging interpolation) can predict the number of pollutants in a certain spatial range from the obtained data, hence, the “hot spots” of pollution can be visually observed. Mathematical statistical methods (e.g., correlation analysis and principal component analysis) extract the required information through
the pollutant data or the analysis of relevant factors and are widely used in the field of soil science. However, these methods lack quantitative analysis of the driving ability of the spatial distribution of pollutants and cannot evaluate the influence of multi-factor interactions. In addition, the socio-economic factors in high-intensity human activity areas may have problems such as multi-source and variety of data, and traditional statistical methods have difficulty meeting the needs of large-scale data analysis or factor screening. Therefore, the introduction of a new method to screen the influencing factors and then to achieve an ideal quantitative characterization of the spatial distribution of soil microplastics is an important path to break through the above-mentioned defects.

(iii) Assess the releasability of chemical additives in microplastics in the soil environment to prevent environmental risks and study the interaction between microplastics and pollutants in soil and the mechanism of compound pollution to evaluate the dose-biological effects and health risks of microplastics as well as to lay a foundation for the risk assessment of microplastics in soil. In addition, since the adsorption and desorption between microplastics and pollutants is affected by many factors such as hydrophobicity ($K_{ow}$), molecular weight, and the three-dimensional geometry of the molecule, it is particularly necessary to clarify the long-term effects of microplastics on pollutants in the future, and to reveal their intrinsic driving forces from the mechanism.

(iv) When analyzing the potential risks of microplastics, future studies should consider differences in the microplastic particle size, shape, and type in addition to the microplastic dosage. Current research on the impact of microplastics on the soil ecosystems often uses higher doses of microplastics to carry out ecological effects studies. However, microplastic doses at real concentrations in the soil environment tend to be lower compared to the experimental value, so future studies should be conducted using microplastic doses that are closer to their real concentrations in the environment, thus more accurately reflecting their in situ ecological effects. Moreover, nanoplastics are more harmful to soil organisms, so the ecological effects of nanoplastics accumulated in the soil should be considered in the future.

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