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Review

Environmental fate and impacts of microplastics in soil ecosystems: Progress and perspective

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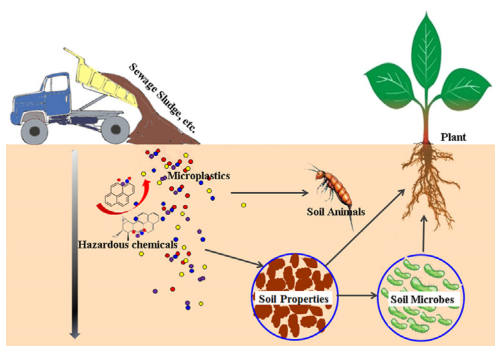
HIGHLIGHTS

- Microplastics monitoring data in soil systems are currently insufficient.
- Standardized analytical methods for soil microplastics are still lacking.
- Microplastics can affect soil physicochemical properties and biota.
- Future studies on occurrence and impacts of microplastics in soils are required.

GRAPHICAL ABSTRACT



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ABSTRACT

The wide and intensive application of plastics and their derived products has resulted in global environmental contamination of plastic waste. Large-sized plastic litter can be fragmented into microplastics (<5 mm), which have attracted increasing concerns from the general public and scientific communities worldwide. Until recently, the majority of microplastics research reported in literatures has been focusing on the aquatic settings, especially the marine environment, while information about microplastics contamination in terrestrial soil systems is highly insufficient. In this paper, we reviewed the latest data regarding the occurrence of microplastics in terrestrial soils and discussed their potential pathways into the soil environment. We also summarized the currently used methodologies for extraction and characterization of microplastics in soil matrices and evaluated their advantages and limitations. Additionally, we assessed the ecotoxicological consequences of microplastics contamination on soil ecosystems, including the effects on soil physiochemical properties, terrestrial plants, soil fauna, and soil microbes. Finally, based on the most current progress summarized in this review, we suggested several directions for future research on microplastics in soil ecosystems.

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1. Introduction

Plastics are versatile, durable and cost-efficient materials, and have been applied in a wide range of strategic sectors including packaging, building and construction, automotive manufacture, electronics, and agricultural production (PlasticsEurope, 2018). The extensive applications of plastics boost the production of these synthetic materials, as a result, alarming amount of plastic litters are disseminated into the environment (Geyer et al., 2017; Jambeck et al., 2015). The estimated global production of plastics was 348 million tons in 2018 (PlasticsEurope, 2018). As of 2015, >6,000 million tons of plastic waste had been generated with roughly 80% of the plastic waste ending up in landfills or being released into the environment (Geyer et al., 2017; PlasticsEurope, 2018). Accumulation of plastic litters has been found in multiple environmental compartments across the globe (de Souza Machado et al., 2018a; Rezania et al., 2018), where they are subjected to progressive fragmentation driven mainly by ultraviolet radiation and mechanical abrasion (Barnes et al., 2009). Unfortunately, the fragmentation process cannot completely decompose the plastic debris, rather, transform them into a myriad of smaller sized plastic particles including microplastics defined as the dimensions of < 5 mm (Arthur et al., 2009; Thompson et al., 2004).

Recently, microplastics pollution has attracted significant attention from the general public and scientific communities worldwide, with special emphasis on the aquatic settings especially in the marine environment (Auta et al., 2017; Rezania et al., 2018). The prevalence of microplastics in oceans has been attributed primarily to continuous inputs and fragmentation of large plastic litters (Auta et al., 2017), the majority of which are believed to originate from terrestrial emissions (Jambeck et al., 2015). Compared with the oceans, terrestrial domains such as soils are more susceptible to plastics contamination. It was estimated that the annual input of microplastics from land application of sewage sludge/biosolids into agricultural lands could exceed the total amount of microplastics currently floating on the global oceans (Nizzetto et al., 2016). Nevertheless, due to the lack of appropriate analytical protocols to detect microplastics in soils, the monitoring data regarding the occurrence and distribution of microplastics in soil environments are currently highly lacking. A better knowledge on microplastics present in soils is prerequisite for scientific assessment of the potential impacts of these emerging contaminants on soil ecosystems.

Microplastics in aquatic environments could be ingested in a broad range of aquatic species such as oligochaeta, crustacea, mollusca, nematode, and vertebrate (Desforges et al., 2015; Hurley et al., 2017; Lei et al., 2018b; Van Cauwenberghe et al., 2015). Ingestion of microplastics and plastic-derived chemicals (e.g., plastic additives and adhered contaminants) has been well documented to relate with a variety of toxicological effects including inflammatory responses, metabolic disorders, growth inhibition, reproduction problems, and even death (Besseling et al., 2013; Lei et al., 2018b; Ma et al., 2016). Such scenarios are also expected to occur for soil biota. Recently, some soil detritus feeders such as earthworms and soil springtails have been observed to ingest microplastics, and consequently suffer from health problems (Huerta Lwanga et al., 2016; Kim and An, 2019; Rodriguez-Seijo et al., 2017). Although there is a large uncertainty about the underlying mechanisms, first data suggest that the presence of microplastics in soils could also lead to consequences to soil properties, plant performance, and microbial activities (de Souza Machado et al., 2018b, 2019; Liu et al., 2017; Zhang et al., 2019). However, research on the impacts of microplastics to soil ecosystems still remains limited. Thus, there is a need to understand the current research status in order to guide the future studies on this issue.

In this paper, we aim to collate the currently available studies on the occurrence, sources, analytical methods, and ecotoxicological effects of microplastics in terrestrial soil ecosystems. Based on these studies, we point out the current knowledge gaps and propose several perspectives for the future research.

2. Literature review

We conducted a comprehensive literature review to retrieve publications on microplastics research in soil ecosystems using databases of ScienceDirect (https://www.sciencedirect.com) and ISI Web of Science (http://www.webofknowledge.com). The literatures were searched for studies published before June 2019 with the keywords of "microplastics" or "plastics" in conjunction with "soil" or "terrestrial". We also checked the reference lists from the retrieved literatures which could trace other relevant publications that may be missed. Only a total of 38 research papers were found, among which 8 papers regarding microplastics detection in soil systems are listed in Table 1 and 21 papers related to the impacts to soil biota are summarized in Table 3.

3. Occurrence and sources of microplastics in soil

Although field monitoring programs on the presence and distribution of microplastics in soils have yet been extensively conducted, the available data suggest that the contamination of microplastics does occur in soils (Table 1). The majority of previous studies concerning soil microplastics detection were conducted in China, the largest producer of plastics all over the world (PlasticsEurope, 2018). Zhou et al. (2018) investigated the distribution of microplastics in coastal soils adjacent to the Bohai Sea and Yellow Sea of China, and found that concentrations of soil microplastics ranged from 1.3 to 14,712.5 items/kg, which were largely influenced by the local anthropogenic activities including aquaculture, port construction and tourism. In Loess plateau of China, Zhang et al. (2018) reported the wide occurrence of microplastics in soils with different land utilization patterns. Microplastics concentrations in soils from rice-fish co-culture ecosystem and vegetable field at the suburbs of Shanghai were found to be 10.3 ± 2.2 and up to 78.0 ± 12.9 items/kg, respectively (Liu et al., 2018; Lv et al., 2019). In southwestern China, microplastics were extensively detected in soil aggregate fractions

Table 1
Available data on microplastics pollution in soils.

Soil type	Location	Extraction	Identification	Abundance	Size	Shape	Polymer	Reference
Industrial soil	Sydney, Australia	Pressurized fluid extraction	FTIR	0.03 ~ 6.7 wt%	/	/	PVC, PE, & PS	(Fuller and Gautam, 2016)
Floodplain Soil	Switzerland	Density separation with 27% NaCl solution, and digestion with 65% HNO_3	μ-FTIR	<593 items/kg	0.125 ~ 5 mm	/	PE (88%), PS, PVC, SBR, & PP	(Scheurer and Bigalke, 2018)
Agricultural soil	Chile	Density separation using H_2O, NaCl and $ZnCl_2$ solutions	Stereomicroscope	Median: 1.1 ~ 3.5 items/g dry soil depending on the amount of sludge input	0.16 ~ 10 mm	Fiber (>97%), film, fragment, & pellet	/	(Corradini et al., 2019b)
Coastal beach soil	Shandong, China	Density separation with saturated NaCl solution and then NaI solution	Stereomicroscope, SEM, & ATR-FTIR	1.3 ~ 14712.5 items/kg dry soil	< 5 mm	Flake (69.0%), foam (27.8%), fragment (1.1%), & fiber (1.0%)	PE, PP, PS, & PU	(Zhou et al., 2018)
Soil from rice-fish co-culture ecosystem	Shanghai, China	Density separation with saturated NaCl solution and digestion with 30% H_2O_2	Stereomicroscope & μ-FTIR	10.3 ± 2.2 items/kg	< 5 mm	fiber (majority), granule, fragment, & film	PE (61.4%), PP (35.1%), & PVC (3.5%)	(Lv et al., 2019)
Vegetable soil	Shanghai, China	Density separation using saturated NaCl solution and digestion using 30% H_2O_2	Stereomicroscope & μ-FTIR	Shallow soil (0–3 cm): 78.0 ± 12.9 items/kg; Deep soil (3–6 cm): 62.50 ± 12.97 items/kg.	20 μm ~ 5 mm	Fiber, fragment, film &, pellet.	PP (50.5%), PE (43.43%), & PET (6.1%)	(Liu et al., 2018)
Agricultural soil Orchard soil Greenhouse soil	Loess plateau, China	Water flotation method	Heating at 130 for 3 ~ 5 s and photographed using a camera connected to microscopy.	40 ~ 100 items/kg 120 ~ 320 items/kg 80 ~ 100 items/kg	>100 μm	/	PE & PP	(Zhang et al., 2018)
Greenhouse soil Forest buffer zone soil	Yunnan, China	Density separation with saturated NaI solution and digestion with 35% H_2O_2	Stereomicroscope	7100 ~ 42960 items/kg 8180 ~ 18100 items/kg	0.05 ~ 10 mm	Fiber (92%), fragment, & film.	/	(Zhang and Liu, 2018)

FTIR: Fourier transform infrared spectroscopy; μ-FTIR: Fourier transform infrared micro-spectroscopy; ATR-FTIR: attenuated total reflectance-Fourier transform infrared spectroscopy; SEM: scanning electron microscopy; PVC: polyvinyl chloride; PE: polyethylene; PS: polystyrene; SBR: styrene butadiene; PP: polypropylene; PU: polyurethane; PET: polyester.

Table 2
Summary of commonly used analytical techniques for identification and quantification of environmental microplastics.

Technique	Detection limit	Advantages	Limitations
Stereomicroscope	>500 μm	Easy to operate; Capable of providing morphological information; Low cost.	Time consuming; High misidentification rate; Unable to characterize chemical composition of micriplastics
FTIR	μ-FTIR can detect particles with a size of down to 10 μm.	ATR-FTIR needs minimal sample preparation; FPA-FTIR can simultaneously provide chemical and physical information of microplastics.	Sensitive to interference from water vapor and organic impurities contained in samples; High cost.
Raman	>1 μm	Minimal sample preparation needed; Non-contact and non-destructive measurement; Insensitive to water interference.	Sensitive to fluorescence interference from color, pigment and bioorganic materials; Time consuming.
NIR	15 g/kg	No sample preparation needed; Fast measurement.	Only applicable for pollution hotspots; Demonstrated to be applicable for only a few polymers.
Hyperspectral imaging technology	>0.5 mm	Portable and feasible; Fast analysis.	Only capable of detecting microplastics on soil surface; Reported to be applicable only for polyethylene particles.
Pyr-GC-MS	>100 μm	Insensitive to background contamination. Simultaneous analysis of polymer types and additives in one run;	Destructive measurement; Incapable of providing the number and morphological information. Sample pre-selection needed.
TED-GC-MS	0.5 ~ 1.0 wt%	No sample preparation needed; Suitable for complex matrices; Faster analysis than Pyr-GC-MS.	Destructive measurement; Unable to provide number and size distribution information; Demonstrated to be only applicable for certain polymer types.
TGA-MS	0.07 wt%	Minimal sample preparation needed; Suitable for heterogeneous soil samples; Much cheaper than Pyr-GC-MS or TED-GC-MS measurements.	Higher quantification limits than Pyr-GC-MS and TED-GC-MS measurements; Unsuitable for samples with high organic content; Unable to give the number and morphological information.

FTIR: Fourier transform infrared spectroscopy; μ-FTIR: Fourier transform infrared micro-spectroscopy; ATR-FTIR: attenuated total reflectance-Fourier transform infrared spectroscopy; FPA-FTIR: focal plane array-Fourier transform infrared spectroscopy; Raman: Raman spectroscopy; NIR: near-infrared spectroscopy; Pyr-GC-MS: pyrolysis-gas chromatography-mass spectrometry; TED-GC-MS: thermal extraction desorption-gas chromatography-mass spectrometry; TGA-MS: thermogravimetric analysis-mass spectrometry.

of both vegetable farmlands and riparian forest zone around Dian Lake with a concentration range of 7,100 to 42,960 items/kg and a mean value of 18,760 items/kg (Zhang and Liu, 2018). Soils from other regions of the world were also reported to be contaminated with microplastics. A study conducted around an industrial area of Sydney, Australia reported that microplastics concentrations in local soils ranged from 300 to 67,500 mg/kg (Fuller and Gautam, 2016). In another study, 90% of Swiss floodplain soils were observed to be contaminated with microplastics (Scheurer and Bigalke, 2018). In Chile, Corradini et al. (2019b) evaluated microplastics contamination in agricultural soils with different application rates of sludge, finding that soil microplastics contents varied from 0.6 to 10.4 items/g, largely depending on the rates of sludge applied. However, data on the occurrence of nanoplastics in soil compartments are at present completely missing.

Microplastics contamination in soils could originate from multiple sources. Concentrations of microplastics in sewage sludge from the wastewater treatment plants could reach up to 15,385 items/kg (Mahon et al., 2017). The application of sewage sludge to farmlands would therefore result in considerable input of microplastics into agricultural soils (Nizzetto et al., 2016). It was estimated that about 63,000 ~ 430,000 and 440,00 ~ 300,000 tons of microplastics are released into European and North American farmlands respectively per year through land application of sewage sludge (Nizzetto et al., 2016). Additionally, organic fertilizers from biowaste fermentation and composting can also act as a carrier for the entry of microplastic into soils (Weithmann et al., 2018). Blasing and Amelung (2018) summarized that microplastics in composts could reach a concentration of up to 1,200 mg/kg. Due to the effectiveness in improving crop quality and yield, plastic film mulching and greenhouse covering have been extensively and intensively applied in agricultural production (Gao et al., 2019; Scarascia-Mugnozza et al., 2011). For instance, in the year of 2017 > 1.47 million tons of agricultural plastic mulching film was consumed in China (Gao et al., 2019). Low recovery of plastic film residues greatly contributes to the increasing accumulation of microplastics in agricultural soils (Kasirajan and Ngouajio, 2012). Atmospheric deposition is another pathway for microplastics entry into soils. A study conducted at Parisian metropolitan area showed that the annual input of fibrous microplastics through atmospheric fallout in this area was up to 10 tons (Dris et al., 2016). Since freshwater lakes or rivers are universally contaminated with microplastics (Wang et al., 2017), irrigation with the polluted water or flooding would consequently introduce microplastics into soils. Other sources like littering along roads, illegal waste dumping and tire abrasion may contribute to the elevated level of microplastics in terrestrial soils (Blasing and Amelung, 2018; Hurley and Nizzetto, 2018). In view of the multiple sources and alarming amount of plastics input into the soil systems, further monitoring programs for microplastics contamination in this important environmental compartment around the globe are warranted.

4. Analytical methods

Generally, the analytical procedures used for microplastics in soils are similar with that for aquatic sediments, which mainly include sample extraction, identification and quantification. The richness of organic matters and complexity of solid matrix combine to make detection of microplastics in soils extremely challenging.

To achieve a preliminary sorting of microplastics, the air-dry soil samples are usually firstly passed through a metal sieve. Although in some studies a 2-mm mesh was utilized to sieve soil microplastics (Zhang and Liu, 2018), the 5-mm mesh seems more recommendatory for the purpose of fitting microplastics definition (Blasing and Amelung, 2018). After sieving, the mineral fractions of soil are removed by the density separation method. In this procedure, soil samples are mixed with a saturated salt solution, such as sodium chloride (NaCl, 1.2 g/cm^3), sodium iodide (NaI, 1.8 g/cm^3), or zinc chloride ($ZnCl_2$, 1.5 ~ 1.7 g/cm^3), and shaken for a specific amount of time (Table 1). Under buoyancy, the lighter microplastic particles, such as polyethylene (0.92 ~ 0.97 g/cm^3) and polypropylene (0.85 ~ 0.94 g/cm^3), will float on the surface of the salt solution and thus become separate from the heavier soil minerals (typically 2.65 g/cm^3) that will eventually sink to the bottom. This method may be less efficient for extraction of higher density polymers, such as polyester (1.4 ~ 1.6 g/cm^3) and polyvinyl chloride (1.3 ~ 1.7 g/cm^3), leading to lower extraction recoveries, especially in the salt solution of relatively less density (Wang and Wang, 2018). Therefore, to improve the extraction recovery of microplastics from soils, high-density salt solutions such as NaI or $ZnCl_2$ are suggested to be utilized for a better separation. Notwithstanding, high-density salts are usually more expensive, and some are even toxic to the environment. These disadvantages could limit their wide application in large scale studies. Considering its superiority in terms of cost and environmental safety, NaCl has become the most extensively used salt in separation of microplastics from soils in most monitoring studies (Table 1). However, the density separation method is incapable of removing the naturally occurring organic matters, which are typically abundant in soils (Hurley et al., 2018). Since organic matters may interfere with the visual analysis of microplastics and distort their signals in Raman and infrared spectroscopies (Blasing and Amelung, 2018), a sufficient removal of these interfering organic impurities is vitally necessary for accurate assessment of microplastics. For sediment samples, digestion of organic matters usually involves the use of acidic, alkaline, oxidizing chemicals, or the mixtures of these agents (Wang and Wang, 2018). This may be transferable also to soil samples. However, microplastic particles are susceptible to damage or degradation by these chemical agents during the digestion process. To address this limitation, Hurley et al. (2018) recently optimized the digestion protocol for organic-rich solid matrices using the Fenton's reagent, and achieved a satisfactory removal efficiency of organic matters and negligible damage to the plastic particles. Nevertheless, the success of this method largely depended on a careful control of the reaction temperature (<40) and pH (optimum at 3.0) (Hurley et al., 2018). This may limit its applicability to calcareous soils, because iron hydroxide precipitates could form when pH value of reaction system exceeds 5 ~ 6. Another potentially promising digestion method involves the combined use of technical enzymes such as cellulase, lipase, proteinase, amylase and chitinase, which has been successfully employed to aquatic samples to separate microplastics from biological materials (Cole et al., 2014; Loder et al., 2017). However, there exists a large uncertainty about the efficacy of enzymatic digestion in eliminating soil organic matters, especially when considering the complex composition of soil matrices and varying physicochemical properties. Although difference in sample handling techniques could cause considerable variations in the final quantification results, no consensus has been achieved with regard to the extraction methodologies, which limits the comparison of the reported data. Further efforts should also include extraction method improvement, validation and standardization in order to collect the comparable results.

After extraction, potential microplastics can be identified and quantified by use of visual sorting, spectroscopic and thermoanalytical techniques (Table 2). Optical microscope, typically the stereomicroscope, is an important tool for visual sorting of microplastics. Morphological characteristics, such as shape, color and surface texture, are the main basis to determine whether or not a suspected particle is microplastic (Wang and Wang, 2018). This leaves visual sorting with the problem of high misidentification rate, especially for the smaller and fibrous items (Hidalgo-Ruz et al., 2012). Therefore, the visual sorting results need to be further validated by characterizing their chemical composition. Fourier transform infrared spectroscopy (FTIR) and its optimized technologies such as focal plane array-FTIR (FPA-FTIR) and attenuated total reflectance-FTIR (ATR-FTIR) have been the most widely used analytical techniques for chemical identification of microplastics. These infrared spectroscopic devices can be coupled to a microscope, making it possible for measurement of much smaller plastic particles (down to 10 μm). In particular, due to the excellent performance in providing chemical and morphological information simultaneously, FPA-FTIR is gaining increasing attention as a promising tool for microplastics analysis. Raman spectroscopy is another commonly used technique in microplastics detection, and is capable of identifying microplastics with a size of < 1 μm when coupled to a microscope. The reliability of FTIR and Raman techniques in identification of microplastics largely depends on the effectiveness of removing the interfering organic matters (Blasing and Amelung, 2018). Anyhow, FTIR and Raman spectroscopies still remain as the key techniques for identification and quantification of microplastics. Some thermoanalytical techniques such as pyrolysis-gas chromatography-mass spectrometry (Pyr-GC-MS), thermogravimetric analysis-mass spectrometry (TGA-MS) and thermal extraction desorption-gas chromatography-mass spectrometry (TED-GC-MS) have also been proved to be efficient in identifying and quantifying environmental microplastics, while they are incapable of providing information about the number and morphological properties of analyzed particles (David et al., 2018; Dumichen et al., 2017; Kappler et al., 2018). Recently, several emerging techniques including combination of the macroscopic dimensioned near-infrared (NIR) process-spectroscopic method and chemometrics, visible NIR spectroscopy, and hyperspectral imaging technique, have been developed for fast measurement of microplastics in soil samples (Corradini et al., 2019a; Paul et al., 2019; Shan et al., 2018). These methods require minimal to no sample pretreatment, thus significantly increasing the detection efficiency. However, it is apparent that these emerging techniques also have inherent deficiencies that likely restrict their applications. For instance, the combined NIR spectroscopic chemometric approach is only limited to assessing whether the studied soil contains plastics, but incapable of providing the quantitative, morphological and structural information of microplastics (Paul et al., 2019); the vis-NIR spectroscopy exhibits low prediction accuracy (10 g/kg) and high detection limit (15 g/kg) for soil microplastics, thus only applicable to pollution hotspots (Corradini et al., 2019a); while the hyperspectral imaging technique is only capable of scanning microplastics (0.5 ~ 5 mm) on the surface of soils (Shan et al., 2018). Therefore, selection of an appropriate technique according to the research target is an important prerequisite for the success of microplastics analysis. In addition, a reasonable combination of several techniques may also assist in comprehensive characterization of microplastics. Undoubtedly, continued attempts to develop more robust and efficient analytical techniques specially aiming at fast assessment of micriplastics in complex and organic-rich solid environmental matrices are highly encouraged.

5. Effects on soil physicochemical properties

Once their arrival in soils, microplastic particles can readily disperse within the soil matrices driven by wet-dry cycles (O'Connor et al., 2019), soil management practices (Steinmetz et al., 2016), harvesting (Rillig et al., 2017), and bioturbation (Huerta Lwanga et al., 2017a; Maass et al., 2017). Sequestration of microplastics inside soil aggregates may trigger alterations in soil physical properties including soil bulk density, water holding capacity, and soil structures (de Souza Machado et al., 2018b, 2019). Plastics usually have a smaller density than soil minerals, which might be responsible for the shifts in bulk density of microplastics-contaminated soils (de Souza Machado et al., 2018b). Once incorporated into the soil matrix, microplastics may alter the soil porosity, thus affecting soil water dynamics and soil aggregation. In a study using polyethylene films, Wan et al. (2018) found that microplastics could accelerate soil water evaporation by creating channels for water movement. Using pot and field experiments, Zhang et al. (2019) observed a significant increase in content of water stable large macroaggregates (>2 mm) and volumes of macropores (>30 μm) after addition of polyester microfibers into a clayey soil. The presence of microplastics could also destruct soil structural integrity, causing desiccation cracking on the surface of soil (Wan et al., 2018). In another study, Liu et al. (2017) investigated the effects of microplastics on soil dissolved organic matter, and found that large amount of polypropylene microplastics input in Chinese loess soil (28% w/w) significantly increased the levels of dissolved organic carbon, nitrogen and phosphorus in soil. This suggests that accumulation of microplastics might influence the nutrient cycling processes in soil ecosystems. However, it is not clear about the underlying mechanisms via which microplastic particles participated in these soil processes.

Due to the large surface areas and hydrophobicity, microplastics are capable of concentrating toxic chemicals such as heavy metals and hydrophobic organic contaminants on their surface (Holmes et al., 2012; Mato et al., 2001), thus serving as a vector for these chemicals in the environment (Koelmans et al., 2016). It was reported that sorption coefficient of polychlorinated biphenyls by microplastics could be up to 10^6 L/kg (Mato et al., 2001). A study by Ramos et al. (2015) showed that polyethylene film residues could concentrate more pesticides (584 ~ 2284 μg pesticide/g plastic) than soil (13 ~ 32 μg pesticide/g soil). These results demonstrate the excellent capability of microplastics to accumulate organic contaminants in soil compartment. Upon moving into a clean system, microplastics may contaminate the ambient matrix by releasing the adhered chemicals (Teuten et al., 2007). In addition, some toxic additives are incorporated into plastic products during manufacture in order to improve their quality and performance (Hahladakis et al., 2018). These plastic additives could leak out during the fragmentation process of plastic debris, thus contaminating the surrounding soils (Hahladakis et al., 2018). For the example of phthalate esters, these chemicals could be released to greenhouse soils with a concentration of up to 35.4 mg/kg soil (Balestrini et al., 2014). Since the sorption potential of sorbates by microplastics demonstrates marked difference compared to that by soils (Teuten et al., 2007), the presence of microplastics in soils could influence the transport behaviors of chemicals (Ramos et al., 2015). A recent study revealed that the presence of microplastics could significantly enhance the mobility of organic contaminants in natural soil columns (Huffer et al., 2019). Additionally, chemical degradation of organic contaminants in soils could be slow down in the presence of plastic fragments plausibly due to the sorption by microplastics (Ramos et al., 2015). Although several studies showed the impact of microplastics to contaminant transport and degradation in soils, more intensive research is still needed to elucidate the consequences of microplastics in soils on soil properties and biota when microplastics act as a carrier of chemical contaminants.

6. Effects on soil biota

Until recently, information about the potential effects of microplastics contamination on terrestrial plants is extremely scarce (Table 3). Qi et al. (2018) first started research on this important topic. In their study, microplastic film residues were added at 1% (w/w) in dry soils. The results showed negative impact to the growth of wheat (*Triticum aestivum*) at both vegetative and reproductive stages, which was attributed possibly to alterations in soil properties elicited by plastics incorporation (Qi et al., 2018). More recently, de Souza Machado et al. (2019) investigated effects of different microplastics (0.2 ~ 2% of soil fresh weight) on performance of spring onion (*Allium fistulosum*) and found that microplastics exposure could induce alterations in plant total biomass, elemental composition of tissue, and root traits, while the actual effects varied considerably with particle types. As discussed above, the presence of microplastics could lead to changes in soil physicochemical parameters, such as soil structure, bulk density, water holding capacity, and nutrition contents (de Souza Machado et al., 2018b, 2019; Liu et al., 2017; Wan et al., 2018). Such changes might affect plant performance directly by altering plant root traits, growth status, and nutrient uptake process (de Souza Machado et al., 2019; Qi et al., 2018; Rillig et al., 2019). Additionally, alterations in soil properties could also affect the composition of soil microbial community and related bioactivity (de Souza Machado et al., 2018b; Rillig et al., 2019), thus indirectly translating to consequences for plant performance. Microplastics with different properties could induce different responses in soil and plant (de Souza Machado et al., 2018b, 2019). These responses are also likely to vary with different plant species and soil types. Given plants as a major component in terrestrial systems and the prevalence of microplastics, further research should include more types of plastic particles, plant species, and soil conditions, in order to systematically evaluate the potential implications of soil microplastics contamination to the terrestrial ecosystems.

Compared with the studies on aquatic fauna, the research on the ecotoxicological effects of microplastics on soil fauna is very limited, with the majority conducted at laboratory scale (Table 3). Only a few kinds of soil animals were investigated, such as oligochaeta, nematode, collembolan, isopod, snail and mice, among which earthworms were the predominant test species. Demonstrated toxicological effects of microplastics exposure on earthworms mainly include growth inhibition, gut damage, weight decrease, immune responses, alterations in gut microbial community, reproduction problems, and even mortality (Huerta Lwanga et al., 2016; Rodriguez-Seijo et al., 2017; Zhu et al., 2018a). However, the actual effects may vary considerably between reported studies. For instance, in a study, earthworms (*Lumbricus terrestris*) experienced growth inhibition and subsequent death when exposed to polyethylene microplastics at concentrations of 0.2 ~ 1.2% (w/w in dry soil) (Huerta Lwanga et al., 2016); another study using earthworms (*Eisenia fetida*) exposed to 0.25 ~ 0.5% of polystyrene microplastics (w/w in dry soil) showed no apparent effects on the fitness of earthworms, with growth inhibition only occurring at higher exposure concentrations (>1%) (Cao et al., 2017). Due to the small size, microplastics are readily ingested by other small soil invertebrates, such as soil insects, nematodes, and snails, consequently translating to various health effects (Table 3). Although most of the previous effect studies have adopted environmentally relevant exposure concentrations and scenarios, the underlying mechanisms of how microplastics interact with soil organisms still need a further elucidation. Microplastics can also be consumed by some important economical poultries (e.g., chickens), hence providing a potential pathway to enter into human bodies (Huerta Lwanga et al., 2017b). Studies on mice suggest that microplastics exposure could pose health risks (e.g., dysbiosis of gut microbiota and metabolic problems) to terrestrial mammals (Jin et al., 2019; Lu et al., 2018), and such effects may be transferable to human beings. In addition, microplastics are known to concentrate hazardous chemicals on their surface (Koelmans et al., 2016), which may lead to changes in their toxicity of microplastics to soil organisms. A mesocosm study demonstrated

Table 3
Studies on ecotoxicological impacts of microplastics to soil biota.

Species	Microplastics			Contaminants	Biological effects	Reference
	Type	Size	Concentration			
Plant						
Wheat (*Triticum aestivum* L.)	LDPE	<1 mm	1% (w/w in dry soil)	/	Decrease in shoot and root biomass; Adverse effects on wheat vegetative and reproductive growth;	(Qi et al., 2018)
Spring onion (*Allium fistulosu*)	PA, PS, HDPE, PP, & PET	15 ~ 5000 μm	0.2 ~ 2.0% (w/w in fresh soil)	/	Alterations in root and leaf traits and biomass.	(de Souza Machado et al., 2019)
Animal						
Earthworm (*Lumbricus terrestris*)	PE	<150 μm	0.2 ~ 1.2% (w/w in dry soil)	/	Increase in mortality; Decrease in growth rate.	(Huerta Lwanga et al., 2016)
Earthworm (*Lumbricus terrestris*)	HDPE	0.92 ± 1.09 m^2	3.5 g/kg dry soil	Zinc	Increased Zinc exposure to earthworm.	(Hodson et al., 2017)
Earthworm (*Eisenia andrei* Bouché)	PE	250 ~ 1000 μm	62.5 ~ 1000 mg/kg dry soil	/	Gut damages; Immune responses.	(Rodriguez-Seijo et al., 2017)
Earthworm (*Enchytraeus crypticus*)	PS	0.05 ~ 0.1 μm	0.025 ~ 10% (w/w in feed)	/	Decrease in body weight; Alterations in gut microbiome.	(Zhu et al., 2018a)
Earthworm (*Metaphire californica*)	PVC	/	2 g/kg dry soil	Arsenate	Decrease in accumulation of total arsenic and transformation of arsenic to arsenite; Alleviation of arsenic toxicity to gut microbiome.	(Wang et al., 2019a)
Earthworm (*Eisenia fetida*)	PS	58 μm	0.25 ~ 2% (w/w in dry soil)	/	Growth inhibition; Increase in mortality.	(Cao et al., 2017)
Earthworm (*Eisenia fetida*)	LDPE & PS	<300 μm	1 ~ 20% (w/w in dry soil)	PAHs & PCBs	Increase in activities of catalase and peroxidase; Increase in the level of lipid peroxidation; Reduction in activities of superoxide dismutase and glutathione S-transferase; Decrease in bioaccumulation of PAHs and PCBs	(Wang et al., 2019b)
Soil springtail (*Lobella sokamensis*)	PE & PS	0.47 ~ 1155 μm.	4 ~ 1000 mg/kg dry soil	/	Decrease in movement.	(Kim and An, 2019)
Soil springtail (*Folsomia candida*)	PE	<500 μm	0.1 ~ 1% (w/w in dry soil)	/	Increase in avoidance rate; Reproduction inhibition; Alterations in gut microbial community.	(Ju et al., 2019)
Soil nematode (*Caenorhabditis elegans*)	PS	0.05 ~ 0.2 μm	1 μg/L ~ 86.8 mg/L	/	Disruption of energy metabolism; Oxidative damages; Reduction of locomotion and reproduction	(Kim et al., 2019)
Soil nematode (Caenorhabditis elegans)	PS	0.1 ~ 5 μm	1 mg/L	/	Decrease in body length, lifespan, and survival fate; Induction of excitatory toxicity on locomotor behavior; Alterations in expression of certain genes; Damage in cholinergic and GABAergic neurons.	(Lei et al., 2018a)
Terrestrial snail (*Achatina fulica*)	PET	1257.8 μm	0.01 ~ 0.71 g/kg dry soil	/	Reduction in food intake and excretion; Villi damage in the gastrointestinal walls; Reduction of glutathione peroxidase and total antioxidant capacity in liver; Increase in malondialdehyde level in liver.	(Song et al., 2019)
Terrestrial isopod (*Porcellio scaber*)	PE	60 ~ 800 μm	4 mg/g food	/	No significant effects on feeding behavior and energy reserve.	(Jemec Kokalj et al., 2018)
Soil collembolan (*Folsomia candida*)	PVC	80 ~ 250 μm	5000 particles/ plate	/	Avoidance behavior	(Zhu et al., 2018b)
Mice	PS	5 μm	100 ~ 1000 μg/L water	/	Reduction in intestinal mucus secretion and damage in intestinal barrier; Dysbiosis of gut microbiota; Metabolic disorder.	(Jin et al., 2019)

(*continued on next page*)

Table 3 (*continued*)

Species	Microplastics			Contaminants	Biological effects	Reference
	Type	Size	Concentration			
Mice	PS	0.5 ~ 50 µm	100 ~ 1000 µg/L water	/	Reduction in body, liver and epididymal fat weights; Decrease in intestinal mucus secretion; Gut microbiota dysbiosis; Hepatic lipid metabolism disorder.	(Lu et al., 2018)
Microbe						
Soil enzyme	PP	<180 µm	7 ~ 28% (w/w in dry soil)	/	Increase in FDA hydrolase activity.	(Liu et al., 2017)
Soil enzyme	PET, PAA, HDPE & PA	15 ~ 9100 µm	0.05 ~ 2% (w/w in dry soil)	/	Increase in FDA hydrolase activity as total microplastics concentration increased; Decrease in FDA hydrolase activity by addition of PAA and PET.	(de Souza Machado et al., 2018b)
Soil enzyme	PA, HDPE, PP, PS, & PET	15 ~ 5000 µm	0.2 ~ 2.0% (w/w in fresh soil)	/	Increase in FDA hydrolase activity by addition of PA and HDPE; Decrease in FDA hydrolase activity by interactive effects of plants and PA, HDPE, and PET.	(de Souza Machado et al., 2019)
Soil enzyme	PS	32.6 ± 11.9 nm	10 ~ 1000 ng/g dry soil	/	Decrease in activities of dehydrogenase, leucine-aminopeptidase, alkaline-phosphatase, β-glucosidase and cellobiohydrolase.	(Awet et al., 2018)
Microbial biomass	PS	32.6 ± 11.9 nm	10 ~ 1000 ng/g dry soil	/	Decrease in microbial biomass carbon.	(Awet et al., 2018)

LDPE: low-density polyethylene; HDPE: high-density polyethylene; PA: polyamide; PET: polyester; PS: polystyrene; PP: polypropylene; PVC: polyvinyl chloride; PAA: polyacrylic; PAHs: polycyclic aromatic hydrocarbons; PCBs: polychlorinated biphenyls; FDA: fluorescein diacetate.

that microplastics could serve as vectors to enhance zinc bioavailability to earthworms (*Lumbricus terrestris*) (Hodson et al., 2017). While in another two recent studies, bioaccumulation of contaminants in earthworms was found to be lowered after addition of microplastics into soil (Wang et al., 2019a, 2019b). In order to evaluate the overall impacts of microplastics contamination on soil ecosystems, further research efforts are suggested to involve more kinds of soil fauna. Trophic transfer of microplastics and the associated contaminants has been confirmed in aquatic food web (Carbery et al., 2018). This could also happen in the soil systems. However, little information is currently available in this area.

Currently, the impacts of microplastics present in soil to soil microorganisms remain largely unknown. The available studies mostly assess the changes in the activities of soil enzymes in the presence of microplastics (Table 3). Alterations in soil microbial activity could be dependent on microplastic particle characteristics, exposure concentrations, enzyme types, and absence or presence of plants (Awet et al., 2018; de Souza Machado et al., 2018b, 2019; Liu et al., 2017). Polyacrylic and polyester particles added at 0.05 ~ 0.4% of soil dry weight could negatively affect soil microbial activity assessed by hydrolysis of fluorescein diacetate (de Souza Machado et al., 2018b), whereas polypropylene microplastics (7 ~ 28% w/w in dry soil) exhibited a positive effect on activity of soil fluorescein diacetate hydrolase (Liu et al., 2017). Although altered soil properties resulting from microplastics are proposed as a possible reason for the changes in soil microbial activities, no solid evidence or robust linkages have been verified. The presence of microplastics also influences bacterial transport and deposition in soils, and dissipation of antibiotic resistance genes (He et al., 2018; Sun et al., 2018). Moreover, the sorbed hydrophobic organic contaminants and heavy metals, along with the leachable plasticizers or additives, combine to render microplastics as a cocktail of hazardous chemicals (Carbery et al., 2018). The combined impacts of microplastics and associated contaminants on soil microbes are rarely addressed, and should be a research priority in the future.

7. Conclusions and perspectives for future research

Microplastics are considered as a class of environmental contaminants of emerging concern. The current microplastics research focuses mainly on the aquatic settings, while environmental distribution, sources, and impacts of microplastics in terrestrial ecosystems remain largely unexplored, despite the important role of soils as an environmental reservoir for microplastics. By collating literatures, this review introduces the current knowledge on the occurrence, sources, analytical techniques, and ecotoxicological effects of microplastics in soil ecosystems. Although only limited studies were conducted, the available monitoring data suggest that microplastics are pervasively distributed in soils. Potential sources to disseminate microplastics to soils mainly include land application of sewage sludge, fertilization, film mulching, atmospheric deposition, irrigation, and so on. Currently, no standard protocol is developed for extraction and identification of microplastics in soils. Microplastics and their associated chemicals could cause certain consequences to soil properties and soil biota, in spite of some uncertainty on the data and the underlying processes. In order to achieve a more accurate assessment of the occurrence, distribution and potential effects of microplastics in terrestrial soil ecosystems, several research priorities are suggested as follows:

(1) Large-scale monitoring programs are urgently needed to evaluate the distribution of microplastics in different regions at the globe scale, and quantify the contributions of various natural processes and anthropogenic practice to microplastics contamination in soils.

(2) Continuous efforts are needed to develop more efficient and reliable analytical techniques as standard method to detect/quantify microplastics in soils.
(3) Further research should investigate interactions between microplastics and soil aggregates, and the impacts to soil properties as well as fate and transport of microplastics in soils.
(4) In light of the important role of plants in terrestrial ecosystems, further studies are encouraged to involve more plant species to evaluate the effects of microplastics contamination on plant performance.
(5) Although laboratory studies have demonstrated that soil animals, such as the earthworm, can consume microplastics, evidence of microplastics ingestion by soil animals in the natural environment is currently scarce. Therefore, it is indispensable to conduct more field studies to examine the accumulation of microplastics in wild soil animals.
(6) Further research should be conducted on the effects of microplastics exposure on a broader range of soil fauna under environmentally realistic scenarios. Additionally, the potential of microplastics to facilitate bioaccumulation and trophic transfer of plastic-derived contaminants (including the plastic additives and sorbed chemicals) also remains to be clarified.
(7) Studies on how microplastics accumulation affects the biophysical parameters of soils and its resultant implications on soil microbes, including microbial activity, microbial community structure, and their functions in soil ecosystems should receive more attention.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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