Microplastics in soils: a review of possible sources, analytical methods and ecological impacts

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Abstract

Microplastics are emerging persistent pollutants that have been extensively detected in aqueous environments. Yet, scientists have little knowledge of microplastic pollution in soils. This study reviewed over 60 articles, with the following objectives: (i) to discuss sources and the global distribution of microplastics in soils; (ii) to evaluate current extraction techniques and analytical methods for microplastics in soils; and (iii) to comprehensively assess their adverse impacts on soils and soil organisms. Moreover, this review highlights the lack of research into microplastic contamination in soils as a significant knowledge gap. Research into the fate, sources and analytical techniques of soil microplastics and the interactions between soil organisms, soils and microplastics is essential in order to underpin management decisions aimed at safeguarding the ecological integrity of our soils.

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Keywords: microplastics; soil; source; analytical methods; ecological impacts

INTRODUCTION

Plastic pollution has become a widespread scientific and social concern because of the dramatic increase in the production of plastics. Globally, the annual production of plastics is approximately 322 million tons. Despite a gradual increase in plastic recycling and energy recovery, most plastic wastes are released into the environment.1 Recently, microplastics (MPs) have become the focus of environmental research owing to their minute particle size and potential impact on aquatic and terrestrial ecosystems. MP is defined as a plastic of less than 5 mm size that is present in a variety of morphologies (i.e. beads, fragments, fibers and films).2 There are two categories of MPs: primary MPs that are produced and released into the environment in small sizes, and secondary MPs that are degraded from larger plastic wastes because of water, wind, sunlight and other environmental stressors. Primary MPs enter the environment directly, whereas secondary MPs originate from the breakdown of large-size pieces.3

Pollution with MPs was first observed in marine environments, so most studies have focused on the origin, occurrence and fate of marine MPs. Scientists agree that MPs in marine environments have potential adverse impacts on aquatic organisms, marine ecosystems and even human health.3 However, few studies have focused on the sources, occurrence and fate of MPs in soil environments. Rillig,5 one of the earliest scholars in the world to study MP pollution in soils, observed that after plastics enter soils, MPs tend to be retained, accumulated and finally increased to levels that can alter soil properties and biodiversity.7 Zhang and Liu5 reported that MP concentrations were much greater in soils than in the water and sediment of aquatic environments. The enormous accumulations of MPs in soils are likely to result from various human activities and environmental origins, such as atmospheric precipitation, contaminated water courses, plastic mulching, irrigation, flooding, littering, street runoff, sewage sludge and agricultural compost.6,7 Furthermore, MP concentrations in soils are predicted to increase continuously in the future owing to the manufacturing and leaking of plastics into the environment.6,9 Soil organisms such as earthworms also contribute to the formation of secondary MPs, because they can take in plastic debris and transform them into MPs. Earthworms, along with other terrestrial organisms, including mites, gophers, collembolans and moles, not only contribute to the degradation of plastic particles on solid surfaces but also incorporate plastic particles into soils.10 MPs can also be vectors for the concentration of hydrophobic organic contaminants such as polychlorinated...
biphenyls, polycyclic organochlorine pesticides and aromatic hydrocarbons, as well as heavy metals such as nickel, zinc, cadmium and lead.11 Thus some studies have identified interactions between MPs and the chemical pollutants that they absorb on their surfaces. In addition, fauna can ingest MPs because of their small sizes, which can result in MPs being transferred up the food chain.12 Besides, the chemical contaminants that are accumulated from MPs can be released into the gastrointestinal tract of organisms, leading to negative impacts.2711 Yet, some scholars demonstrated that the effects were likely caused by the plastics themselves as opposed to the absorbed chemical contaminants.12 The soil biota, on the other hand, affects how MPs move and are distributed in soils.13 Once MPs enter soils, they are incorporated into a complex mixture of mineral substituents and organic matter. In addition, MPs can change the physical properties of soils and may reach levels that can threaten biodiversity, soil ecological functions and even global food production.14 In fact, the long-term fate of MPs is still unclear.1,7 Thus MP transportation and its interaction with the soil biota and mineral particles are of great interest.1,13 Methods of sampling and analyzing MPs in marine environments have been widely published; however, our knowledge of standard sampling and processing methods for MPs in soils is still insufficient. Few studies have been conducted to comprehensively analyze and characterize MPs in soils.14 In addition, soils play a significant role in human survival and development.15 There are numerous ways for MPs to enter the human food chain. For example, MPs can stick to the surfaces of root vegetables in soils and be taken up by livestock from soils, thus transferring them to the human food chain.16

In this study, we have comprehensively summarized the situation of MP pollution in soils. First, we discuss existing knowledge regarding the sources and fate of MPs in soils. Second, we provide an overview of the recent progress in extraction techniques and analytical methods for the determination of MPs in soils. Third, our understanding concerning the interactions between soil organisms, soils and MPs is evaluated. Finally, we make suggestions for future research through existing crucial challenges and issues.

**SOURCES OF MICROPLASTICS IN SOILS**

As shown in Fig. 1, anthropogenic activities are closely related to MP pollution. The sources of MPs in soils consist of inputs from compost, sewage sludge, irrigation, plastic mulching, street runoff, littering and atmospheric deposition.1,16 Furthermore, inputs from agricultural practices are sources of MPs (Table 1, Fig. 1).

In freshwater environments, the main source of MPs is wastewater, which transports plastics from various sources, such as fragmented plastics and tire debris from urban/road runoff, polymeric flocculants from wastewater treatment, fibers from washed synthetic garments and microbeads from cosmetic products and industries.19,21 The removal efficiency of wastewater treatment plants (WWTPs) depends on their size and the treatment processes employed.22 Meanwhile, many studies also found that the amount of MPs detected in sludge was higher than those found in raw and treated wastewaters.22 The most common MPs found in sludge are polyethylene (PE), polypropylene (PP), poly(vinyl chloride) (PVC), poly(ethylene terephthalate) (PET) and polystyrene (PS).23 The annual amount of MPs that enter soils through the use of sewage sludge on arable lands is larger than that released into the oceans. Furthermore, sewage sludge discharged into agricultural soils is estimated to be one of the largest sources of MPs entering the environment.21 Applying sewage sludge as a fertilizer to the soil environment leads to pollution by synthetic fibers, which are mobile and persistent. Therefore MPs possibly follow sludge and enter soils, causing risks via their leachate (Fig. 1). To examine such a hypothesis, studies have been carried out to investigate the fate and concentration of MPs in WWTPs (Table 1).11,24 Zhang and Liu6 found that ~38 080 fiber particles kg−1 dry sludge sample, accounting for 86% of each sample, were present in the sewage sludge used as organic amendment in China’s Chai river valley. A large number of organic amendments and inorganic fertilizers (~23 000 kg ha−1 year−1, dry matter) were applied in the vegetable fields of the research area.5 Corradini et al.19 (Table 1) found that when continuous sludge applications were carried out, the amount of MPs increased over time. A majority of MPs were observed in the form of fibers: 97% in soil and 90% in sludge. Therefore many countries have banned the application of sewage sludge.

Meanwhile, irrigation with wastewater has become another significant source of MPs in agricultural soil (Fig. 1). As vegetable production within plastic greenhouses5 (Table 1) involves intensive cropping, excessive fertilization and heavy irrigation, it may lead to large amounts of MPs that are capable being transported through irrigation and drainage systems. The accumulation of MPs in agricultural soils is also affected by management practices or conventions. For example, many farmers tend to heavily apply sewage sludge and wastewater to irrigate farms closer to villages because of easy accessibility.5 MPs can also come from agricultural plastic mulching (Fig. 1). Plastic film mulching (PFM) is adopted globally to enhance crop yield and water consumption efficiency by saving water, suppressing weeds, retaining soil moisture, increasing temperature and enhancing cold resistance.15,25 Over 80% of agricultural films are made of low-density polyethylene (LDPE), mainly used in greenhouse films (150–200 μm).28 The global use of PFM is substantial and has grown rapidly in recent years.27 Around 700 agricultural plastic particles kg−1 soil were found in agricultural land in Europe.28 In China, especially in north China, the application of PFM has contributed to the accumulation of MPs in agricultural lands. From 1991 to 2011, the use of PFM increased 4-fold from 0.32 to 1.25 million tons.25,29 Moreover, PFM is expected to cover more cultivation areas at a growth rate of 8–10%.25 In Mexico, plastic covers around 40–60% of the surface of home garden soils of Centla, Tabasco in order to prevent inundation.18 In Shanghai, plastic mulching has been widely applied to suburban agricultural lands for the past two decades. Liu et al.20 observed that the accumulation of MPs was 78.00 ± 12.91 items kg−1 in shallow (0–3 cm) farmland soil and 62.50 ± 12.97 items kg−1 in deep (3–6 cm) farmland soils. The difference is due to the soil profile, which results in different MP distributions, and the application period of PFM, which leads to different concentrations. In addition, the majority of MPs were PE and PP, mainly in the shape of fibers and films. This indicated that MP contamination was caused by plastic materials widely used for different applications in agriculture.20 Besides, plastic films also contain ~20–60% phthalate esters (PAEs), which can affect soil enzymatic activities and microbial communities.15,25 Although the use of PFM in agricultural lands ensures food security and income growth of farmers, considerable plastic residues in soils have severely challenged environmental protection.4 As
a result, the application of PFM is no longer regarded as ‘white revolution’ but as ‘white pollution’ in the public’s eyes. However, high costs and practical difficulties impede attempts to recycle MP residues.27

Film coating of agronomic seeds has been widely applied in modern agriculture, which not only enhances seed germination but also improves seed handling and flowability (Fig. 1). This technology employs thin adherent plastic coatings consisting of pesticides, plasticizer agents and binder. Synthetic pigments are also used in pesticide-treated seed coatings.30,31 The abrasion of such seed coatings may result in the detachment of plastic film fragments that enter the soil. Previous research found that the size of detached seed-coating fragments typically does not exceed 5 mm, with a thickness of less than 5–10 μm.30,31 Accinelli et al.31 referred to them as microplastic coating film (MPCF) fragments. Although Accinelli et al.31 noticed that MPCF fragments could not persist in soils for long, their degradation rate varied depending on the coating composition. As a result, the fate of MP coatings in soils, such as their degradation process and corresponding mobility, remains uncharted.30,31

Other potential input pathways of MPs in soils include littering, atmospheric input and street runoff (Fig. 1).20 Airborne MPs such as landfill deposits and other surface deposits may even spread into the atmosphere and enter soils or terrestrial systems through atmospheric deposition.3 For example, Dris et al.18 found a significant amount of fibers in atmospheric fallout from urban and suburban areas of Paris. It was estimated that considerable synthetic fibers, ranging from 3 to 10 t year−1, were deposited via atmospheric fallout. Besides, the atmospheric fallout showed significant differences between urban and suburban sites. The flux was correlated with the density of the surrounding population, which was an indicator of local activity (Table 1).18 In addition, the results indicated that rainfall was a significant factor that influenced the fallout flux. It remains to be explored whether the fallout flux was influenced by other mechanisms and whether it was temporal.32 However, measuring MPs via atmospheric fallout is challenging owing to the lack of studies and data, which usually addresses the issue of MP sources and fluxes in the environment. Scheurer and Bigalke14 (Table 1) showed that MPs were found even in samples from remote mountainous areas in the Swiss floodplains. In addition, MPs can also accumulate through burials, as contaminated layers are buried into alluvial soils by successive flood events.17 These findings support that diffuse sources in river or aeolian transport contribute to the supply of MPs. In addition, as the human population expands, MP pollution will increase further.

Thus MPs in soils are a significant source of plastic in the farmland system. However, their sources and fate remain to be studied in detail.
## Table 1: Studies showing source, type and concentration of MPs in soils

| Study area | MP type | MP size | Concentration | Detection method |
|------------|---------|---------|---------------|-----------------|
| Swiss floodplain soils | PE, PS, SBR, ABS, PA, PET, PP and PVC | <5 mm | 55.5 particles kg⁻¹ | FTIR + Raman spectroscopy |
| Urban and sub-urban in Paris | Fibers (mainly poly(ethyleneterephthalate)) | 200–600 μm | 593 particles kg⁻¹ | FTIR + Raman spectroscopy |
| 28 WWTPs located in Ireland | HDPE, PE, PES, acrylic, LDPE and PVC | >2 mm | 7100 particles kg⁻¹ | FTIR + Raman spectroscopy |
| Waste WWTPs in China | PP, PE and PES | 20–400 μm | 62.50 12.97 (shallow) items kg⁻¹ | Microscopy + FTIR |
| Vegetable farmlands around suburbs of Shanghai | PP, PE and PES | 0.25–0.05 mm | 6.250 ± 12.97 (deep) items kg⁻¹ | Microscopy + FTIR |

## Analytical Methods for Microplastics in Soils

Although various technical methods have been developed to study MPs in marine or freshwater systems, there is no uniform method available to qualify and quantify synthetic polymers in the soil system. Soil is a complex heterogeneous system consisting of a number of complex components such as organic matter, mineral soil and chemical ingredients. Organic matter compromises a high portion of soil with highly diverse ingredients, including residues from decomposed microorganisms and plants at different stages. MPs may be embedded into soil organic matter (SOM), as the interaction between SOM and soil minerals or other components is a complex process. This complex composition has an adverse effect not only on their detection via Fourier transform infrared (FTIR) and Raman spectroscopies but also on the efficiency of their flotation and separation. Zhang et al. reported that most significant deviation errors during the collection and recovery stages were observed in soils. The study confirmed that MP recovery was strongly influenced by high concentrations of organic matter as well as fine soil particles. Therefore a fast, high-output, facile and reliable analytical technique is required to characterize MPs in soils, despite the apparent challenges.

A typical process of analysis of MPs in soils can be divided into the following steps: (i) soil sample collection, which is a crucial step in MP analysis; (ii) density extraction and digestion of organic matter after soil samples are dried, sieved, floated, filtered and separated; (iii) visual identification of potential MPs.

### Microplastic extraction versus separation

The first step of soil sample analysis is to ground and sieve the sample. Previous research has shown that various sizes of sieves are adopted in different countries. Bläsing and Amelung recommended sieving soil samples that are below 5 mm or even 1 mm for MP analysis in order to ensure consistency. After sieving has been carried out, density separation is used to extract MPs from the remaining supernatant. Typically, saturated salt solutions such as NaCl, NaI and ZnCl₂ are used to extract MPs from the sediment of water bodies through differences in density. Yet, such a method may need fine tuning, as soil particles can significantly adsorb or embed MPs. Bläsing and Amelung and Van Cauwenberge et al. recommended using sodium polytungstate (SPT), which is capable of isolating free organic matter particulates (e.g. MPs), and SOM in various organic–mineral complexes. As the majority of agricultural PFM is made of LDPE or PP with specific density <1, PFM can float on distilled water and reduce the cleanup costs. When the density of MPs is unknown, extraction and flotation of MPs require the use of higher-density salt solutions. Saturated NaCl solution is commonly used to separate MPs from a variety of environmental matrices; however, it fails to separate PET or PVC, which have a higher density than saturated NaCl solution. From the perspective of economic cost as well as extraction efficiency, Han et al. (Table 2) recommended the use of a 1:1 mixture of saturated solutions of NaCl and NaI for optimal flotation. Given the environmental hazard of NaI, especially its embryo-toxicity to aquatic organisms, Liu et al. (Table 2) suggested the use of NaBr solution to extract MPs in soils, because NaBr is a safe, non-corrosive and inexpensive reagent for sediment separation. Fuller and Gautam (Table 2) explored a new technique based on pressurized fluid extraction (PFE) which efficiently extracted MPs from <30 μm solid materials. They showed that MPs could be extracted.
through a solution of methanol and dichloromethane. In environmental laboratories, this technique is commonly utilized to extract organic pollutants in soils, sediments and wastes. However, the extraction procedure obliterates the morphology of MPs at high temperatures; therefore this method does not retain the size of MPs, which is important to assess the toxicity, source attribution and mobility of MPs in soils. Zhang et al.33 (Table 2) also found this problem and developed a method of repetitive flotation to extract LDPE and PP MPs from agricultural soils. This method is accurate, simple and cost-saving as it only needs few a chemical samples and does not require FTIR to characterize MPs. It is worth noting that the method was only applicable to LDPE and PP.

Furthermore, as MPs have different shapes, their settling velocity is also important. Different settling speeds require varied settling time. There is still a lack of standard settling precipitation time for MP analysis in soils, and various researchers have used their own settling time. A large number of studies indicate that the settling time varies from to 2 to 48 h.20,37

| Task | Method | Specification and advantage | Drawback | Reference |
|------|--------|----------------------------|----------|-----------|
| MP extraction versus separation | Use of NaCl and NaI (1:1) as extraction reagent | Achieved a density greater than most common MP materials | Nal is hazardous to the environment | Han et al.36 |
| | Use of NaBr as extraction reagent | NaBr is economic and environmentally friendly; the method showed the highest recovery rates | — | Liu et al.37 |
| | Repetitive floatation | A floatation method using distilled water carried out at least four times, then the soil solutions were subjected to 2 h of ultrasonic vibrations; simple and cost-saving | Only for PE and PP | Zhang et al.33 |
| Identify and quantify MPs | PFE | Simplicity, cost, speed and uniformity in reporting concentration results | Inability to measure size fractions of MPs in samples | Fuller and Gautam38 |
| | TED-GC/MS | This method allowed the identification and even the quantification of polymers in different solid environmental samples without any pre-selection | Information about size distribution was lost | Dümichen et al.39,40 |
| | Vis-NIR spectroscopy | A novel, fast and scalable method to identify and quantify the amount of MPs in soil | Only for pollution hotspots | Corradini et al.41 |
| | TGA-MS | TGA-MS measurements were generally cheaper, requiring minimal sample preparation effort | Only for PET | David et al.42 |
| | SUMM | This method can determine the MP load in soil without any further detection techniques | SUMM failed to determine PE | David et al.43 |
| | Hyperspectral imaging technology and chemometrics | This method has the potential to detect MPs (0.5–5 mm) without separation from soil | Only coverage on soil surface was studied | Shan et al.44 |

Recovery of the four methods was between 93 and 98% and not significantly different; however, in terms of efficiency, the centrifugation method was much faster than other methods.

From all these studies, we can conclude that it is important to develop a versatile and efficient method for isolation of MPs in soil samples.

### Identifying and quantifying microplastics

Generally, we use microscopic techniques (mainly light microscopy) to distinguish MPs from other impurities and determine the size and quantity of MPs after extraction.33 However, it is difficult to observe MPs with diameter <1 mm. Thus only visible MPs are easily determined. Furthermore, the procedure requires labor-demanding pre-concentration and laboratory cleanliness in order to prevent false positives and other misinterpretations.42,43 On the other hand, connecting high-resolution digital cameras to microscopes enables the detection of smaller particles as well as the measurement of particle dimensions. The advantage of this method is that it is non-destructive.39 Unfortunately, visual identification of MPs is sometimes inaccurate; furthermore, the microscope itself cannot identify the detailed chemical composition of MPs without the help of FTIR and Raman spectroscopy, which use the characteristic absorption spectrum to identify the corresponding functional groups. In Raman microscopy, SOM can hide MPs and show artifacts induced by SOM autofluorescence.1 The spectral quality of FTIR spectroscopy is better than that of Raman spectroscopy, which can melt MP particles through high laser energy.14 The most suitable mode of FTIR is the transition mode, because its spectral quality is superior to that of the reflectance mode.14 However, these techniques do not

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Table 2. Detection techniques of MPs

| Task | Method | Specification and advantage | Drawback | Reference |
|------|--------|----------------------------|----------|-----------|
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| | Use of NaBr as extraction reagent | NaBr is economic and environmentally friendly; the method showed the highest recovery rates | — | Liu et al.37 |
| | Repetitive floatation | A floatation method using distilled water carried out at least four times, then the soil solutions were subjected to 2 h of ultrasonic vibrations; simple and cost-saving | Only for PE and PP | Zhang et al.33 |
| Identify and quantify MPs | PFE | Simplicity, cost, speed and uniformity in reporting concentration results | Inability to measure size fractions of MPs in samples | Fuller and Gautam38 |
| | TED-GC/MS | This method allowed the identification and even the quantification of polymers in different solid environmental samples without any pre-selection | Information about size distribution was lost | Dümichen et al.39,40 |
| | Vis-NIR spectroscopy | A novel, fast and scalable method to identify and quantify the amount of MPs in soil | Only for pollution hotspots | Corradini et al.41 |
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| | SUMM | This method can determine the MP load in soil without any further detection techniques | SUMM failed to determine PE | David et al.43 |
| | Hyperspectral imaging technology and chemometrics | This method has the potential to detect MPs (0.5–5 mm) without separation from soil | Only coverage on soil surface was studied | Shan et al.44 |
guarantee that every particle can be detected owing to the size limitation. As scanning procedures of these methods are time-consuming, these techniques are rarely used as routine analysis methods.39,40

Thus it is of interest to develop a novel technique to characterize MP distributions in soils in a rapid and accurate manner.41 The hyperspectral technique analyzes the chemical composition of each spatial pixel based on spectral information because it contains thousands of narrow spectral bands ranging from the visible to the infrared region as well as thousands of spatial pixels. Shan et al.42 (Table 2) explored the use of hyperspectral imaging technology together with chemometrics to rapidly monitor MPs in soils. In their study, Raman spectroscopy was first used to identify MPs, after which hyperspectral imaging technology was used to scan soil samples to gain spectral and imaging information. Finally, chemometrics and image-processing algorithms were adopted to characterize MPs having dimensions between 0.5 and 5 mm. Corradini et al.43 (Table 2) also explored an extraction-free method to rapidly measure MP concentrations via a portable spectroradiometer working in the 350–2500 nm near-infrared (NIR) region. This method was faster than conventional FTIR analysis as it did not require extraction and MPs could be directly quantified. This can be useful in MP quantification, given that the visible–NIR spectrum has a strong correlation with the chemical composition of MPs. However, a versatile technique that is applicable to various environments remains to be explored.

Thermogravimetric analysis (TGA) is a thermoanalytical method that can fractionate soils according to thermal (under inert atmosphere) or thermo-oxidative (under air or oxygen) stability.42 TGA has gradually drawn more attention compared with other methods. Dümichen et al.44 (Table 2) used a Berlin urban soil spiked with PE MPs to study a method based on TGA for identifying and quantifying MPs in soils. First, thermal extraction was carried out in a TGA instrument, which was connected with a solid phase adsorber that was then analyzed via thermal desorption coupled with gas chromatography/mass spectrometry (TD-GC/MS). Thermo-extraction and desorption coupled with gas chromatography/mass spectrometry (TED-GC/MS) is the first single-step technique to quantify PE in soil samples. Dümichen et al.45 (Table 2), applied the same setup for PP, PS, PET and polyamide (PA) MPs. As MP analysis in soils requires a labor-consuming sample cleanup procedure, David et al.46 (Table 2) developed a new method to directly quantify PET with no sample pretreatment step. According to their study, the use of capillary thermogravimetric analysis coupled with mass spectrometry (TGA-MS) is suitable to quantify PET MPs in standard loamy sand with an organic matter concentration of 1.61 ± 0.15%. Cysteine was adopted as an internal standard (IS); the pyrolysis ramp was 5 K min⁻¹ from 40 to 1000 °C. This method can significantly enhance signal sensitivity and linearity because it records the mass loss and pyrolysis signal intensity of the sample. However, it is necessary to develop an analytical method to analyze soils with various SOM levels and soil samples contaminated with MPs. A soil universal model method (SUMM) was developed by David et al.47 (Table 2), who used TGA to identify and quantify PET, PS and PVC MPs in standard loamy sand. In this method, the determination of MPs in soil samples did not require any pre-separation or other detection technique such as TGA-MS. However, the SUMM could not analyze MPs made of PE, which has a similar degradation temperature to SOM.

To summarize, the quantification and identification of MPs in soils remains challenging, therefore innovative analytical methods need to be developed. Standardized methodologies for sediment are needed to analyze MPs in soils. The standard sizes of sieves, saturated solutions in the density separation method and optimization of the extraction method or detection techniques based on various soil properties should be considered.

**IMPACTS OF MICROPLASTICS ON SOIL QUALITY**

**Soil properties**

As shown in Fig. 2, soils are essential environments for many physical and biological processes. Therefore the impact of MPs on soil structures is important to assess their influence on soil environments.6 Some researchers found that MPs can affect the bulk density of soils and their water-holding capacity.6,45 This is because the density of plastics is usually less than that of natural minerals in soils. Moreover, increasing concentrations of polyester fiber significantly enhanced the soil water-holding capacity in comparison with other MPs (Table 3).6 However, Zhang et al.13 (Table 3) found that polyester microfibers (PMFs) could not alter the soil bulk density. This is because the density of PMFs was too low (≤0.3%) to significantly impact the soil bulk density. They assumed that the water-holding capacity was reduced by ultrafine PMFs owing to their hydrophobic nature and size. In addition, De Souza Machado et al.48 found that increasing the polyester concentration decreased the water-stable aggregates. However, another study by Zhang et al.13 found that as PMFs increased, the water-stable macroaggregates that were larger than 2 mm also increased. It is suggested that these differences in observations are due to a combination of soil texture, soil mineralogy and entanglement of soil particles with PMFs.13 A previous study found that MPs in soil could create channels for aqueous movement and increase the water evaporation rate of soil. Soil with MPs showed desiccation cracking because of the possible destruction of soil structure.47 The impacts of MPs on the physicochemical properties of soils require further research work and laboratory observations at field scales.

De Souza Machado et al.13 suggested assessing the impact of soil property alteration due to MPs on soil organisms. Kim and An45 (Table 3) studied the response of soil organisms to contaminated soils with different MPs. Their study indicated that the presence of MPs could change the behavior of springtails in addition to the alteration of soil properties. Springtails are decomposers of earthworms in the food chain of soil systems. Their movement creates bio-pores in soils. The MPs in soils disrupted the movement of springtails because they filled these bio-pores very quickly.

The presence of MPs not only changes the physical properties of soils but changes soil fertility as well.5 Soil microorganisms produce soil enzymes of high catalytic capacity; their activity indicates the availability of substrates for uptake by microorganisms and microbial activities.7 Various researchers have reported that the activities of soil urease, catalase,46,47 phosphatase,48 phenol oxidase and fluorescein diacetate hydrolase (FDase)49 could be significantly stimulated by MPs. Furthermore, they have suggested that more information on the mechanisms requires further investigation. Dissolved organic matter (DOM) is crucial in driving soil biogeochemistry, such as the soil organic carbon (SOC) cycle and nutrient transport. DOM is a complex mixture of different labilities and accounts for less than 0.25% of the total SOM.7 Liu et al.7
found that higher levels of MP addition led to an increase in the nutrient contents of the DOM solution. The above findings show that MPs can change soil physical properties such as pore size distribution, water-holding capacity, soil bulk density and water-stable aggregates. On the other hand, MPs can also alter soil fertility. Overall, these findings offer valuable evidence to study how MPs influence soil properties; further studies may be needed to explore the various aspects (e.g. different polymer types, different soil properties, different plants) of the relationships between MPs and soils.

Microplastics as vectors for pollutants and additives in soils

As shown in Fig. 2, after plastics enter the soil environment, they release toxic plastic additives (plasticizers, retardants, antioxidants and photostabilizers), which threaten ecosystems and impact long-term soil quality. Furthermore, the weathered surfaces of MPs can act as high-capacity carriers by adhering microorganisms (pathogens) and other toxic pollutants (organic contaminants, heavy metals, pesticides, etc.) in the soil to them. Under certain conditions, the slow degradation process of plastics can release these adsorbed toxic chemicals back to the surrounding environment. Moreover, soil organisms can have access to high concentrations of MPs via ingestion; hence MPs are transported to the food chain and act as potential vectors that may carry pathogens and contaminants in soil systems. Therefore MPs, which act as vectors for these chemicals, move along with soil particles and not only threaten the aquatic environment but also the soil environment.

Plastic additives

PAEs are widely used plasticizers that are frequently found in soils. In Xinjiang Province, China, a PAE concentration as high as 510 mg kg$^{-1}$ was detected in cotton fields because of the long-term use of plastic films for cotton cultivation. The biological effects and various toxic effects of PAEs, such as teratogenicity, mutagenicity and carcinogenicity, have drawn increasing public discussion and concern. Six PAEs, namely dimethyl phthalate (DMP), dibutyl phthalate (DBP), di(2-ethylhexyl) phthalate (DEHP), diethyl phthalate (DEP), butyl benzyl phthalate (BBP) and di-n-octyl phthalate (DnOP), are the top environmental pollutants on the list of the US Environmental Protection Agency. In some cases, MPs can serve as vectors for PAEs, which are additives of plastic mulch, and release them directly to the environment. Increasing use of plastic films has already raised public concern about the potential health risk of PAEs through the food chain. Li et al. found that the concentration of 16 PAEs in Shandong Peninsula, China was ~6.470 mg kg$^{-1}$ on average, ranging from 1.374 to 18.810 mg kg$^{-1}$. Moreover, when the impact of PFM on soils was assessed, the study found that DMP, DEP and
| MP type | Options and details | Soil | Sampling location | Methodology | Soil physicochemical analysis | Reference |
|---------|---------------------|------|------------------|-------------|-------------------------------|-----------|
| PP      | The density of MP was 0.91 g cm\(^{-3}\), with a bending strength of 200 kg cm\(^{-2}\) | Loessial soils | Loess Plateau, China | A soil incubation experiment was carried out in a chamber with controlled climate with three levels of MP added to loess soil | Dissolved organic carbon, dissolved organic nitrogen, \(\text{NH}_4^+\), \(\text{NO}_3^-\), dissolved organic phosphorus, \(\text{PO}_4^{3-}\), fluorescein diacetate hydrolase (FDAse) and phenol oxidase activities | Liu et al. \textsuperscript{7} |
| PE      | 2 mm × 2 mm fragments (thickness 0.01 mm) | Cinnamon soil | Beijing, China | Exposed soil to MPs (90 days) | Soil catalase, urease and invertase activities | Huang et al. \textsuperscript{46} |
| Polyacrylic fibers, PA beads, PES fibers and PE fragments | Produced | Loamy sand soil | Berlin, Germany | Exposed a loamy sand soil to four common MP types (5 weeks) | Bulk density, water-holding capacity, hydraulic conductivity, soil aggregation and microbial activity | De Souza Machado et al. \textsuperscript{6} |
| Polyester microfiber (PMF) | <5 μm, average length 2.65 mm | Clayey soil | Yunnan, China | A field experiment for 1 year; a pot experiment for six wet–dry cycles | Bulk density, porosity, hydraulic conductivity and aggregation | Zhang et al. \textsuperscript{13} |
| PS, PE  | 0.47–0.53, 27–32 and 250–300 μm | LUFA standard soil type no. 2.2 (Landwirtschaftliche Untersuchungs- und Forschungsanstalt Speyer, Germany) | Ilsan, Korea | Exposed springtails (\textit{Lobella sokamensis} Deharveng and Weiner) to MP-contaminated soils | FTIR, SEM | Kim and An \textsuperscript{46} |
### Table 4. Studies showing different arguments regarding role of MPs as vectors of pollutants and additives to soil (or soil organisms)

| MP type           | MP size | Soil Description                                      | Pollutant Description                                      | Additive | Organism/plant          | Technique for detection of contaminant | Reference  |
|-------------------|---------|-------------------------------------------------------|-------------------------------------------------------------|----------|-------------------------|----------------------------------------|------------|
| Plastic film      | —       | Soil samples collected from vegetable fields          | —                                                           | —        | —                       | GC/MS                                  | Li et al.  |
| PUR foam microparticles | —   | Artificial soil                                        | PBDE                                                         | —        | Earthworms (Eisenia fetida) | GC/MS                                  | Gaylor et al.  |
| —                 | —       | Agricultural surface layer soils                       | DBP                                                          | —        | Vegetable seeds (Brassica napus) | 16S rDNA MiSeq high-throughput sequencing, HPLC analysis | Kong et al.  |
| PVC               | 1 mm    | Anaerobically digested sludge                          | —                                                           | BPA      | —                       | GC/MS                                  | Wei et al.  |
| Polyolefin film   | <1 mm   | Tetracycline–MP mixed contaminated soil                | TC, ARG                                                      | —        | Soil bacteria, soil phages | HPLC/MS/MS (Waters Acquity UPLC system), spectrophotometric analysis | Sun et al.  |
| LDPE              | <250 μm | Sandy loam                                             | Atrazine (Atz), 4-(2,4-dichlorophenoxy) butyric acid (2,4-D) | —        | —                       | Inverse liquid chromatography          | Hugerer et al.  |
| LDPE              | 25, 100 μm | Horticultural soil                                      | Endosulfan, chlorpyrifos, procymidone, trifluralin and deltamethrin | —        | —                       | GC-ECD                                 | Ramos et al.  |
| PE, PS            | ≤300, ≤250 μm | Clean agricultural soil sample (sandy loam)          | PAH: phenanthrene (PHE), fluoranthene (FLA), pyrene (PYR) and benzo[α]pyrene (BαP); PCB: PCB52, PCB70 and PCB153 | —        | Earthworms (Eisenia fetida) | GC/MS                                  | Wang et al.  |
| HDPE              | 0.92 ± 1.09 mm² | Arable and woodland soil                               | Zn                                                           | —        | Earthworms (Lumbricus terrestris) | FTIR                                   | Hodson et al.  |
di-n-butyl phthalate (DnBP) exceeded the maximum allowable concentrations by 63.9–100% at various soil depths. Kong et al.49 (Table 4) reported that bacterial growth was depressed under high DBP concentrations, except in the case of DBP-degrading bacteria. As a result, the diversity of the bacterial community dropped, even though the total numbers of bacteria increased. Besides, vegetable roots can also absorb DBP, which can suppress the growth and health of vegetables.49

Polybrominated diphenyl ethers (PBDEs) are widely used in consumer plastics at high loading dosage as flame retardant agents and can be transported into soils through polymer fragmentation or sewage sludge-derived biosolids. There is limited research on the uptake of PBDEs from these materials by soil organisms.50 Gaylor et al.50 (Table 4) observed that PBDEs become bioaccessible following volatilization or polymer deterioration, and PBDEs that leach from polyurethane (PUR) foam (<75 mm) may end up in soil invertebrate organisms.

Bisphenol A (BPA), which is an extremely predominant additive, is highly toxic to microbes and can be traced back to PVC MPs. PVC is a plastic that is widely regarded as the most hazardous MP, with strong mutagenicity and carcinogenicity in sludge.23 Wei et al.23 (Table 4) observed that the influence of PVC MPs on methane production from waste activated sludge in anaerobic digestion. Their results showed that BPA leaching from MPs was the primary reason for decreased methane production, causing significant inhibitory effects on the hydrolysis–acidification process.

Toxic pollutants

Conventional high-density polyethylene (HDPE) bags are lightweight single-use carrier bags used in many countries. Most bags ultimately end up in landfills. However, these single-use bags are also common items of litter along roadsides in urban and rural environments, where they may can come into contact with common roadside contaminants such as metals.54 Therefore it is important to study the interaction between metals and microplastics and evaluate the risk that both pose to soil organisms. Zinc (Zn) is an essential element for earthworms; however, at elevated concentrations (>200 mg kg⁻¹), it can have a toxic effect. In adsorption and desorption experiments, Hodgson et al.54 (Table 4) showed that there was the potential for MPs to accumulate metals, but competitive adsorption with soil particles results in relatively low levels of metal sorption. In addition, their exposure experiment suggested that earthworms did not avoid the ingestion of Zn-laden MPs, and that there was no preferential ingestion of MPs.

To increase vegetable production and farming profits, various measures have been employed, such as the use of organic fertilizers and plastic films. At the same time, simultaneous application of plastic films and organic fertilizers has resulted in mixed contamination of MPs, antibiotics, antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs).51 This emerging mixed contamination in greenhouse soils has made the control of ARG transmission a novel challenge. It has been observed that bacteriophage (phage) transduction might be a crucial way for ARG transmission. Sun et al.51 (Table 4) showed that the existence of MPs significantly inhibited the dissipation of tetracycline (TC) and ARGs in soils, but sophorolipid could break the barrier caused by MP adsorption and exert a positive impact on the stimulation of the natural attenuation of soil TC.

Considering that pesticides are an important component of horticultural soils, Ramos et al.29 (Table 4) studied the interaction between MPs, soils and pesticides. They found that pesticides could not only migrate from the surface to the interior of plastic films without the assistance of an organic solvent, but could also migrate to soils and concentrate in them. Also, Hüffer et al.52 (Table 4) found that PE MPs reduced soil sorption capacities, which might increase the mobility of organic contaminants in soils and reduce the natural retention capacity of soils. This was likely to increase the risk of organic contaminants reaching groundwater, thereby presenting an additional risk to human health. Several studies have also shown that MPs can affect the transport of organic contaminants such as hydrophobic organic compounds (HOCs), as their sorption behavior can differ from that of organic matter and minerals in soils. However, Wang et al.53 (Table 4) suggested that MPs did not act as vectors to enhance contaminant uptake, but that the competitive sorption of MPs resulted in decreased bioavailability of HOCs in soil pore water. The biodynamic model analysis confirmed that ingestion of MPs contributed negligibly to contaminant bioaccumulation. These results on sorption behavior have been inconsistent, which could partly be related to different study methods. Thus sorption of organic compounds to MPs in the soil environment warrants further study.

MPs act as vectors for pollutants and plastic additives when ingested by the biota and, in this way, adsorbed pollutants and toxic additives may be introduced to the food chain.1 It is also important to properly investigate sorption mechanisms.55 In sorption experiments of Seidensticker et al.55 sorption to plastic particles was stronger for hydrophobic compounds. Moreover, neutral species usually contribute more to the overall sorption. Zhang et al.56 also found that pH affects the sorption between microplastic PS foam and oxytetracycline. Furthermore, Hüffer et al.52 showed that the effect of pH is mainly driven by changes in sorbate properties rather than changes in PE surface properties. The interactions of MPs with HOCs in soil further depends on the physicochemical properties of HOCs, such as hydrophobicity.57 From these results, we can conclude that some factors affect adsorption, but more factors affecting the adsorption behavior of soil MPs should be considered.

Although many studies have focused on the sorption of organic compounds to MPs in the marine environment, their sorption in soils is scarcely studied, except for the direct impacts of MPs on organisms; MPs can act as vectors by transferring other pollutants or plastic additives into the body of organisms.54 Furthermore, MPs can increase pollutants and the bioavailability of plastic additives. Thus it is necessary to determine the content and distribution of MPs in agricultural soils (Fig. 2).53

**ECOLOGICAL RISKS OF MICROPLASTICS ON SOIL ORGANISMS**

Numerous investigations have suggested the potential impacts of MPs on marine species. In contrast, limited research has been conducted on the effects of MPs in soils.1 Only a few studies have dealt with the ecological risks of MPs to soil organisms and the toxic effects of MPs on soil organisms, indicating that soil organisms can ingest and transport MPs in soils, resulting in unwanted impacts on these soil organisms.57

**Soil microbial communities**

Many investigations have indicated that MPs in the marine environment constitute a unique microbial habitat known as the ‘plastisphere’.58 The diversity and composition of microbial communities in soils, similar to marine organisms, are critical in
| MP type       | Options and details | MP size          | Sampling location       | Test species                  | Experimental conditions | Experimental conditions | Main analytical method or assessment point | Reference |
|--------------|---------------------|------------------|-------------------------|-------------------------------|-------------------------|-------------------------|------------------------------------------|-----------|
| PP           | From plastic film or products | <250 mm          | North Shaanxi Province, China | —                             | Topsoil of a farm       | Microcosm experiment over 30 days incubation | Glyphosate/AMPA analysis, microbiology activity measurement (respiration and enzymatic) | Yang et al. |
| PVC          | Produced            | 80–250 μm        | Denmark                 | Collembolan (Folsomia candida) | Control: 0 g MPs kg⁻¹ dry soil; MP exposure: 1 g MPs kg⁻¹ dry soil | Clay loam              | Exposed collembolans to MPs              | Detection of MPs (FTIR), DNA isolation (1.0% agarose gel electrophoresis and spectrophotometric analysis), 16S rRNA gene amplification, high-throughput sequencing and bioinformatic analysis | Zhu et al. |
| Nano-polystyrene | Produced          | 0.05–0.1 mm      | China                   | Enchytraeus crypticus        | 0, 0.025, 0.5 and 10% (dry weight basis) | —                      | Directly exposed soil oligochaete E. crypticus to nanoplastics | 16S rRNA amplification and high-throughput sequencing | Zhu et al. |
| LDPE         | Produced            | 200–300 and <150 μm | Netherlands | Anecic earthworm (Lumbricus terrestris) | 7, 28, 45 and 60% dry weight | Sandy soil              | Directly exposed earthworm L. terrestris to MPs | Mortality, growth, reproduction and tunnel formation at various concentrations of MPs in litter deposited at the soil surface; the rate of ingestion of MPs and the resulting content in the casts | Huerta Lwanga et al. |
| LDPE         | Produced            | 200–300 μm       | Netherlands | Anecic earthworm (Lumbricus terrestris) | 7, 28, 45 and 60% w/w | Sandy soil              | Worms were exposed to soil surface litter treatments containing MPs | Bioturbation efficiency ratio, biomass, burrow formation, burrow characteristics and biogenic transport | Huerta Lwanga et al. |
| LDPE         | Produced            | 150 μm           | Netherlands | Anecic earthworm (Lumbricus terrestris) | 7, 28, 45 and 60% dry weight | Sandy soil              | Bacteria isolated from the earthworm’s gut were used in a short-term microcosm | Bacterial sequencing and identification, bacterium enumeration, volatile trapping and | Huerta Lwanga et al. |
| MP type          | Options and details                                                                 | MP size                  | Sampling location | Test species                | Experimental conditions                                                                 | Methodology                                                                 | Main analytical method or assessment point                                                                 | Reference |
|------------------|-----------------------------------------------------------------------------------|--------------------------|-------------------|-----------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------|
| LDPE; Bio        | Biodegradable plastic film consisted of 37.1% pullulan, 44.6% poly(ethylene terephthalate) (PET) and 18.3% poly(butylene terephthalate) (PBT) | 1 mm–500 μm (12.5%), 500–250 μm (62.5%), 250–50 μm (25%) | Netherlands        | Wheat seeds (Triticum aestivum), anecic earthworm (Lumbricus terrestris) | 1% (w/w) Sandy soil experiment performed with gamma-sterilized soil with or without LDPE MPs | measurement and MP decay determination | Plant height, number of tillers and fruits, stem diameter, number of leaves, leaf area and relative chlorophyll | Qi et al.27 |
| PA, PES, HDPE, PP, PS, PET | Beads (PA), fibers (PES), spheres (HDPE, PP), cylinders (PS, PET) | 15–20 μm (PA), 8 μm (PES), 2–3 mm (HDPE, PP, PS, PET) | Berlin, Germany | Spring onion (Allium fistulosum) | 0.2% of soil fresh weight (PES), 2.0% of soil fresh weight (PA, HDPE, PP, PS, PET) | Evapotranspiration, computed bulk density, water-stable aggregates | De Souza Machado et al.67 |
| PS               | Purchased from Sigma-Aldrich (USA)                                                | 50–80 μm                 | Shandong Province, China | Earthworm (Eisenia fetida) | 0, 0.25, 0.5, 1 and 2% (w/w) 40% sea sand and 60% soil | Directly exposed earthworms (E. fetida) to MPs | Growth parameters and mortality of earthworms | Cao et al.64 |
| PE               | Linear low density                                                                | 250–1000 mm              | —                 | Earthworm (Eisenia fetida) | 0, 62.5, 125, 250, 500 and 1000 mg kg⁻¹ dry soil OECD artificial soil | Directly exposed earthworms (E. fetida) to MPs | Reproduction, survival and growth of adults; histopathology and FTIR-ATR were performed to observe MPs | Rodriguez-Seijo et al.10 |
| PE, PS           | Produced                                                                          | ≤300, ≤250 μm            | Southern California | Earthworm (Eisenia fetida) | 0, 1, 5, 10 and 20% clean agricultural | Directly exposed earthworms (E. fetida) to MPs | Growth of earthworms, enzyme activity assays; fluorescent microscopy | Wang et al.53 |
terms of sustaining the normal functions of soils. Thus one of the most important biological indicators of soil quality change is the composition and activity of soil microbial communities, as they are the main decomposers of fresh organic matter, which influences various cycles in the soil, such as carbon cycling and nitrogen cycling.\textsuperscript{7,29} Thus we need to know the relationship between MPs and soil microbes to understand the impact of MP pollution on soils.

MPs impact soil microbial communities by influencing soil physical properties and nutrient conditions.\textsuperscript{16,46,58} According to Yang et al.\textsuperscript{48} the addition of MPs could particularly increase the soil microbial respiration rate by affecting the soil porosity and air circulation.\textsuperscript{59} Furthermore, MPs in soils may choose soil microbial assemblages that differ dramatically from those of natural substrates and surrounding soil.\textsuperscript{58,61,62} For example, several studies have shown that MPs may influence the soil conditions to maintain the abundance of soil microbes such as Proteobacteria, Bacteroidetes, Gemmatimonadetes, Actinobacteria and Nitrospirae.\textsuperscript{16,46,58} The enrichment of Bacteroidetes in MP-contaminated soils may be due to the change in soil DOM content.\textsuperscript{46} Many members of Proteobacteria, which prefer to colonize nutrient-rich and low-bulk-density soils, were also enriched in MP-contaminated soils.\textsuperscript{63} Thus soil moisture may be the reason for Gemmatimonadetes to significantly enrich MP-contaminated soils.

Furthermore, colonization of MPs by potential plastic-degrading bacteria has also been observed in soils. Huang et al.\textsuperscript{46} found that Actinobacteria were specially enriched in PE MPs. Moreover, previous studies have shown that some members of Actinobacteria (e.g. \textit{Streptomyces iakyrus}, \textit{Streptomyces humidus}, \textit{Streptomyces werraensis} and \textit{Streptomyces misionensis}) may be capable of degrading synthetic polymers. Zhang et al.\textsuperscript{58} have shown that MPs that are originally from mulching films prove to be a unique habitat for certain soil microbes, thus enriching the bacterial groups involved in their own biodegradation. In addition to the potential plastic-degrading bacteria, MPs might lead to potential risks of pest infestation. For example, members of the family Nocardiaceae, which are potential opportunistic pathogens of humans, were observed on MPs in the soil environment.\textsuperscript{46}

In summary, the addition of MPs may alter the soil microbes and increase the number of degrading bacteria. When soil microbes are exposed to MPs, especially to high concentrations for extended times, they show decreased fecundity as well as growth rate, indicating potential adverse effects of MPs on the soil ecosystem (Fig. 2).\textsuperscript{28} In order to expand our knowledge in this area, more studies are needed to implement a comprehensive sampling scheme that includes more regions, soil organisms and crop systems. This would largely benefit our understanding of the alteration of MPs on soil function and nutrient cycling.\textsuperscript{58}

### Soil organisms

So far, many researches have focused on the interactions between soil MPs and soil organisms.\textsuperscript{21} First, the fitness of soil organisms is significantly influenced by the MP pollution concentration as well as the exposure time. \textit{Lumbricus terrestris} is an earthworm that feeds on soil surface litter and moves into the lower part of the soil, forming burrows. According to Huerta Lwangh et al.\textsuperscript{32} when earthworms were exposed to high concentrations of MPs (such as 28, 45 and 60\% w/w MPs in litter), their growth rate and weight decreased. On comparing a 60-day treatment versus a 14-day treatment, their mortality was found to be much higher in the 60-day one. Similarly, Cao et al.\textsuperscript{64} found that MPs impacted the

| Table 5. Continued |
|---------------------|
| **MPS** | **Options and details** | **MP type** |
| Virgin PET fibers, Nile red-stained PET fibers | China | PET |
| **Test species** | **Sampling location** | **Soil sample(s)** |
| Achatina fulica | Land snail (Achatina fulica) | soil sample(sandy loam) |
| **Experimental conditions** | **Methodology** | **Main analytical method or assessment point** |
| dry weight | Soil sample(sandy loam) | Soils were mixed 2:1 with sand |
| MP size | **MP type** | PET fibers, Nile red-stained PET fibers |
| 0.014, 0.14 and 0.71 g kg\textsuperscript{-1} dry soil | Soil sample(sandy loam) | Assay for food intake, excretion and shell changes, histopathology investigations and quantification of oxidative stress; SEM was performed to observe MPs |

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fitness of earthworms (Eisenia fetida) when the exposure concentration was lower than 0.5% (w/w). However, when the exposure concentration was increased to 1 and 2%, a significant inhibition effect was observed on their growth, with a significant increase in mortality. However, the impact of MP pollution on the reproduction of soil organisms was hardly observed, even with higher MP pollution concentrations. In addition, a high rate (20%) of MPs significantly increased the activity of peroxidase and catalase and inhibited the activity of superoxide dismutase (SOD) and glutathione S-transferase (GST) in the soil. This result suggests that MPs and their resulting oxidative stress could damage tissues (Table 5). Similarly, Song et al. found that MP exposure can reduce the total antioxidant capacity (T-AOC) and glutathione peroxidase (GPx) activity and elevate malondialdehyde (MDA) levels in snail liver tissues. Thus previous findings indicated that MP toxicity could be caused by oxidative damage, which has a damaging impact on soil organisms’ growth as well as fitness.

Furthermore, various researchers have indicated that soil organisms (e.g. L. terrestris, Folsomia candida and Eisenia fetida) can accumulate MPs, and they contribute to the ingestion as well as transportation of MPs in soils (Table 5). Huerta Lwanga et al. thought that this transportation was size-selective and could result in groundwater pollution and affect the food webs in the soil ecosystem. Furthermore, Huerta Lwanga et al. observed that chickens ingested macroplastics on the soil surface in home gardens, as MPs were found in chicken organs (i.e. gizzards). This could be a serious issue, because chickens are one of the most highly consumed food sources globally. Thus consumption of MP-polluted chickens could negatively impact human health at higher exposure concentrations.

Soil invertebrates are important to sustain the quality of soils. However, the importance of the gut microbiome in soils has only recently been recognized. Recent findings indicate that MPs have adverse effects on soil organisms, resulting from their great accumulation inside the gut of soil organisms, which further influences the development of organisms and their feeding behavior. According to Rodriguez-Seijo et al. (Table 5), concentrations of MPs did not impact survival, the number of juveniles or the final weight of adult earthworms after 28 days of exposure. However, there was much evidence indicating damage to the gut and immune system. For example, Zhu et al. indicated that the microbiota in the collemboian gut changed and the bacterial diversity increased when exposed to MPs. Zhu et al. observed that nanoplastics (NPs) reduced the body size and weight of F. candida and negatively impacted its growth and reproductive fitness. They also found that when soil organisms were fed 10% MPs, there was a significant shift in their gut microbiota. In addition, a recent study conducted by Huerta Lwanga et al. found that the bacterial consortium isolated from the earthworm’s gut could contribute to the degradation of LDPE and generate many volatile compounds, including octadecane and eicosane. These compounds were the byproducts of LDPE MP decay, which plays an important role in ecosystem functions. Thus the gut microbiota of soil fauna plays a key role in soil decomposition processes. Further studies are needed to investigate the effect of MPs on the gut microbiota.

Some researchers have indicated that wastes from mulch films could damage the quality of soils and affect soil organisms; thus biodegradable plastic mulch films were invented to control the accumulation of plastic residues. These are advantageous over traditional plastic mulch films such as LDPE (Table 5). However, Qi et al. found that (i) biodegradable plastic mulch film residues showed severe effects on wheat growth compared with LDPE film residues and (ii) the presence of earthworms alleviated the impairment caused by MPs, thereby positively altering the wheat growth status. From these findings, we can conclude that the growth rate of wheat could be impacted by this type of biodegradable MP, which is widely utilized and available in the market. With the development of the bioplastic film market, many researchers have studied new biodegradable plastics to replace traditional agricultural mulch films. Thus the effects of these newly developed biodegradable plastics as sources of MPs in the soil system should be studied further. Compared with other relevant studies by Huerta Lwanga et al., earthworm mortality was relatively high in this study, which may indicate the need for earthworms, including different types and species, and plants in the soil system. This could help understand how MPs interact with different soil organisms. Recently, De Souza Machado et al. also investigated the possible effects of MPs using a terrestrial plant-soil model. They revealed that soil bulk density, water-stable aggregates and rhizosphere were affected when exposed to MPs at different concentrations. This triggered a series of changes in the soil organism behaviors, growth, plant biomass and root traits. However, MPs with variable features such as variable size and composition could lead to dramatic consequences on soils and plants. This indicates that MP contamination in soils may affect plant performance, thereby affecting agroecosystems and soil biodiversity. Nevertheless, some studies have focused on the impacts of MP pollution on different plants.

In summary: (i) MP exposure at high concentrations could inhibit the growth of soil organisms and increase the mortality rate of soil organisms; (ii) soil organisms could transfer MPs that are deposited at the surface of the soil to much deeper parts inside the soil, resulting in potential accumulated pollution; (iii) oxidative damage was one of the mechanisms of MP toxicity; moreover, MP pollution in soils could damage the growth rate as well as the fitness of soil organisms; (iv) different food chains contributed to the uptake of MPs; (v) extended exposure to MPs, especially at higher concentrations, could damage the feeding and excretion mechanisms of soil organisms; (vi) MPs may alter plant growth status. Thus MP pollution in soils could have adverse effects on the fitness of soil organisms. Further research is needed to study the mechanisms behind these effects, besides understanding the negative impacts of MPs on various animals (Fig. 2).

**PERSPECTIVES FOR FUTURE STUDIES**

Important advances have been made with respect to the occurrence and impacts of MPs in the ocean environment. However, knowledge on MPs in the soil environment is still limited. This article summarizes the existing studies on soil MPs. As there are many unanswered questions, we suggest that future studies should consider the following topics.

Possible plastic sources should be identified in order to reduce the amount of plastics that are accumulated or transformed in soils. At the same time, future research should strengthen data collection with respect to concentrations, volumes, types and compositions of MPs in different soil environments. In addition, wind could transport and deposit MPs on buildings or plant surfaces. Thus more research is required to investigate these atmospheric fibers and identify their original sources. This can help study the wider domain of MP research.

Because of the unique characteristics of soil media, the quantification and identification of MPs in soils is a challenge and the
analytical techniques required for this analysis still need to be innovated.9 Besides, environmental regulators need such analytical analyzing techniques in order to quantitatively identify MPs in soils rapidly and accurately, which will enable timely monitoring of MPs in oceans or soils in order to determine priority investigation areas.38

For long-term development, the chances that MPs in soils will turn into NPs are high. For example, NPs found in the ocean have proven to impact on the feeding behavior, growth and reproduction of several aquatic organisms. There are risks that humans would also be affected by ingesting plants from these aquatic ecosystems. Therefore the development of the quantification of NPs is highly needed.7 In the long term, NP pollution might have potentially important effects on the biodiversity of soil systems.65

Residual plastic film mulch pollution has become a serious issue. Large amounts of residual plastic film have detrimental effects on soil structure, water and nutrient transport and crop growth, thereby disrupting the agricultural environment. To control this pollution, governments urgently need to (i) raise plastic film standards and (ii) invest in biodegradable mulch films and multifunctional mulch recovery machinery that will control and manage residual mulch pollution.25 However, based on the study by Qi et al.,27 biodegradable plastic mulch films in agriculture with commercial-scale production still need to be further evaluated. Therefore (iii) we need to test the safety and reliability of biodegradable mulch films.

Our understanding of the implications of MPs in soil food webs is still limited.9 Thus various scenarios could occur in real environments. To understand these, the interactions between MP accumulation and different plants, as well as the risk assessment of particle uptake by these plants, should be further investigated.29 Furthermore, the influence of MPs as vectors of pollutants and additives in soils should be studied.52 Besides earthworms that have been studied as test species, other small soil invertebrates, including enchytraeids, nematodes and termites, need to be studied, as they also have the ability to ingest and transport MPs or NPs. Song et al.68 suggested that land snails might be utilized as biomonitors to study MP pollution. Therefore further research is required on the impact of MPs on diverse organisms and microorganisms.

**ABBREVIATIONS**

| Acronym | Description |
|---------|-------------|
| ARB     | antibiotic-resistant bacteria |
| ARG     | antibiotic resistance gene |
| BBP     | butyl benzyl phthalate |
| BPA     | bisphenol A |
| DEBP    | di(2-n-butoxyethyl) phthalate |
| DBP     | dibutyl phthalate |
| DCB     | diclohexyl phthalate |
| DEEP    | di(2-ethylhexyl) phthalate |
| DEHP    | di(2-ethylhexyl) phthalate |
| DEP     | diethyl phthalate |
| DHP     | di-n-hexyl phthalate |
| DiBP    | diisobutyl phthalate |
| DMGP    | dimethyglycol phthalate |
| DMP     | dimethyl phthalate |
| DMPPP   | di(4-methyl-2-pentyl) phthalate |
| DnBP    | di-n-butyl phthalate |
| DnOP    | di-n-octyl phthalate |
| DNP     | di-n-nonyl phthalate |
| DOM     | dissolved organic matter |
| DPhP    | diphenyl phthalate |
| DPP     | dipentyl phthalate |
| FDase   | fluorescein diacetate hydrolase |
| FTIR    | Fourier transform infrared |
| GC/MS   | gas chromatography/mass spectrometry |
| GPx     | glutathione peroxidase |
| GST     | glutathione S-transferase |
| HDPE    | high-density polyethylene |
| HOC     | hydrophobic organic compound |
| IS      | internal standard |
| LDPE    | low-density polyethylene |
| MDA     | malondialdehyde |
| MPCF    | microplastic coating film |
| MP      | microplastic |
| NIR     | near-infrared |
| NP      | nanoplastics |
| PA      | polyamide |
| PAE     | phthalate ester |
| PBDE    | polybrominated diphenyl ether |
| PE      | polyethylene |
| PES     | polyester |
| PET     | polyethylene terephthalate |
| PFE     | pressurized fluid extraction |
| PFM     | plastic film mulching |
| PMF     | polyester microfiber |
| PP      | polypropylene |
| PS      | polystyrene |
| PUR     | polyurethane |
| PVC     | poly(vinyl chloride) |
| SEM     | scanning electron microscopy |
| SOC     | soil organic carbon |
| SOD     | superoxide dismutase |
| SOM     | soil organic matter |
| SPT     | sodium polytungstate |
| SUMM    | soil universal model method |
| T-AOC   | total antioxidant capacity |
| TC      | tetracycline |
| TDS     | thermal desorption coupled with gas chromatography/mass spectrometry |
| TED     | thermo-extraction and desorption coupled with gas chromatography/mass spectrometry |
| GC/MS   | thermogravimetric analysis |
| TGA     | thermogravimetric analysis coupled with mass spectrometry |
| WWTP    | wastewater treatment plant |

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