

Editorial

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Soil microplastics: we need to pay more attention

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INTRODUCTION

Plastic are stable, recycled, and low-cost materials which are employed in many ways, from industrial manufacture to daily life. Plastic debris has been released into the environment due to the limited recycling frequency. It has been reported that the amount of plastic waste emitted into the environment has reached six million tons, four-fifths of which ultimately entered landfills^[1]. Unfortunately, the fragmentation process does not break down plastics completely, but renders them into millions of smaller plastic particles including microplastics (MPs) with a size of < 5 mm^[2,3]. Thus, studies on MP pollution have received great interest in recent years. The existence of MPs has been found in many environmental media, including atmosphere, seawater, freshwater, and even human tissues^[4-7].

Soil, as an important environmental component, undertakes essential ecological functions and interacts with other environmental media simultaneously. The importation of large plastic waste and its fragments from terrestrial sources has led to the widespread presence of MPs in the aquatic environment. Therefore, the soil environment is an important “sink” of MPs^[8]. The inherent complex characteristics of soil have a great impact on the environmental behavior and effects of MPs. On the one hand, MPs are prone to be transferred by organisms, posing a potential threat to organisms when the particle size reaches the nanoscale^[9-11]. In addition, some inherently toxic substances, such as lubricants, pigments, and other



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additives, which are mainly used to improve the plastic product's performance, pose the risk of secondary release with the natural aging process. For example, phthalate esters (PAEs) are typical plasticizers that are widely detected in manufactured products and commodities^[12]. Li *et al.* investigated the content of PAEs in 36 vegetable fields with plastic film mulching in Shandong Peninsula, China^[13]. Besides, MPs can also serve as carriers for various hazardous substances (e.g., heavy metals, pesticides, and polychlorinated biphenyls) due to the evolution of the hydrophobicity and surface functional groups, which will further increase their risk of environmental pollution^[10,14]. On the other hand, the physicochemical properties of soil, including pore, pH, minerals, soil animals, *etc.*, also affect the transferring behaviors of MPs. For example, soil has mesopores and macropores in the millimeter range, whose size directly affects the migration process of MPs. Moreover, external forces such as agricultural tillage and bioturbation can also affect the migration of larger MPs in soil. Rillig *et al.* found that MPs can adhere to earthworms (*Oligochaeta*), which promotes the vertical migration of MPs in the soil; the smaller the particle size of MPs, the easier it is to migrate^[15].

ANALYSIS AND DETECTION OF MPS IN SOIL

The method of MPs analysis and detection in water and sediment is suitable for the analysis and detection of MPs in soil to some extent, but it is more difficult to separate and identify MPs from soil. Sample collection mainly includes single point sampling and compound sampling. Compound sampling is suitable for agricultural soil with an uneven distribution of MPs. Single point sampling is suitable for soils with little human activity including farming^[16]. Here are the analysis methods of soil MPs: (1) dry and screen soil samples; (2) remove organic matter from mixed MPs particles and soil substrate; (3) separate MPs from the soil matrix; and (4) identify and characterize the MPs in soil^[17].

Among the analysis methods of MPs, the methods commonly used to characterize the physical and chemical properties of MPs include microscopic identification of MPs, spectroscopy or thermodynamic methods [Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy (Raman), thermogravimetric analysis-differential scanning calorimetry, pyrolysis gas chromatography-mass spectrometry (Py-GC-MS), thermal extraction desorption gas chromatography-mass spectrometry, and scanning electron microscopy (SEM), which is often used in conjunction with energy dispersive spectroscopy (EDS)], and X-ray diffraction. These methods have their own advantages and disadvantages. The visual analysis method has the advantages of simple operation, low cost, and no chemical hazard, but the naked eye and microscope can only vaguely identify MPs through their appearance and morphology and cannot obtain the composition information of the sample. FTIR has the advantages of not destroying the sample, simple pretreatment, and no fluorescence interference, and it is widely used in the qualitative detection and composition analysis of MPs^[18]. However, it is currently impossible to detect smaller MPs in the environment, and it is also difficult to analyze opaque/black MPs. In recent years, FTIR based on a focal plane array (FPA) has received increasing attention in the field of MPs analysis. Compared with FTIR, which can only analyze MPs one by one, FPA-FTIR can analyze MPs in a large area, and the efficiency has been greatly improved^[19]. Raman is favored by researchers due to its significant advantages in detecting MPs such as non-destructive, low-sample-volume testing, high-throughput screening, and environmental friendliness^[19]. However, biological contamination or surface aging of MPs may produce fluorescence, and fluorescent samples cannot be detected by Raman. Among the thermal analysis methods, Py-GC-MS has the risk of misidentification as different polymers may produce similar pyrolysis products. It can only analyze one particle at a time and cannot be applied to the analysis of large-scale samples in large-scale sampling and routine monitoring work^[20]. In addition, thermal analysis methods are destructive to samples and can only be used for chemical characterization; they cannot obtain physical characteristics such as the size and morphology of MPs. Therefore, the thermal analysis methods need to be further optimized to become efficient and widely used MPs analysis techniques. Finally, SEM-EDS also has certain limitations,

such as cumbersome sample preparation steps and time-consuming full inspection of all samples^[21], resulting in low work efficiency. In addition, SEM-EDS cannot analyze the color of MPs samples, so this technique is mainly used to analyze specific MPs.

Overall, there are still many problems to be solved with the current MP analytical detection methods. Since there is no standardized detection method for MP analysis, the abundance of MPs detected in different studies varies widely. Variability occurs not only at the upper limit of MP size but also at the lower limit. There are various reasons for this to happen. Firstly, in some cases, the soil needs to be sieved to 2 mm. However, if applied to MP analysis, this procedure will lose some MPs, resulting in a decrease in their abundance. Secondly, the use of different salts has advantages and disadvantages when extracting MPs by density separation. In addition, after pretreatment, the MPs need to be filtered onto the membrane. However, different studies use different membrane apertures, which also leads to changes in the abundance of MPs^[22].

In summary, in recent years, MP analysis methods have developed rapidly, but they still cannot fully solve the problems faced when studying MPs in soil and other complex environmental substrates. To comprehensively compare the occurrence of MPs in soil from different research regions, it is necessary to establish standard and uniform MP analysis and testing methods. In addition, MP concentration reporting data must be representative, scientific, and reproducible.

ABUNDANCE OF MPS IN SOIL

Although the occurrence and distribution of soil MPs are still not the focus of current research, existing studies indicate that MP pollution exists in soils around the world^[23]. Researchers examined MPs in soils from coastal Shandong province, China, and recorded the abundance of MPs as ranging from 1.3 to 14,712.5 items/kg^[24]. Agricultural soils are mainly studied in inland areas, where MPs are mainly derived from improper disposal of agricultural plastic film. A study on farmland soil in the suburbs of Harbin, Heilongjiang province, found a low-density abundance of 107 items/kg^[25]. MPs have also been detected in agricultural areas in northern China, such as soil in Tianjin (95 items/kg), the Loess Plateau Region (40-320 items/kg), and Shaanxi province (1430-3410 items/kg)^[26-28]. MPs have even been detected in farmland on the Tibetan Plateau without direct anthropogenic plastic pollution, with an abundance between 20 and 110 items/kg^[29].

Extensive research on MPs has been conducted in soils around the world. The mean abundance of MPs was 306 and 184 items/kg in farmland and pasture soils collected from the Chilean metropolitan area^[30]. A similar abundance of MPs (593 items/kg) has been reported in a Swiss floodplain wetland soil^[31]. The problem of MP pollution caused by the long-term application of sludge is attracting attention. The abundance of MPs reaches 600-10,400 items/kg in Mellipilla, Chile, where sludge has been continuously applied^[32].

Currently, there are few studies on the distribution of MPs in global soils. The range of MP abundances reported from various countries varies dramatically, mainly because not all MPs in soils were detected due to the lack of uniform research methods. In addition, a convertible method needs to be established between the expression methods of quantity (items/kg) and mass (mg/kg). In the future, a unified and comparable research method needs to be established to standardize the expression of MP abundance.

BEHAVIOR OF MPS IN SOIL

There are many sources of MPs in soil. The main sources include agricultural plastic film residues, land use of sewage sludge, long-term application of organic fertilizers, surface runoff and irrigation, and atmospheric deposition. MPs entering the soil environment have complex migration behaviors, which could undergo diffusion and migration under the action of wind, soil organisms, surface runoff, gravity, *etc.* Some MPs may enter the ground under the action of soil animals^[33,34], microorganisms^[35], plant roots^[36,37], or gravity, then enter the freshwater environment through underground runoff, and eventually accumulate in the ocean. Other MPs, which remain on the surface, may enter freshwater under the action of wind^[38] or surface runoff^[39,40], and then may migrate over a long distance to the ocean. Soil MPs may also be transported into the air by wind and dust^[41]. Animals in soil and sea could feed on MPs and pass them on^[42], and MPs could also be absorbed and accumulated by plants^[43], which could ultimately allow MPs to enter the food chain and cause unpredicted risks to human health. In addition, due to the hydrophobicity and large specific surface area of MPs, they can adsorb various pollutants (such as heavy metals, antibiotics, pesticides, polycyclic aromatic hydrocarbons, *etc.*) and can be used as a carrier or transport medium for these pollutants and pathogens, which in turn affects their migration and distribution in the environment^[10,14]. Along with these properties, MPs are inherently toxic, which is mainly due to the addition of toxic substances such as plasticizers, flame retardants, colorants, antioxidants, and light and heat stabilizers during plastic processing^[44,45]. As plastics undergo mechanical wear, photodegradation, photooxidation, thermal oxidation, and biodegradation in soil, these substances can be released into the environment^[46,47]; moreover, it is possible to form nanoplastics with larger specific surface area, stronger fluidity, and easier ingestion by organisms^[40], threatening ecosystems and human health. These reasons lead MPs to be viewed as a combination of various pollutants, while the bioavailability of MPs and other pollutants by soil organisms, and their combined toxicity, may be different from individual pollutants, potentially posing additional or greater risks to soil ecosystems and human health.

EFFECTS OF MPS ON SOIL QUALITY

As a common solid pollutant, MPs may change the basic physical and chemical properties of soil, including soil structure^[48], soil density^[49], soil water infiltration rate^[50], and soil nutrient element utilization^[51]. When MPs enter the soil, due to the intervention of new cementing substances, the isoelectric coagulation Coulomb force and van der Waals force between soil particles and their biochemical environment are changed, which may affect the formation and process of soil aggregates. Machado studied the impact of four common MPs on soil structure and found that polyester reduced soil water-stable aggregates, while PE caused the opposite effect. The reduction of soil water-stable aggregates weakens the diversity of the soil microenvironment^[52]. Once incorporated into the soil matrix, MPs change the size of soil porosity, soil water dynamics, and the formation of soil aggregates. Related studies have shown that, after adding polyester microfibers to cohesive soils, water-stable macro-aggregates and pore volume significantly increase^[53]. The density of most MPs is lower than soil minerals, which may be the reason for the changes in soil bulk density caused by MP pollution^[49]. The presence of MPs can also damage the integrity of the soil structure, leading to drying and cracking of the soil surface^[48]. Besides, MPs have prominent effects on soil organic carbon or nitrogen cycling. Previous studies have shown that, under the comprehensive action of soil organic matter, minerals, organisms, and other complex environmental factors, MPs can have significantly enhanced adsorption capacity for some heavy metal ions and organic pollutants after entering the soil, thus affecting the soil nutrient availability and soil ecosystem health^[54]. However, one study concluded that the addition of MPs poses no obvious harm to soil quality, based on the finding that soil saturated hydraulic conductivity and bulk density were not dramatically affected by ultrafine polyester fibers^[53].

EFFECTS OF MPS ON SOIL ORGANISMS

There are many living organisms in the soil system, including microorganisms, animals, and plants. They are of great significance to maintaining a certain range of soil ecological stability^[55,56]. As an exogenous substance, MPs affect the soil properties after entering the soil, thereby causing disturbance to the balance of the ecosystem^[36]. This may lead to greater environmental stress and the abnormal growth of the organisms and plants in the soil. In addition, MPs can absorb toxic pollutants in soil and cause more pollutants to accumulate in soil organisms, which will change the bioavailability of pollutants^[57]. Thus, if MPs are ingested by organisms, they may be toxic to the organisms and enter the food chain, resulting in great environmental risks.

Effect of MPs on microorganisms

MPs, as exogenous materials, provide a new ecological habitat for microorganisms after entering the soil, and the microbial community that grows on MPs is also called a “plastic circle”^[58]. The microbial communities growing on MPs are significantly different from the plastic and the surrounding environment. For example, the agricultural PE microfilm surface is enriched in some taxa, such as *Actinobacteria*, *Bacteroidetes*, and *Proteobacteria* in farmland soil, as a “special microbial accumulator”^[59]. The microbial community in soil with PEMP was significantly different from those in the soil without PEMP^[60]. Soil porosity and moisture can also be changed by MPs, thereby affecting the distribution of different microorganisms and even resulting in the destruction of microhabitats and the extinction of some microorganisms^[61,62]. MPs in the soil environment may accumulate a lot of organic matter or heavy metal pollutants, such as pesticides and metals, e.g., copper, which might inhibit microbial growth^[63]. Antibiotic resistance genes (ARGs) in soil environments have also attracted extensive public attention in recent years^[64-66]. Existing studies have shown that MPs in the soil can enrich ARGs in soil. Song *et al.* found that the presence of MPs not only increased the content of ARGs in soil but also increased the content of ARG-containing hosts in *Pseudomonas*^[67]. This increases the risk of horizontal transfer of ARGs in microbial communities formed on MPs. Although MPs can adversely affect soil microorganisms, some microorganisms in soil can also promote the degradation of specific types of MPs; for example, *Cladosporium cladosporioides*, *Xepiculopsis graminea*, *Penicillium griseofulvum*, and *leptophaeria sp* could all promote the degradation of polyurethane (PU)^[68].

Effect of MPs on animals

Besides microorganisms, previous studies have demonstrated that the presence of MPs has a great impact on soil animals. MPs may be ingested by soil animals to enter the soil food chain and continuously accumulate, thus affecting the total nutrients level of the soil^[42]. When exposed to MPs, the feeding behavior of soil animals is altered^[69], which affects the metabolism of carbon and nitrogen uptake, leading to decreased development and even death^[69,70]. Many studies have shown that earthworms might ingest MPs, causing intestinal damage, which affects their survival, growth, and reproduction^[10,71-72]. In addition, the negative effects of MPs on several soil invertebrates (e.g., springtails, nematodes, collembola, and snails) have been demonstrated in previous work^[73]. The adverse effects of MPs on soil animals were related to the particle size and concentration of MPs. For example, Selonon *et al.* found that long fiber MPs concentrations of 0.17% and 0.5% decreased the reproduction of *E. crypticus* by 20%; when the concentration increased to 1.5%, the reproduction decreased by 30%^[72]. Lei *et al.* found that the excitability and toxicity of *C. elegans* behavior were related to the size of MPs, and they deteriorated as the size of the MPs decreased^[74]. In addition to the MPs themselves, the additives in plastics also significantly affect and poison the growth and survival rate of the host as well as the intestinal flora^[75]. Behaviors of soil animals, such as crawling, scraping, chewing, and excretion, can lead to vertical and horizontal migration of MPs in soil^[56].

Effect of MPs on plants

The effect and damage of MPs to plants are also multifaceted, because of the diversity of MPs and the mechanisms of MPs and plants. It can be summarized in two ways: (1) directly changing the physiological and biochemical properties of plants through the roots; and (2) changing the physicochemical properties or biological conditions of the soil to indirectly affect the growth of plants^[62,76-77]. The toxicity of MPs to plants after being absorbed by plants is related to other pollutants bound to MPs, such as organic or heavy metal pollutants^[78]. In addition, MPs are further aged in the soil and their additives are directly toxic to plants^[46]. Numerous studies have demonstrated the adverse effects of exposure to soil MPs on plants, especially crops, including inhibition of seed germination and plant growth, reduction in biomass, interference with metabolism, and genotoxicity^[76,79-81]. However, in recent years, some MPs have also been found to promote plant growth. For example, Shi *et al.* found that PEMP significantly improved the biomass growth rates of sweet potatoes by adsorbing more available P and K in the soil^[77]. Rillig *et al.* indicated that the potential positive and negative mechanisms of MPs to plants were related to the plant species. In summary, the interaction between MPs in soil and plants is very complex and needs to be further studied in the future^[82].

CONCLUSIONS AND PROSPECTS

As a global problem, soil MP pollution has become the focus of research by scholars around the world. Their environmental behavior not only affects soil properties, crop growth, microbial activity, animals, *etc.* but also may pose serious threats to human health. At present, the research on soil MPs is not systematic and comprehensive enough, and some systematic thinking and research are needed. Here, we put forward several prospects for future research:

- (1) Separation and detection of MPs in soil: At present, the separation and detection methods of MPs in soil are limited and different, so it is difficult to compare horizontally. In addition, nanoscale plastics are neglected and difficult to separate and extract. It is difficult to accurately analyze and judge the overall abundance and pollution degree of MPs in soil. Therefore, it is urgent to establish a standardized and structurally damage-free MP separation and detection method.
- (2) Environmental health risk assessment of soil MPs and their additives: MPs contain plasticizers such as phthalates (PAEs), which are not covalently bound to the polymer and may leach during the chemical and non-chemical aging of the plastic. Therefore, it remains unclear whether the environmental behavior and risks of MPs are due to the particle effect of MPs, the chemical effect of plastic additives, or the effect of combined pollution.
- (3) Control and reduction of soil MPs: Soil MPs will bring a series of risks to the ecosystem. Therefore, soil microplastic pollution remediation needs to be carried out through source control or indirect reduction. To mitigate the risk of MP pollution from the perspective of source control, environmentally friendly biodegradable plastics have been widely promoted and used as substitutes for non-degradable plastics, but there is a lack of research on their possible ecological and environmental effects during the process of biodegradation, requiring further exploration. For the indirect reduction process of MPs, biodegradation and abiotic processes, synergistic removal with other pollutants, and synergistic operation with agricultural production should be taken into consideration.
- (4) Food chain transmission mechanism and risk research of soil MPs: MPs ingested by soil animals can be transmitted to the human body through the food chain; however, due to ethical restrictions, little is known about the transmission mechanism of MPs entering the human body and their risk effects on human tissues and organs. Subsequent studies should be carried out through *in vitro* cell models.

DECLARATIONS

Authors' contributions

Made a substantial contribution to conceptualization, supervision, writing original draft, reviewing and editing: Guo X

Made a substantial contribution to writing original draft: Cui Q, Ma S, Xiao C, Yang Z

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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