Environment International 137 (2020) 105263

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Source, migration and toxicology of microplastics in soil

Jing-Jie Guo[a], Xian-Pei Huang[a,b], Lei Xiang[a], Yi-Ze Wang[a], Yan-Wen Li[a], Hui Li[a], Quan-Ying Cai[a], Ce-Hui Mo[a,*], Ming-Hung Wong[a,c]

[a] Guangdong Provincial Research Center for Environment Pollution Control and Remediation Materials, College of Life Science and Technology, Jinan University, Guangzhou 510632, China

[b] Shanwei Marine Industry Institute, Shanwei 516600, China

[c] Consortium on Health, Environment, Education and Research (CHEER), The Education University of Hong Kong, Tai Po, Hong Kong, China

ARTICLE INFO

Handling Editor: Da Chen

Keywords:
Microplastics
Soil
Migration
Toxicology
Health risks

ABSTRACT

Microplastics are emerging contaminants and their presence in water and soil ecosystems has recently drawn considerable attention because they pose a great threat to entire ecosystems. Recent researches have focused on the detection, occurrence, characterization, and toxicology of microplastics in marine and freshwater ecosystems; however, our understanding of the ecological effects of microplastics in soil ecosystems is still limited compared with that in aquatic ecosystems. Here, we have compiled literature, studying the sources, migration of microplastics in soil, negative impacts on soil health and function, trophic transfer in food chains, and the corresponding adverse effects on soil organisms in order to address the potential ecological and human health risks caused by microplastics in soil. This review aims to address gaps in knowledge, shed light on the ecological effects of microplastics in soil, and propose future studies on microplastic pollution and the resultant soil ecotoxicity. Furthermore, this review is focused on limiting microplastics in soil and establishing management and remediation measures to mitigate the risks posed by microplastic pollution.

1. Introduction

Millions of tons of plastic are produced each year, facilitating all aspects of people's lives. According to the incomplete statistics reported by PlasticsEurope (the Association of Plastics Manufacturers in Europe) and EPRO (the European Association of Plastics Recycling and Recovery Organizations), global plastic production was estimated to be 335 million tons as of 2016, with an average annual growth rate of 8.6% since the 1950s (1.7 million tons) (PlasticsEurope, 2017; UNEP, 2015). The current levels of plastic production, use/disposal patterns, low recovery rate, and demographic data all point to increasing accumulation of plastic waste (Dahlbo et al., 2018; Hahladakis et al., 2018a; Hahladakis and Iacovidou, 2018; van Velzen et al., 2019). While plastics are both persistent and recyclable materials, less than 5% are reclaimed (Sutherland et al., 2010) and 4.8–12.7 million tons of plastic waste entered the ocean in 2010 (Jambeck et al., 2015). Projected over one hundred years, the degradation cycle of plastics waste predicts severe environmental problems as surface embrittled plastics are microcracked by microbial-mediated and weathering conditions and mechanisms, such as ultraviolet (UV) light and hydrolysis, and are progressively broken down into the small fragments and particles known as microplastics (Andrady, 2011; Auta et al., 2017).

Microplastics are heterogeneously mixed plastics that are less than 5 mm in diameter, they include plastic fibers, granules, and fragments, and they are considered to be emerging contaminants of concern (Cózar et al., 2014; Ryan et al., 2009; UNEP, 2014). The paper "Lost at sea: Where is all the plastic?" published in *Science* (Thompson et al., 2004) initiated enthusiasm for research on marine microplastics. Since then, microplastics contamination has been found to be ubiquitous and pervasive from the equator to the poles (Barnes et al., 2009; Imhof et al., 2017; Lusher et al., 2015; Peeken et al., 2018), present in surface and deep waters of oceans, lakes, estuaries, shorelines, intertidal zones, and mangroves as well as beaches and sediments (Alomar et al., 2016; Browne et al., 2011; Claessens et al., 2011; Hoffman and Hittinger, 2017; Naidoo et al., 2015; Ng and Obbard, 2006; Reisser et al., 2015). Based on the latest global estimate of microplastics, there are 93–236 thousand tons of microplastics floating on the ocean surface, which corresponds to as many as 51 trillion particles (Sebille et al., 2015). Substantial concentrations of microplastics have also been found in frozen ice areas; for example, 38–234 particles per m^3 of ice have been reported in the Arctic (Obbard et al., 2014).

Growing evidence has demonstrated that microplastics are also

* Corresponding author.
E-mail address: tchmo@jnu.edu.cn (C.-H. Mo).

https://doi.org/10.1016/j.envint.2019.105263
Received 20 July 2019; Received in revised form 21 September 2019; Accepted 10 October 2019
Available online 19 February 2020

present in terrestrial ecosystems (Cao et al., 2017; Rillig, 2012; Rillig et al., 2017a; Horton et al., 2017), and that 79% of global plastic waste is stacked in landfills; thus, soil is likely a large microplastics sink (Geyer et al., 2017; Ng et al., 2018). Recent estimates have reported that the annual input of microplastics by farmlands ranges from 63 to 430 thousand tons in Europe and 44–300 thousand tons in North America, both of which exceed the extrapolated annual emissions of microplastics to ocean surface waters (Nizzetto et al., 2016a, 2016b). Farmlands in Shanghai, China have reported 62.5 microplastic items per kilogram of deep soil and 78.0 items kg^{-1} of shallow soil (Liu et al., 2018), and microplastics have also been detected in home garden soils in Campeche, Mexico, where the mean concentration was 0.87 ± 1.9 particles g^{-1} (Huerta Lwanga et al., 2017a). Furthermore, Scheurer and Bigalke (2018) found microplastics in approximately 90% of Swiss floodplain soils at depths between 0 and 5 cm and determined the mean microplastics concentration to be 5 mg kg^{-1}, with a maximum value of 55.5 mg kg^{-1}. Microplastics have also been found to constitute up to 0.002% of soil dry weight in nonurban soil reserves, such as remote high mountain areas (Scheurer and Bigalke, 2018), and Fuller and Gautam (2016) reported that soils sampled from an industrial area in Australia were 0.03–6.7% microplastics, with concentrations ranging from 300 to 67,500 mg kg^{-1} (Table 1).

Microplastics have been demonstrated to cause deleterious effects to soil health and function (de Souza Machado et al., 2018a, 2018b; Liu et al., 2017), and as in the marine environment, microplastic pollution in soil will inevitably lead to accidental ingestion of microplastics by soil organisms Earthworms have been shown to ingest microplastics and the ingestion rate has been reported to increase significantly as the concentration of microplastics increases; for example, Huerta Lwanga et al. (2017a) detected 14.8 ± 28.8 microplastic particles per gram of earthworm casts and 129.8 ± 82.3 particles g^{-1} of chicken feces in home garden soils. Panebianco et al. (2019) found microplastics were presented in more than 50% of the snails (a total of 425 specimens), with the average of 0.92 ± 1.21 particles per 5 snails.

In summary, microplastics have become a global environmental issue and have aroused widespread concern about health risks. As the number of researches regarding microplastics in soil has considerably increased in recent years, it is important to examine the interactions between soil and microplastics, and identify research gaps and directions. The objectives of this review are to (1) summarize the source and transfer of microplastics in soil, (2) analyze their effects on soil health and function, and (3) discuss their potential ecological and health risks in soil. By integrating and summarizing previous research, we have developed a body of knowledge on the migration and toxicology of microplastics in soil that we hope will be used to reduce microplastics in soil and establish management and remediation measures to mitigate the risks posed by microplastic pollution.

2. Methodology

Here, the authors attempt to provide a generic overview on several implications associated with soil microplastics. Although we are as comprehensive as possible, there still leaves much to be desired. The methodology of the present work is briefly outlined in the following.

2.1. The methodological approach to this review

The authors thoroughly reviewed literatures related to microplastics, finding that current researches are predominantly focused on aquatic ecosystems rather than soil-microplastic interactions; thus, while several studies have investigated microplastic pollution in terrestrial ecosystems, a deeper understanding of microplastics in soil is required as the influences of microplastics on soil ecosystem and human health remain poorly understood. This review went through under a three-pillar approach:

(1) to briefly delineate the urgency and seriousness of microplastics in soil through emphasizing on the various ways for microplastics to enter soil, and their migration within soil;
(2) to outline the impacts of microplastics on soil properties and function through multiple aspects, as well as the potential risks when dispersed into other environment media, transferred along the food chains, and accumulated by animals, plants and humans;
(3) to summarize the prevention countermeasures for soil microplastics and propose future research directions according to the existing literatures.

2.2. Data sources assimilation and analysis

The keywords “microplastic”, “soil”, “terrestrial ecosystem”, “toxicity”, “transfer”, or “transport”, were selected individually or jointly to search for relevant information on Web of Science and Google Scholar. Key literatures published between 2010 and 2019 (up to September) were assimilated and analyzed.

3. Sources and migration of microplastics in soil

3.1. Sources of soil microplastics

The sources of microplastics are mainly classified as either primary or secondary microplastics (Cole et al., 2011; Duis and Coors, 2016; Thompson 2015). Primary microplastics are purposefully manufactured for specific applications, which include cosmetic abrasives, drug vectors, and industrial and engineering applications such as air blasting (Hays and Cormons 1974; Auta et al., 2017). These microplastics are usually difficult to remove using sewage disposal technologies and once they enter wastewater, they will ultimately accumulate in the environment (Castañeda et al., 2014; Zitko and Hanlon, 1991). Secondary microplastics originate from larger plastics as they are progressively fragmented into smaller pieces by multiple, complex environmental conditions such as wind, waves, temperature, and UV light (Andrady, 2011; Cole et al., 2011; Rocha-Santos and Duarte, 2015). Furthermore,

Table 1
Microplastic distribution in soils from four countries.

Location	Abundance (mean value)	Reference
Industry areas, Sydney, Australia	4191 mg kg^{-1}	Fuller and Gautam (2016)
Floodplain soils, Switzerland	5 mg kg^{-1}	Scheurer and Bigalke (2018)
Homegarden soil, Campeche, SE Mexico	0.87 particles kg^{-1}	Huerta Lwanga et al. (2017a)
Deep soils, Shanghai, China	62.5 items kg^{-1}	Liu et al. (2018)
Shallow soils, Shanghai, China	78 items kg^{-1}	
Estuary of the Cha river, Yunnan, China	26,410 particles kg^{-1}	Zhang and Liu (2018)
Dagoujian, Yunnan, China	48,960 particles kg^{-1}	
Dunshang, Yunnan, China	27,310 particles kg^{-1}	
Anle, Yunnan, China	53,090 particles kg^{-1}	
Shangsuan, Yunnan, China	22,610 particles kg^{-1}	

repeated use of plastic products can also cause fragmentation and result in the formation of secondary microplastics. Hartline et al. (2016) discovered that microfiber masses from top-load conventional home machines were 1471–2121 microfibers per garment, which was approximately 7 times higher than that those from front-load machines. And a recent study reported 30,000–465,000 microfibers per m^2 (or 175–560 microfibers/g) were detached from textile garments (Belzagui et al., 2019). Besides, plastic emissions related to vehicle transport, including tire wear and tear, brakes, road markings, are another main source of microplastics in the environment (Gieré et al., 2018; Kole et al., 2017). The global average of microplastic emissions from the abrasion of road vehicle tires was estimated to be 0.81 kg/year per capita (Kole et al., 2017). Apart from road traffic, wear and tear released from airplane tires accounts for approximately 2% of total emissions from tire wear and tear in the Netherlands (Kole et al., 2017). In addition, artificial turf also plays an important role in secondary source of microplastics, with the rough estimate of artificial turf emissions ranging from 760 to 4500 tonnes/year (Kole et al., 2017; Lassen et al., 2015; Magnusson et al., 2016). Therefore, diverse types of microplastics are being emitted into various natural habitats and ecosystems.

Much different from the sources of microplastics in ocean, which mainly includes land-based sources (contributing ~80%), costal tourism, recreational, commercial fishing (e.g. plastic fishing gear applications, etc., contributing ~18%), marine vessels and marine-industries (e.g. aquaculture, oil-rigs, etc.) (Andrady, 2011; Cole et al., 2011; Doyle et al., 2011), microplastics enter soil via multiple sources, including landfills (He et al., 2019), soil amendments (UBA, 2015; Zubris and Richards, 2005), land application of sewage sludge (Corradini et al., 2019; Li et al., 2018a; Mintenig et al., 2017; Ziajahromi et al., 2017), wastewater-irrigation (Gündoğdu et al., 2018; Mason et al., 2016), compost and organic fertilizer (Weithmann et al., 2018), residues of agricultural mulching films (Ramos et al., 2015; Steinmetz et al., 2016), tire wear and tear (Kole et al., 2017), and atmospheric deposition (Dris et al., 2015, 2016, 2017; Liu et al., 2019), etc. Besides, plastic waste in soil can be fragmentized into microplastics by biological processes of soil organisms, e.g. feeding activities, digestion, and excretion process (Chae and An, 2018). The presence of microplastics severely reduces soil quality (de Souza Machado et al., 2018a), and the migration and trophic transfer of microplastics in heavily contaminated soils, particularly those in wastewater-irrigated and plastic-film covered areas, pose substantial risks to the ecosystem (Fig. 1).

3.2. Migration of microplastics in soil

The vertical and horizontal distribution of microplastics in soil can be influenced by several factors (Fig. 2), including soil biota, soil features such as soil macropores (pores > 75 µm), soil aggregation and soil cracking, and agronomic practices such as plowing and harvesting (Rillig et al., 2017a, 2017b). The general literature on microparticle migration in soil by bioturbation (Gabet et al., 2003) suggests that plant processes (e.g., root growth and uprooting) and inputs from various animals (e.g., larvae, earthworms, vertebrates, etc.) can serve as preferential paths for microplastics movement. For example, indigenous fungal mycelia may also contribute to the migration of microplastics as they can bridge air-filled pores and efficiently translocate pollutant degrading bacteria (Wick et al., 2007). Microplastics can be swallowed and subsequently excreted by earthworms (Cao et al., 2017; Huerta Lwanga et al., 2016; Rillig et al., 2017a), vertically transported from shallow to deep soils by the burrows of anecic earthworms, and laterally spread across wide areas by the movement of geophagous earthworms and mosquitoes (Huerta Lwanga et al., 2016; Hurley and Nizzetto, 2018; Ziajahromi et al., 2018). Mosquito larvae have been reported to readily eat microplastics, which can persist in a mosquito's guts during metamorphosis from the larval to adult stage (Al-Jaibachi et al., 2019). Moreover, earthworm casts, which can contain concentrated microplastics, may be ingested by soil microarthropods (Gutierrez-Lopez et al., 2011; Salmon and Ponge, 2001). Mites and collembola have also been found to disperse and redistribute microplastics by scraping or chewing microplastics, and digging mammals, such as gophers and moles, are likely to contribute to the migration of microplastics in soil by a similar mechanism (Maaß et al., 2017; Rillig, 2012). The distance of microplastics (100–200 µm) was much further and faster transported by larger *Folsomia candida* (up to 4 cm after 5 days) than smaller *Proisotoma minuta* (about 1 cm after one week), and the ability of collembola to disperse microplastics was strongly associated with the size of organisms and microplastics as well as their types (Maaß et al., 2017). Furthermore, Zhu et al. (2017) found that the ability of microarthropods to transport and distribute microplastics in soil was significantly enhanced when there exists a predator-prey relationship. Thus, we can speculate that intricate food webs in soil ecosystems which is composed of diverse and complex species relationships (Bardgett and van der Putten, 2014; Bradford 2016;

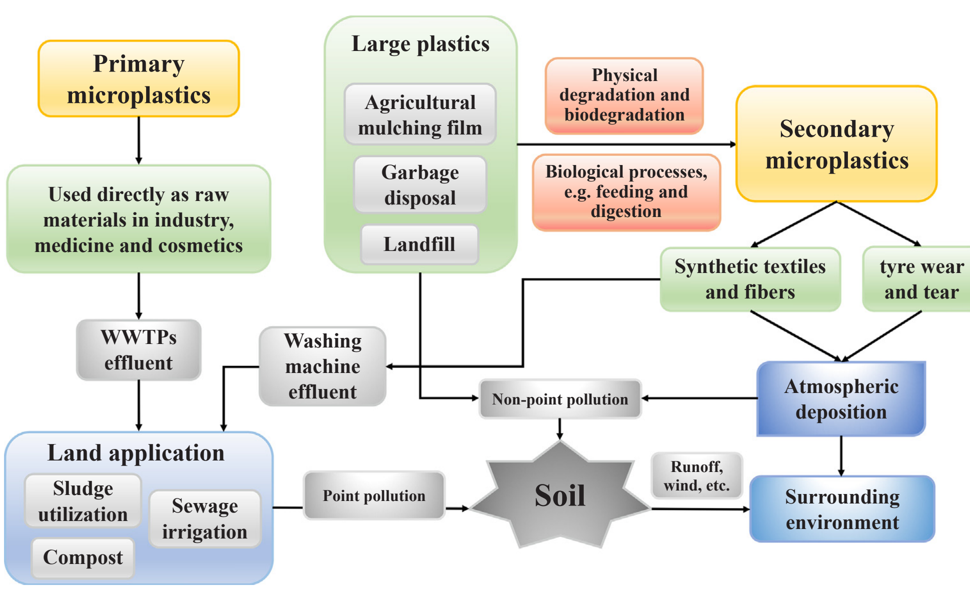

Fig. 1. Sources of microplastics in soil. WWTPs indicates wastewater treatment plants.

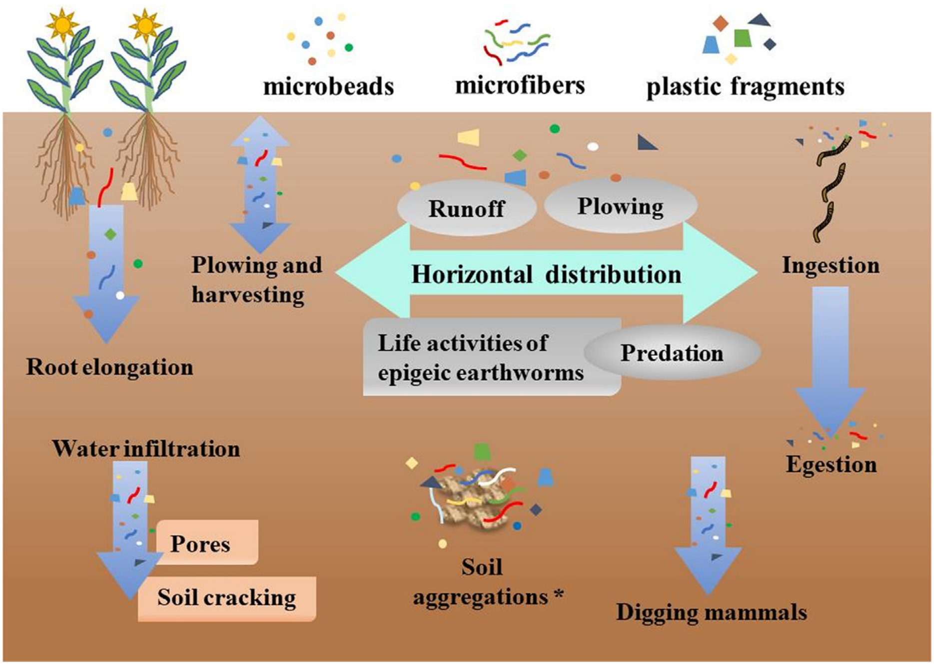

Fig. 2. The various factors affecting the migration of microplastics in soil. Vertical arrows indicate the vertical transport of microplastics in soil. * Microplastic particles can integrate into soil aggregations and incorporate into soil clumps to varying degrees: loosely in microbeads and fragments, while more tightly in microfibers, thus influencing the transport of microplastics in soil.

Bradford et al., 2002) will promote the migration of microplastics compared with the contribution of single species.

That is, soil cracking, pores, agronomic practices (e.g. plowing and harvesting), root elongation of plants, the activities of ingestion and egestion of geophagous soil fauna (notably anecic earthworms), as well as the digging behaviors of other soil animals contribute likely to the most vertical transport of microplastics in soil; whereas the activities of hunting, life activities of epigeic earthworms, as well as agronomic practices can facilitate the horizontal distribution of microplastics in soil (Gabet et al., 2003; Rillig et al., 2017a, 2017b). Additionally, plastic types can also influence the migration, because that microbeads and microfibers have been proved to show different interaction with soil aggregation (de Souza Machado et al., 2018a), which may exert potentially blocking effects on the transport of microplastics in soil. Moreover, transport may be influenced by plastic surface properties and ecocorona altered by the process of degradation (Galloway et al., 2017; Rillig et al., 2017a, 2017b). The concept diagram (Fig. 2) shows the various factors affecting the migration of microplastics in soil.

3.3. *Dispersion of soil microplastics to the surrounding environment*

In addition to migration within the soil, microplastics in soil can migrate to surrounding environmental medium, like air and water, through natural or human phenomena such as wind, dust, erosion and surface runoff (Dris et al., 2017; O'Connor et al., 2019; Rezaei et al., 2019). Microplastics, especially microfibers, loading on soil surface can be lifted into the air thanks to wind and air flows, remaining suspended in the air for some time (Dris et al., 2016; Yurtsever and Kaya, 2018). Microplastics in soil may also be feasibly entered to subsurface receptor, such as aquifers. It has been found recently that wet-dry cycle numbers were positively linear correlated with penetration depths of microplastics, and 100-year penetration depth was estimated as 5.24 m in average (range 1.48–7.42 m) for the 347 cities in China based on the weather data (O'Connor et al., 2019). Using the INCA-Contaminants model, Nizzetto et al. (2016c) developed a simulation to determine the portion of microplastics transferred from soil to the Thames River. Their results demonstrated that more than 60% of microplastics in the soil will eventually migrate into the river catchments and contaminate the water environment. Thus, soil is not only a sink for microplastics but also a source for the surrounding environments.

4. Effects of microplastics in soil

Soil nature influences the migration of microplastics, and microplastics change the properties of soil, such as soil structure and function as well as microbial diversity (He et al., 2019; Rillig, 2012), which may translate to plant and animal consequences and present potential concerns for food quality and safety, ultimately threatening human health (Murugan et al., 2014; Rillig et al., 2019).

The presence of relatively large residual plastic films in soil has been found to reduce the soil saturated hydraulic conductivity and affect the soil microbial activity and abundance, ultimately influencing the soil fertility (Kasirajan and Ngouajio, 2012; Wang et al., 2015a; Zhang et al., 2017). In return, in the complex soil environment, the properties of microplastics in soil are affected by physical and abiotic factors (such as erosion) and biotic factors (such as microbes, earthworms and plant), which depend on the basic physical and chemical properties of soil. The interactions between MPs and the soil may result in an unpredictable impact on the environmental behaviors of other pollutants in soil, thus, causing more serious soil problems. The majority of studies on microplastics are still focused on characterization of semi-quantitative and qualitative metrics; however, a few studies have focused on the alteration of soil physicochemical properties, soil microbes, and also the toxicology of microplastic contamination (de Souza Machado et al., 2018a; He et al., 2018; Liu et al., 2017; Yang et al., 2018) and these will be discussed in this section.

4.1. *Impact on soil health and function*

4.1.1. *Soil structure*

Soil nature may be the primary measure for understanding the risks posed to terrestrial ecosystems by microplastics as microplastics can interact with multiple soil properties (Fig. 3) (de Souza Machado et al., 2018a, 2018b; Lehmann et al., 2019; Liu et al., 2017; Rillig, 2012). Microplastic particles can integrate into soil aggregations and incorporate into soil clumps to varying degrees: loosely in fragment-types and more tightly in linear-types (de Souza Machado et al., 2018a; Zhang and Liu, 2018). Moreover, de Souza Machado et al. (2018a) has found that polyester fibers can significantly increase water holding capacity and significantly decrease bulk density and water-stable aggregation; however, the effects of polyethylene (PE) and polyacrylic

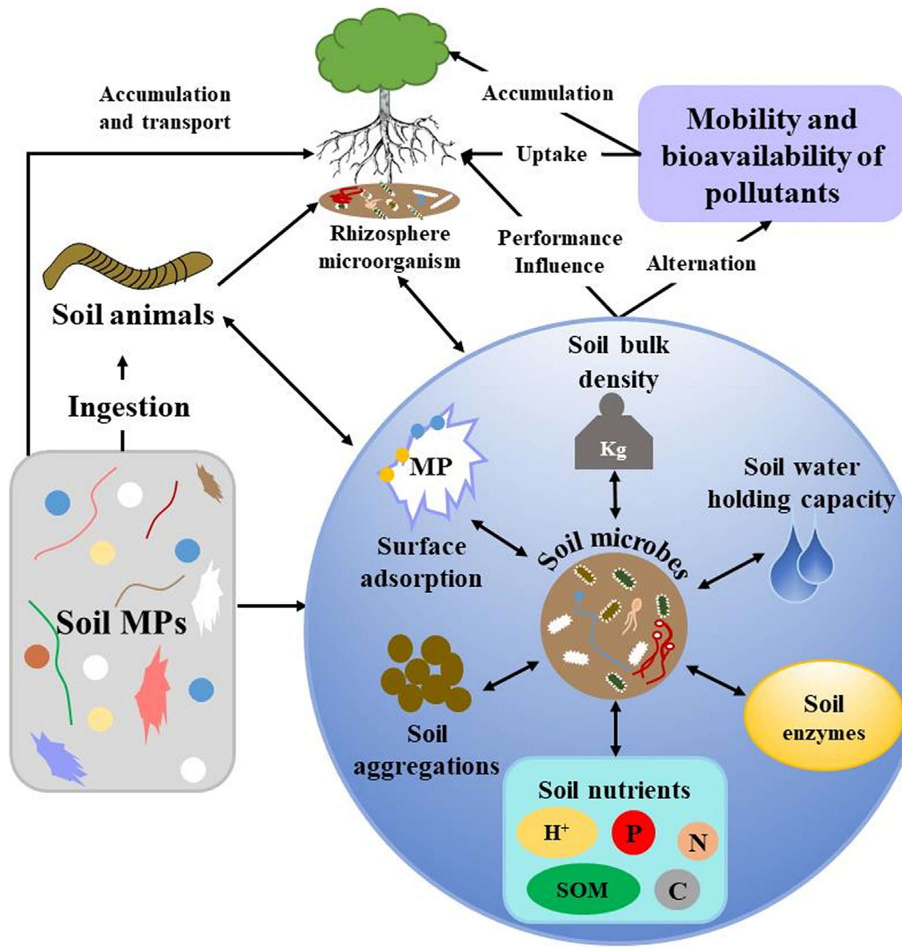

Fig. 3. Impact of microplastics on soil health and function, and potential selection pressures on microbes triggered by microplastics, as well as the corresponding effects to plant growth and ion adsorption. MPs indicates microplastics.

acid on water holding capacity do not exhibit clear trends (de Souza Machado et al., 2018a). Therefore, microplastics of different materials have different effects on soil. Differ from de Souza Machado et al. (2018a), Zhang et al. (2019a) found that no detectable changes were observed in the soil bulk density and indicated a negative effect on the water holding capacity under polyester microfibers treatments, compared with the control treatment. These different findings may ascribe to the physical-chemical character of soil, like soil solids (such as minerals and humus), the soil pore size distribution and so on (Sollins and Gregg, 2017; Zhang et al., 2019a). These changes in soil water dynamics triggered by microplastics could induce the response of multiple physiological indexes of photosynthetic efficiency, thus probably indicating potential consequences for plant performance (de Souza Machado et al., 2019; Faucon et al., 2017). Studies have also shown that microplastics alter the permeability and water retention of soil, which affect water evaporation (de Souza Machado et al., 2018a; Wang et al., 2015a). Wan et al. (2019) investigated how water evaporation and desiccation cracking in two clay soils were affected by the addition of microplastics and reported that both are prominent and increase with increasing microplastic content. Besides, the accumulation of high-molecular-weight humic-like materials promoted by microplastic addition might indicate that microplastics may play a role in improving the soil quality, since that humic-like materials can improve the soil stability, water holding capacity, and nutrient availability, etc. (Liu et al., 2017; Schnitzer, 2000). Based on these results, microplastics can alter the water cycle in soils, exacerbate soil water shortages, and affect the migration of pollutants into deep soil layers along cracks (Rillig et al., 2017a). However, whether the impacts on the soil is positive or negative still requires more in-depth research.

4.1.2. Soil fertility and nutrient

Soil enzymes with a high capacity for catalysis are closely associated with multiple soil biochemical processes; these enzymes act as an indicator for evaluating soil fertility and play an essential role in the regulation of soil nutrient cycling for nutrients such as C, N, and P (Allison and Jastrow, 2006; Trasar-Cepeda et al., 2008). For example, it has been demonstrated that microplastics exhibit significant effects on the activity of the urease, catalase activities, fluorescein diacetate hydrolase (FDAse), and phenol oxidase, (Huang et al., 2019; Liu et al., 2017), which can cause short-term changes in soil quality (Muscolo et al., 2014, 2015). Soil bulk density is an important parameter for extrapolating soil carbon storage and the presence of microplastics may lead to misestimation of soil carbon storage (Rillig, 2018). Furthermore, since microplastics contain high carbon polymers, microplastic-C may be disguised as a significant anthropogenic component of the soil organic carbon pool (Rillig, 2018). For the duration of a 30 - day experiment (Liu et al., 2017), high levels of microplastics (28% w/w) significantly increased the accumulation of DOM and facilitated the release of soil nutrients, such as dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and dissolved organic phosphorus (DOP). However, when the microplastics content was reduced (7% w/w), the accumulation of DOM slowed; the effects of the microplastics were negligible during days 0–7 and the soil nutrient concentrations did not significantly increase until days 14–30. Therefore, the effects of microplastics on soil strongly depend on the concentration of microplastics as well as the exposure time (de Souza Machado et al., 2018a;

Liu et al., 2017).

4.1.3. Soil microbes

Studies have shown that soil features and nutrients are closely correlated with soil microbial activity (Arthur et al., 2012; Girvan et al., 2003; Naveed et al., 2016; Rillig et al. 2017b). Changes to the soil physical environment – especially soil aggregation, which has been found to integrate linear microfibers (de Souza Machado et al., 2018a; Zhang et al., 2019a) – are expected to affect microbial evolution differently than non-microfiber-structured soil (Rillig et al., 2017b, 2018). *De novo* formed aggregates were significantly increased when soil microbe alive compared with the sterile treatment, while this positive effect was neutralized under microfibers treatment (Lehmann et al., 2019). Moreover, changes in soil porosity and soil moisture caused by microplastics may alter the flow of oxygen in soil, which would change the relative distribution of anaerobic and aerobic microorganisms (Rubol et al., 2013). And changes to pore spaces caused by microplastics may lead to microhabitat loss and the extinction of indigenous microorganisms (Veresoglou et al., 2015). Besides, Judy et al. (2019) found that the addition of microplastics significantly interfered with the microbial community structure, and the substrate-induced respiration (SIR) rates significantly decreased, indicating changes in soil microbial function were induced by microplastics. Since DOM acts as a substrate and important source of carbon for microorganisms, it is closely linked to water eutrophication and the greenhouse effect (DeForest et al., 2004a, 2004b; Marschner and Kalbitz, 2003); hence, changes to DOM induced by microplastics (delineated in "4.1.2 Soil fertility and nutrient") may affect soil function and microbial communities. The activity of soil enzymes can reflect microbial activity and the availability of substrates for microorganism uptake; therefore, changes to soil enzymes can indicate potential effects of microplastics on soil microbes. de Souza Machado et al. (2019) found soil fungus, such as the root colonization rate of AMF, were also changed in different degrees by microplastics Generally, microplastics can cause a range of effects on soil properties and exert certain selection pressures on soil microorganisms, which lead to changes in community structure and diversity, and evolutionary consequences (Fig. 3) (Rillig et al., 2018).

4.1.4. Soil contamination

The emergence of microplastics as an ecosystem stressor not only affects soil health and function but also alters soil biophysical properties that lead to complex changes in the environmental behavior of other soil pollutants (Alimi et al. 2018; Wang et al., 2018a; Yang et al., 2019a). Microplastics have an elevated adsorption capacity as the result of their large specific surface area; thus, while microplastics contain additives such as diethylhexyl phthalate (DEHP), which is prevalent organic pollutant during plastic production (Hahladakis et al., 2018b; Groh et al., 2019), they also adsorb hazardous contaminants, including toxic organic chemicals such as polybrominated diphenyl ether (PBDE) and perfluorochemicals (PFOS), heavy metals such as zinc, copper, and lead, and antibiotics (Brennecke et al., 2016; Gaylor et al., 2013; Hodson et al., 2017; Li et al., 2018b; Laganà et al., 2018; Wang et al., 2015). Previous researchers have comprehensively reviewed the presence and release/migration patterns of additives and various other potentially toxic substances of concern (e.g. toxic metals, POPs, etc.) existing in all types of plastics (Hahladakis et al., 2018b; Groh et al., 2019). Their overviews provide very valuable implications that the toxic chemicals present in microplastics can slowly migrate within microplastics to the surface and have the potential to spread in the soil as microplastics migrate in the soil, thus posing ecological and health risk. Hüffer et al. (2019) compared the sorption capacities of soil, polyethylene (PE) microplastics and soil added with 10% of polyethylene microplastics (abbreviated as Soil + PE) to organic contaminants. They found the sorption capacity of Soil + PE was significantly lower than that of soil, i.e. polyethylene microplastics could weaken the sorption capacity of soil, thus facilitating the mobility of organic contaminants in soil. This could be attributed to the fact that the molecular interactions (mainly non-specific van-der Waals interactions) between PE and the sorbates were weaker (Hüffer and Hofmann, 2016) and no cation bridging between PE and the sorbates existed, thus resulting in dilution effects after adding polyethylene microplastics to soil (Hüffer et al., 2019). In turn, the capacity of microplastics to adsorb other pollutants in soil will be influenced by soil and microplastic properties (Yang et al., 2019a). Li et al. (2018b) reported that antibiotics containing carbonyl groups, such as amoxicillin, tetracycline, and ciprofloxacin, exhibit a particularly high sorption capacity on polyamide (PA), which they attributed to its porous structure and hydrogen bonding between its amide group (proton donor group) and the carbonyl groups (proton acceptor group) in amoxicillin, tetracycline, and ciprofloxacin (Antony et al., 2010).

DOM affects the transformation of contaminants by competing for adsorption sites, exposing new reactive surface sites and electron shuttling (Polubesova and Chefetz, 2014). Furthermore, DOM can decrease the sorption of contaminants to soil and enhance the desorption (Yu et al., 2011). Therefore, increased accumulation of DOM induced by microplastics may facilitate the transformation and mobility of contaminants in soil, thus affecting their toxicity and bioavailability (Li et al., 2018c; Liu et al., 2017). Besides, as a photosensitizer, DOM can affect the photolysis of contaminants (Luo et al., 2017). Under certain conditions, DOM can also significantly affect the hydrolysis and redox, which may be ascribed to the competitive adsorption and acceleration of mineral dissolution, as well as metal complexation (Polubesova and Chefetz, 2014). Consequently, alternations of content and composition of DOM will inevitably influence the environmental behavior and degradability of contaminants in soil, probably aggravating soil pollution. Moreover, Liu et al. (2017) has reported that FA-like material increased after adding microplastics, hence affecting the transportation and bioavailability of contaminants in soil. This can be explained by the fact that fulvic acids (FA), which account for a large proportion of DOM in soil, can also act as carrying agents and complexing media for soil contaminants, such as heavy metals and organic chemicals (Chirenje et al., 2002; Perminova et al., 2001). Besides, high-density polyethylene was able to decrease the soil pH (Boots et al., 2019), which might result in an increase of soluble/exchangeable form for heavy metal, thus increasing the mobility and bioavailability (Yu et al., 2016). Therefore, microplastics serve as scavengers and transporters in both marine and soil environments while acting as a multiple stressor (Wang et al., 2018a).

4.2. Ecological and health risks

Regarding the microplastic contamination of soil, the ecological and health risk resulting from microplastic exposure was of significant concern (Carbery et al., 2018; Wright and Kelly, 2017; Zhu et al., 2019). Microplastics may concentrate in human body through various exposure pathways (Fig. 4), such as inhalation of dust, consumption of food or direct drinking water contaminated by microplastics (Dris et al., 2017; Oßmann et al., 2018; Prata, 2018; Schymanski et al., 2018). The estimated intakes of microplastic from dust ingestion for adults and children were in averages of 1063 and 3223 particles per year, respectively (Dehghani et al., 2017).

4.2.1. Trophic transfer of microplastics in terrestrial food chains

Small plastic fragments discovered in the otoliths of lantern fish (*Electrona subaspera*) and the feces of Hooker's sea lions (*Phocartos hookeri*) and fur seals (*Arctocephalus* spp.) hint at the natural trophic transfer of microplastics (Eriksson and Burton, 2003; McMahon et al., 1999). Food chain simulations have confirmed the hypothesis that microplastics can transfer from prey (lower trophic levels) to predators (higher trophic levels) in a food web (Batel et al., 2016; Nelms et al., 2018; Murray and Cowie, 2011; Santana et al., 2017; Setälä et al., 2014). When the retention time of microplastics in the organs of prey is

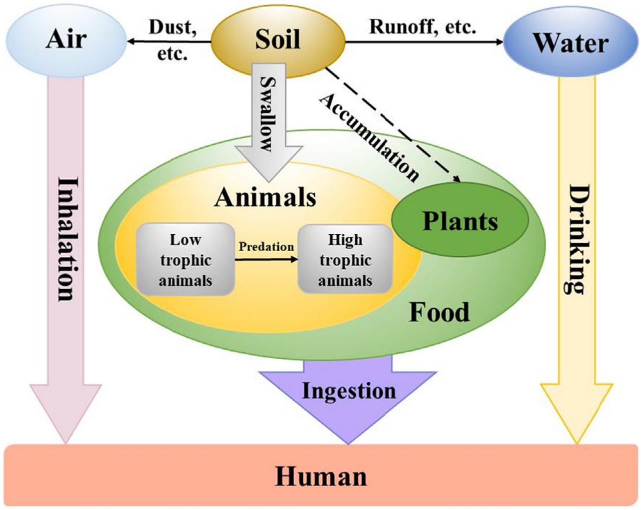

Fig. 4. The human exposure to microplastic through different routes. Inhalation, ingestion of dust, and daily intake of polluted food and water are the major sources of microplastic body burden in humans. The dotted line indicates there is no direct evidence that plants can absorb and accumulate microplastics.

longer than the time from ingestion to egestion, predators are more likely to consume microplastics (Farrel and Nelson 2013; Watts et al., 2014). This indicates that the transfer of microplastics along natural trophic chains appears to be a ubiquitous phenomenon; thus, biomagnification is expected to occur in both marine or terrestrial ecosystems (Au et al., 2017).

There is only limited information about the trophic transfer of microplastics in terrestrial food chains. A recent study (Huerta Lwanga et al., 2017a) reported microplastic particles in the gizzards and feces of chickens that were fed with microplastic-clean crops; two conjectural explanations are (1) macroplastics are converted to microplastics when passing through the digestive tract; and (2) microplastics in chickens may originate from the consumption of earthworms, which are concentrated in microplastics. A demonstration of the second hypothesis would indicate that trophic transfer of microplastics is possible in terrestrial food chains (Huerta Lwanga et al., 2017a). Furthermore, a toxicological experiment studying microplastics in mice has reported the accumulation of microplastics in tissues, including the liver, kidney, and gut (Deng et al., 2017), which suggests that mice can ingest and store microplastics in tissues that will be eaten by animals in higher trophic levels. Thus, the bioaccumulation and biomagnification of microplastics may adversely affect terrestrial food webs and human health.

4.2.2. Effects of microplastics on soil animals

Microplastics adhering to the external surface of organisms may directly hinder their mobility (Kim and An, 2019). In most cases, the ingestion of microplastics is accidental, as organisms mistake microplastics for food (Cole et al., 2013). The ingestion of microplastics can cause false satiation, which reduces the ingestion of carbon biomass, further leading to energy depletion, decreased growth, and even death (da Costa et al., 2016; Setälä et al., 2015). Besides, microplastics can also cause mechanical damage to the esophagus, intestinal obstruction, decreased reproduction, and biochemical responses, like decreased immune response, metabolism disorders, etc. (Lahive et al., 2019; Lönnstedt and Eklöv, 2016; Wang et al., 2019a).

Results from Cao et al. (2017) suggest that microplastics can significantly inhibit the growth of earthworms and have a lethal effect at exposure concentrations of 1% and 2% (w/w). After exposure to microplastics for 28 days, histopathological damage to the earthworms was observed and immune system responses were confirmed by increases to nutrients such as proteins, lipids, and polysaccharides (Rodriguez-Seijo et al., 2017). The food intake and excretion of snails (*Achatina fulica*) were reduced to different degrees after 28-day exposure to microfibers and microfibers induced significant villous injury of gastrointestinal wall of snails (Song et al., 2019). Lu et al. (2018) have reported that exposing mice to microplastics can induce hepatic lipid metabolism disorder, decrease gut mucin secretion, and decrease the mRNA expressions of some key genes controlling lipogenesis and hepatic triglyceride synthesis in the liver and epididymal fat. Furthermore, the consumption of sufficient microplastics can disrupt the gut microbial community structures, cause dysbiosis, and significantly change the richness and diversity of intestinal microbiota (Lu et al., 2018). Microbiota dysbiosis and gut inflammation induced by microplastics have also been found in *Enchytraeus crypticus* (Zhu et al., 2018a) and *Folsomia candida* (Zhu et al., 2018b; Ju et al., 2019). These results imply that the uptake of microplastics by organisms can damage important ecophysiological functions that control health and biodiversity (Browne et al., 2013).

In addition to the hazards of direct ingestion and the intrinsic toxicity of additives in plastics, toxic contaminants such as toxic organic chemicals, heavy metals, and antibiotics can be adsorbed to microplastics, which aggravates soil pollution and amplifies the hazards posed to organisms and humans (Hahladakis et al., 2018a; Hodson et al., 2017; Groh et al., 2019; Besseling et al., 2013; Rodríguez-Seijo et al., 2019). Considerably more zinc was desorbed from microplastics in synthetic earthworm guts than from soil, which suggests that the bioavailability of zinc could be increased by adsorption to microplastics (Hodson et al., 2017). However, Wang et al. (2019b) reported some different findings that the addition of microplastics in high levels, e.g. 5% and 10% (w/w), generally decreased the accumulation of PAHs and PCBs in the earthworm *E. fetida*. This can be explained by the mechanisms hydrophobic organic contaminants (HOCs) entered earthworms, i.e., mainly dermal absorption and ingestion. On the one hand, dermal absorption is closely related to the concentration of freely dissolved chemical in soil porewater, which is decreased by the addition of microplastics due to the hydrophobicity and strong absorption to HOCs (Wang et al., 2018b). On the other hand, the ingestion rate of soil for earthworms significantly higher than that of microplastics (around 10–1000 fold) (Wang et al., 2019b). And even though earthworms take up microplastics, the retention time of microplastics in the earthworms' digestive tract is too short to allow the desorption and redistribution for contaminants pre-absorbed in microplastics, further contributing to the decreased bioaccumulation of contaminants (Besseling et al., 2017; Koelmans et al., 2013, 2016; Wang et al., 2019b). These contrary results give the implication that the adsorption/desorption mechanisms of microplastics to organic and inorganic contaminants, as well as in vitro and in vivo, may be different, which need further in-depth research.

4.2.3. Effects of microplastics on plants

The effects of microplastics on higher plants are still unclear and relative researches are scarce. Existing researches indicated significant effects of microplastics on plants, including wheat (*Triticum aestivum*) (Qi et al., 2018), perennial ryegrass (*Lolium perenne*) (Boots et al., 2019), *Vicia faba* (Jiang et al., 2019), cress (*Lepidium sativum*) (Bosker et al., 2019), and spring onion (*Allium fistulosum*) (de Souza Machado et al., 2019). Polystyrene microplastics (PS-MPs) could induce obvious growth inhibition, genotoxic and oxidative damage to hydroponic *Vicia faba*, and a large amount of 100 nm PS-MPs were observed to accumulate in root tips with the laser confocal scanning microscopy (Jiang et al., 2019). Bosker et al. (2019) discovered that microplastics (4.8 μm) could accumulate on pores in cress (*Lepidium sativum*) seed capsule, and found a significant decrease of gemination rate after 8 h microplastic exposure and significant differences in root growth after 24 h exposure. Microplastics accumulated in plants may trigger a blockade effect on cell connections or cell wall pores thus influencing the absorption and transport of nutrients by plant (Asli and Neumann, 2009; Ma et al., 2010). de Souza Machado et al. (2019) investigated the effects of six different microplastics of three types, including fibers, beads and fragments, on performances of spring onion (*Allium fistulosum*), finding that microplastics cause significant changes in biomass, tissue elemental composition (like water content, leaf nitrogen content and C–N ratio), root traits (including root length, root average diameter, total root area, and root tissue density) and root symbioses; and these consequences were particle types dependent (de Souza Machado et al., 2019). However, Judy et al. (2019) reported some different findings that no significant changes in seedling emergence and biomass of wheat were observed when exposing to microplastics. Therefore, much more researches need to be conducted to address knowledge gaps of influences of microplastics on plants and future studies will be of great interest.

5. Prevention countermeasures for microplastics in soil

Sources of microplastics to soil ecosystems are expected to continue increasing for many years to come because of increasing production, extensive use scaling with the expanding population, their degradation-resistant properties, and the substantial quantities that already exist (Hahladakis et al., 2018a, 2018b; Thompson 2015). Therefore, potential control and remediation measures are urgently needed to attempt to mitigate microplastic pollution and alleviate the risks posed by microplastics.

Over the past decades, plastic waste has been exported to countries where recyclable plastics were manually picked and reused because it is difficult for recycling machines to separate plastics into reusable forms. However, relocating waste rather than improving the treatment process is not a long-term solution. In 2017, China introduced a regulation that prohibits the import of foreign garbage (General Office of the State Council, 2017). This ban on plastic waste imports should be regarded as an impetus to develop sustainable plastic waste management, improve treatment, and boost recycling rates in waste exporting countries (UNEP, 2018a, UNEP, 2018b).

Extensive research studying the ecology and health risks associated with microplastic pollution in marine environments has been conducted and relevant supervision and management strategies for marine environments have been promulgated (UNEP, 2018a, UNEP, 2018b; MST, 2018). However, policies managing microplastic pollution in soil are lagging. Specific regulations need to be implemented and pollution control legislation for microplastics in soil need to be developed. Government departments can contribute to the reduction of soil microplastic pollution through the following four efforts: (1) clarifying the responsibilities, and associated penalties, of government departments and businesses in the production, use, recycling, and disposal of plastics; (2) instituting polluter-pays and beneficiary-compensation as basic principles when designing environment taxes; (3) raising awareness about microplastics through education; and (4) consulting the public, from individuals to non-profit environmental groups, improving public participation, and developing relevant feedback mechanisms and public interest litigation mechanisms.

Further development of microplastic removal technologies is urgently needed; for example, the addition of microplastic removal processes during wastewater treatment will help to reduce the amount of microplastics that enter soil ecosystems from sewage irrigation. In recent years, the removal of microplastics through bioremediation has aroused widespread interest because of its potential for energy conservation and environmental protection. In bioremediation, microorganisms can be employed to biodegrade polymer plastics, which act as a carbon source and provide energy for the microorganisms (Caruso, 2015). As an example, Yang et al. (2014) reported that two bacterial strains, *Enterobacter absuriae* YT1 and *Bacillus* sp. YP1 isolated from the guts of Indian mealmoths (the larvae of *Plodia interpunctella*), have degradation capacity for PE. Mealworms (the larvae of *Tenebrio molitor* Linnaeus) and *Exugiobacterium* sp. YT2 isolated from the guts of mealworms were also reported to have the capacity for polystyrene (PS) degradation, and mealworms can depolymerize and mineralize PS into CO_2 (Yang et al., 2015a, 2015b). Brandon et al. (2018) subsequently demonstrated that mealworms can also degrade chemically dissimilar plastics, such as PE and mixtures (PE + PS), which suggests that mealworm gut microbes are not plastic-specific. They also found that mealworm gut microbes, *Citrobacter* sp. and *Kosakonia* sp., strongly associated with both PE and PS. Similarly, Huerta Lwanga et al. (2017b) extracted two Gram-positive bacteria belonging to the Actinobacteria and Firmicutes phyla from the earthworm guts; these bacteria could break down low-density polyethylene (LDPE) to significantly smaller sizes. Furthermore, the bacteria species *Pseudomonas putida* and *Rhodococcus ruber* were found to be capable of degrading for plastics (Caruso, 2015; Mor and Sivan, 2008). These bacteria have the potential for bioremediation of microplastic-polluted soil. However, the potential risk of the removal of microplastics through bioremediation should be considered. For example, recalcitrant pollutants left as residuals, and the release of sorbed pollutants and the formation of toxic secondary metabolites of plastics from bioremediation may be toxic to terrestrial invertebrates and other specific ecological targets (Andersson et al., 2009; Tang et al., 1998; Ortega-Calvo et al., 2013). Therefore, in order to avoid the secondary pollution to the environment as much as possible, several different organisms are required in biodegradation of microplastics, i.e., the first one is able to break down complex polymers into smaller molecules of short chains (e.g. oligomers or their constituent monomers); the second one is capable of using the oligomers or monomers and excreting simple waste compounds; and the third one is capable of using the excreted wastes (Shah et al., 2008). Even so, on account of the incorporating into humus, natural products, and microbial biomass, the biodegradation of microplastic can hardly reach 100% (Narayan, 1993). In this case, combined multiple technologies to control microplastics, including physical/chemical removal and degradation (e.g. photodegradation, oxidation, thermal degradation, etc.), as well as bioremediation, are expected to yield better effects (Shah et al., 2008).

6. Future research – Priority recommendations

Despite progress in the isolation, measurement, and identification of microplastics in soil, there are still many scientific problems that must be solved. Here, we highlight several major knowledge gaps that need to be addressed.

- Microplastics of different types, sizes, shapes, and product uses have distinct effects on soil because of their structure and nature. Therefore, diverse types of microplastics with various purposes and origins should be included in an experiment studying their environmental effects. Besides, results from both marine or soil organisms suggest that the toxicity of microplastics is dependent on dosage and exposure time. Therefore, purely qualitative or quantitative studies of soil microplastics may underestimate the influence of microplastics on soil and organisms. Field and laboratory experiments are needed to establish the extent to which minimum concentration and exposure time induce adverse effects. Moreover, Zhang et al. (2019a) found that polyester microfibers significantly induced the contents of water-stable large macroaggregates (> 2 mm) increasing, while this phenomenon was not observed in the field experiment. Therefore, more field experiments are needed to further demonstrate the impacts of microplastics on soil physical properties. And uniform standard for quantification and qualification of microplastics in soil urgently need to be established to make different researches comparable.
- Browne et al. (2015) developed a methodology to establish ecological linkages to anthropogenic debris and to examine and guide the management of ecological impacts using population models. This recommends that more research on different microplastics is needed to assess impacts to ecological linkages and to help reduce the

threats posed by microplastics, rather than more research focusing on the presence of microplastics and their sublethal effects. Furthermore, how to distinguish the toxicity and risk of MPs from their carried contaminants and the plastic additives should be considered and need in-depth research.

- The adsorption capacity of microplastics is generally comparable to that of other environment pollutants, but the adsorption capacity of different microplastic materials differs greatly for different antibiotics under various environment conditions (Antony et al., 2010). Moreover, humic acid (HA) is reported to be connected to the fate and transport of nanoparticles (Chae et al., 2012; Chen et al., 2012). Wu et al. (2019) found that humic acid (HA) accelerated the aggregation of negative charged nanoplastics, i.e. presenting a significantly stable effect. It could be speculated that the surface properties of microplastics might be changed by soil HA, thus affecting the adsorption of pollutants on microplastics and soils, which is worth to study in-depth.
- Nanoplastics with dimensions less than 6 nm are speculated to permeate the plant cell wall (Carpita et al., 1979). Bandmann et al. (2012) demonstrated that nanopolystyrene beads with dimensions of 20 and 40 nm can be taken up by tobacco BY-2 cells via endocytosis in vitro. There has yet to be a study investigating the uptake, translocation, and accumulation of microplastics in plants. Although the uptake of microplastics by plants is not expected, further studies are needed to confirm this hypothesis and investigate stress responses induced by microplastics. Moreover, changes to soil properties triggered by microplastics have the potential to affect the chemical forms and bioavailability of soil contaminants; thus, the effects of microplastics on plants' accumulation of other soil pollutants should also be considered.
- Some marine colonies of microbiota live in plastic environments, which are collectively referred to as the plastisphere (Zettler et al. 2013). However, only a few researches are conducted in soil. Zhang et al. (2019b) discovered that a significant difference in bacterial community structure was existed between microplastic surfaces and surrounding soil or other organic residues; the former was enriched taxa that can degrade microplastics, especially pits and flakes, indicating an active hydrolysis effect of bacteria on microplastics. More research is needed to uncover these biological mechanisms and improve our understanding of the plastisphere.
- High values on the Shannon-Wiener index, which correspond to diverse communities, and the relative diversity of antibiotic and metal resistance genes (ARGs and MRGs) in plastisphere microbiota compared with seawater microbiota indicate that microplastics act as a reservoir for ARGs and MRGs (Yang et al., 2019b). Arias-Andres et al. (2018) investigated whether aquatic bacteria that formed biofilms on microplastics were permissive towards a model antibiotic resistance plasmid, and discovered that microplastics profoundly affect the evolution of microbial communities and increase the frequency of gene exchange. These results pose serious health risks that cannot be ignored. Besides direct soil contamination, microplastics have been found to indirectly affect the natural functions of terrestrial ecosystems by influencing the fundamental properties of soils in important ways. However, there is only limited information about how microplastics disturb the microbiome in soil, as well as the phyllosphere, endosphere, spermosphere, and rhizosphere of plants. Thus, there are probably functional genes that control changes to soil properties and toxicological responses of organisms that ingest or are exposed to microplastics.

7. Conclusions

Microplastics are small, heterogeneously mixed plastics that enter soil ecosystems through landfills, agricultural mulching films, sewage irrigation, and other sources, and are pervasive in arable soils. The vertical and horizontal migration of microplastics within soil is influenced by several factors, such as soil biota and soil features, and microplastics change the structure of soil when they are integrated into soil aggregates. Microplastics can also interact with other soil factors, influencing soil health and function, and they have elevated adsorption capacity for hazardous contaminants, which aggravates soil pollution and increases adverse effects to organisms and human health. Furthermore, microplastics are easily ingested by soil organisms because of their small size and are transferred through the food chain; the ingestion of microplastics causes both mechanical and physiological damage. And microplastics have potential effects on plant growth and may accumulate and transport in plants. Here, we have recommended several areas for future research on soil microplastics and potential remediation measures are urgently needed to mitigate risks posed by microplastic pollution. Bacteria that can biodegrade microplastics provide a promising, environmentally friendly measure for bioremediation of microplastic-polluted soil.

Acknowledgements

This work was supported by the NSFC-Guangdong Joint Fund (U1501233), National Natural Science Foundation of China (NSFC) (41301337), Research Team Project of the Natural Science Foundation of Guangdong Province (2016A030312009), Science and Technology Project of GuangzhouCity (201704020074), and the Program of the Guangdong Science and Technology Department (2016B020242005, 2017B020238002).

References

Al-Jaibachi, R., Cuthbert, R.N., Callaghan, A., 2019. Examining effects of ontogenic microplastic transference on Culex mosquito mortality and adult weight. Sci. Total Environ. 651, 871–876. https://doi.org/10.1016/j.scitotenv.2018.09.236.

Alimi, O.S., Farner Budarz, J., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52 (4), 1704–1724. https://doi.org/10.1021/acs.est.7b05559.

Allison, S.D., Jastrow, J.D., 2006. Activities of extracellular enzymes in physically isolated fractions of restored grassland soils. Soil Biol. Biochem. 38, 3245–3256. https://doi.org/10.1016/j.soilbio.2006.04.011.

Alomar, C., Estarellas, F., Deudero, S., 2016. Microplastics in the Mediterranean Sea: deposition in coastal shallow sediments, spatial variation and preferential grain size. Mar. Environ. Res. 115, 1–10. https://doi.org/10.1016/j.marenvres.2016.01.005.

Andersson, E., Rotander, A., von Kronhelm, T., Berggren, A., Ivarsson, P., Hollert, H., Engwall, M., 2009. AhR agonist and genotoxicant bioavailability in a PAH-contaminated soil undergoing biological treatment. Environ. Sci. Pollut. Res. 16 (5), 521–530. https://doi.org/10.1007/s11356-009-0121-9.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Antony, A., Fudianto, R., Cox, S., Leslie, G., 2010. Assessing the oxidative degradation of polyamide reverse osmosis membrane-accelerated ageing with hypochlorite exposure. J. Membr. Sci. 347, 159–164. https://doi.org/10.1016/j.memsci.2009.10.018.

Arias-Andres, M., Klümper, U., Rojas-Jimenez, K., Grossart, H.P., 2018. Microplastic pollution increases gene exchange in aquatic ecosystems. Environ. Pollut. 237, 253–261. https://doi.org/10.1016/j.envpol.2018.02.058.

Arthur, E., Moldrup, P., Holmstrup, M., Schjonning, P., Winding, A., Mayer, P., de Jonge, L.W., 2012. Soil microbial and physical properties and their relations along a steep copper gradient. Agric. Ecosyst. Environ. 159, 9–18. https://doi.org/10.1016/j.agee.2012.06.021.

Asli, S., Neumann, P.M., 2009. Colloidal suspensions of clay or titanium dioxide nanoparticles can inhibit leaf growth and transpiration via physical effects on root water transport. Plant Cell Environ. 32, 577–584. https://doi.org/10.1111/j.1365-3040.2009.01952.x.

Au, S.Y., Lee, C.M., Weinstein, J.E., Peter, V.D.H., Klaine, S.J., 2017. Trophic transfer of microplastics in aquatic ecosystems: identifying critical research needs. Integr. Environ. Asses. 13 (3), 505–509. https://doi.org/10.1002/ieam.1907.

Auta, H.S., Emenike, C.U., Fauziah, S.H., 2017. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ. Int. 102, 165–176. https://doi.org/10.1016/j.envint.2017.02.013.

Bandmann, V., Müller, J.D., Köhler, T., Homann, U., 2012. Uptake of fluorescent nano beads into BY2-cells involves clathrin-dependent and clathrin-independent endocytosis. FEBS Lett. 586, 3626–3632. https://doi.org/10.1016/j.febslet.2012.08.008.

Batel, A., Linti, F., Scherer, M., Erdinger, L., Braunbeck, T., 2016. The transfer of benzo[a]pyrene from microplastics to artemia nauplii and further to zebrafish via a trophic food web experiment - cyp1a induction and visual tracking of persistent organic pollutants. Environ. Toxicol. Chem. 35 (7), 1656–1666. https://doi.org/10.1002/etc.3361.

Bardgett, R.D., van der Putten, W.H., 2014. Belowground biodiversity and ecosystem functioning. Nature 515, 505–511. https://doi.org/10.1038/nature13855.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. T. R. Soc. B 364, 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

Belzagui, F., Crespi, M., Álvarez, A., Gutiérrez-Bouzán, C., Vilaseca, M., 2019. Microplastics' emissions: Microfibers' detachment from textile garments. Environ. Pollut. 248, 1028–1035. https://doi.org/10.1016/j.envpol.2019.02.059.

Besseling, E., Wegner, A., Foekema, E.M., van den Heuvel-Greve, M.J., Koelmans, A.A., 2013. Effects of microplastic on fitness and PCB bioaccumulation by the lugworm *Arenicola marina* (L.). Environ. Sci. Technol. 47, 593–600. https://doi.org/10.1021/es302763x.

Besseling, E., Foekema, E.M., van den Heuvel-Greve, M.J., Koelmans, A.A., 2017. The effect of microplastic on the uptake of chemicals by the lugworm Arenicola marina (L.) under environmentally relevant exposure conditions. Environ. Sci. Technol. 51 (15), 8795–8804. https://doi.org/10.1021/acs.est.7b02286.

Boots, B., Russell, C.W., Green, D.S., 2019. Effects of microplastics in soil ecosystems: above and below ground. Sci. Technol. Environ. https://doi.org/10.1021/acs.est.9b03304.

Bosker, T., Bouwman, L.J., Brun, N.R., Behrens, P., Vijver, M.G., 2019. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *Lepidium sativum*. Chemosphere 226, 774–781. https://doi.org/10.1016/j.chemosphere.2019.03.163.

Bradford, M.A., 2016. Re-visioning soil food webs. Soil Biol. Biochem. 102, 1–3. https://doi.org/10.1016/j.soilbio.2016.08.010.

Bradford, M.A., Jones, T.H., Bardgett, R.D., Black, H.I.J., Boag, B., Bonkowski, M., Cook, R., Eggers, T., Gange, A.C., Grayston, S.J., Kandeler, E., McCaig, A.E., Newington, J.E., Prosser, J.I., Setala, H., Staddon, P.L., Tordoff, G.M., Tscherko, D., Lawton, J.H., 2002. Impacts of soil faunal community composition on model grassland ecosystems. Science 298, 615–618. https://doi.org/10.1126/science.1075805.

Brandon, A.M., Gao, S.H., Tian, R., Ning, D., Yang, S.S., Zhou, J., Wu, W.M., Criddle, C.S., 2018. Biodegradation of polyethylene and plastic mixtures in mealworms (Larvae of *Tenebrio molitor*) and effects on the gut microbiome environ. Sci. Technol. 52, 6526–6533. https://doi.org/10.1021/acs.est.8b02301.

Brennecke, D., Duarte, B., Paiva, F., Cacador, I., Canning-Clode, J., 2016. Microplastics as vectors for heavy metal contamination from the marine environment. Estuar. Coast. Shelf. Sci. 175, 189–195. https://doi.org/10.1016/j.ecss.2015.12.003.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T.S., Thompson, R.C., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179. https://doi.org/10.1021/es201811s.

Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., Thompson, R.C., 2013. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr. Biol. 23, 2388–2392. https://doi.org/10.1016/j.cub.2013.10.012.

Browne, M.A., Underwood, A.J., Chapman, M.G., Williams, R., Thompson, R.C., van Franeker, J.A., 2015. Linking effects of anthropogenic debris to ecological impacts. Proc. R. Soc. B Biol. Sci. 282. https://doi.org/10.1098/rspb.2014.2929.

Cao, D., Xiao, W., Luo, X., Liu, G., Zheng, H., 2017. Effects of polystyrene microplastics on the fitness of earthworms in an agricultural soil. IOP Conf. Ser. Earth Environ. Sci. 61, 12148. https://iopscience.iop.org/article/10.1088/1755-1315/61/1/012148/meta.

Carbery, M., O'Connor, W., Palanisami, T., 2018. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ. Intern. 115, 400–409. https://doi.org/10.1016/j.envint.2018.03.007.

Carpita, N., Sabularse, D., Montezinos, D., Delmer, D.P., 1979. Determination of the pore size of cell walls of living plant cells. Science 80, 1144–1147. http://science.sciencemag.org/content/205/4411/1144.

Caruso, G., 2015. Plastic degrading microorganisms as a tool for bioremediation of plasticcontamination in aquatic environments. Pollut. Eff. Control 3, e112. https://doi.org/10.4172/2375-4397.1000e112.

Castañeda, R.A., Avlijas, S., Simard, M.A., Ricciardi, A., 2014. Microplastic pollution in St. Lawrence River sediments. Can. J. Fish. Aquat. Sci. 70, 1767–1771. https://doi.org/10.1139/cjfas-2014-0281.

Chae, S.R., Xiao, Y., Lin, S., Noeiaghaei, T., Kim, J.O., Wiesner, M.R., 2012. Effects of humic acid and electrolytes on photocatalytic reactivity and transport of carbon nanoparticle aggregates in water. Water Res. 46 (13), 4053–4062. https://doi.org/10.1016/j.watres.2012.05.018.

Chae, Y., An, Y.J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. Environ. Pollut. 240, 387–395. https://doi.org/10.1016/j.envpol.2018.05.008.

Chen, G., Liu, X., Su, C., 2012. Distinct effects of humic acid on transport and retention of TiO_2 rutile nanoparticles in saturated sand columns. Environ. Sci. technol. 46 (13), 7142–7150. https://doi.org/10.1021/es204010g.

Chirenje, T., Rivero, C., Ma, L.Q., 2002. Leachability of Cu and Ni in wood ashamended soil as impacted by humic and fulvic acid. Geoderma 108, 31–47. https://doi.org/10.1016/S0016-7061(02)00120-9.

Claessens, M., De, M.S., Van, L.L., De, C.K., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204. https://doi.org/10.1016/j.marpolbul.2011.06.030.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moge, R.J., Galloway, T.S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47, 6646–6655. https://doi.org/10.1021/es400663f.

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., Geissen, V., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci. Total Environ. 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368.

Cózar, Z., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Ubeda, B., HernándezLeón, S., Palma, Á.T., Navarro, S., García-de-Lomas, J., Ruiz, A., Fernández-de-Puelles, M.L., Duarte, C., 2014. Plastic debris in the open ocean. P. Natl. Acad. Sci. USA 111, 10239–10244. https://doi.org/10.1073/pnas.1314705111.

da Costa, J.P., Santos, P.S., Duarte, A.C., Rocha-Santos, T., 2016. (Nano) plastics in the environment - sources, fates and effects. Sci. Total Environ. 566, 15–26. https://doi.org/10.1016/j.scitotenv.2016.05.041.

Dahlbo, H., Poliakova, V., Mylläri, V., Sahimaa, O., Anderson, R., 2018. Recycling potential of post-consumer plastic packaging waste in Finland. Waste Manage. 71, 52–61. https://doi.org/10.1016/j.wasman.2017.10.033.

DeForest, J.L., Zak, D.R., Pregitzer, K.S., Burton, A.J., 2004a. Atmospheric nitrate deposition and the microbial degradation of cellobiose and vanillin in a northern hardwood forest. Soil Biol. Biochem. 36, 965–971. https://doi.org/10.1016/j.soilbio.2004.02.011.

DeForest, J.L., Zak, D.R., Pregitzer, K.S., Burton, A.J., 2004b. Atmospheric nitrate deposition, microbial community composition, and enzyme activity in northern hardwood forests. Soil Sci. Soc. Am. J. 68, 132–138. https://doi.org/10.2136/sssaj2004.1320.

Dehghani, S., Moore, F., Akhbarizadeh, R., 2017. Microplastic pollution in deposited urban dust, Tehran metropolis. Iran. Environ. Sci. Pollut. R. 24 (25), 20360–20371. https://doi.org/10.1007/s11356-017-9674-1.

Deng, Y., Zhang, Y., Lemos, B., Ren, H., 2017. Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. Sci. Rep. 7, 46687. https://doi.org/10.1038/srep46687.

de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R., Rillig, M.C., 2018a. Impacts of Microplastics on the Soil Biophysical Environment. Global Change Biol. 24, 1405–1416. https://doi.org/10.1021/acs.est.8b02212.

de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018b. Microplastics as an emerging threat to terrestrial ecosystems. Global Change Boil. 24 (4), 1405–1416. https://doi.org/10.1111/gcb.14020.

de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., Becker, R., Görlich, A.S., Rillig, M.C., 2019. Microplastics can change soil properties and affect plant performance. Environ. Sci. Technol. 53, 6044–6052. https://doi.org/10.1021/acs.est.9b01339.

Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. Mar. Environ. Res. 71 (1), 41–52. https://doi.org/10.1016/j.marenvres.2010.10.001.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., 2015. Microplastic contamination in an urban area-a case study in greater Paris. Environ. Sci. Technol. 12, 592–599. https://doi.org/10.1071/EN14167.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104 (1), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006.

Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., Tassin, B., 2017. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ. Pollut. 221, 453–458. https://doi.org/10.1016/j.envpol.2016.12.013.

Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ. Sci. Eur. 28, 1–25. https://doi.org/10.1186/s12302-015-0069-y.

Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. AMBIO: J. Human Environ. 32, 380–384. https://doi.org/10.1579/0044-7447-32.6.380.

Farrel, P., Nelson, K., 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ. Pollut. 177, 1–3. https://doi.org/10.1016/j.envpol.2013.01.046.

Faucon, M.-P., Houben, D., Lambers, H., 2017. Plant functional traits: soil and ecosystem services. Trends Plant Sci. 22 (5), 385–394. https://doi.org/10.1016/j.tplants.2017.01.005.

Fuller, S.G., Gautam, A., 2016. A procedure for measuring microplastics using pressurized fluid extraction. Environ. Sci. Technol. 50, 5774–5780. https://pubs.acs.org.ccindex.cn/doi/10.1021/acs.est.6b00816.

Gabet, E.J., Reichman, O.J., Seabloom, E.W., 2003. The effect of bioturbation on soil processes and sediment transport. Ann. Rev. Earth Planet. Sci. 31, 249–273. https://doi.org/10.1146/annurev.earth.31.100901.141314.

Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 0116. https://doi.org/10.1038/s41559-017-0116.

Gaylor, M.O., Harvey, E., Hale, R.C., 2013. Polybrominated diphenyl ether (PBDE) accumulation by earthworms (Eisenia fetida) exposed to biosolids-, polyurethane foam microparticle-, and Penta-BDE-amended soils. Environ. Sci. Technol. 47, 13831–13839. https://doi.org/10.1021/es403750a.

General Office of the State Council, China, 2017. http://www.gov.cn/zhengce/content/2017-07/27/content_5213738.htm.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, 1–5. https://doi.org/10.1126/sciadv.1700782.

Gieré, R., Sommer, F., Dietze, V., Baum, A., Gilge, S., Sauer, J., Maschowski, C., 2018. Tire-wear particles as a major component of microplastics in the environment. Geol. Soc. Am. 50 (6). https://doi.org/10.1130/abs/2018AM-319219. 149-1.

Girvan, M.S., Bullimore, J., Pretty, J.N., Osborn, A.M., Ball, A.S., 2003. Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. Appl. Environ. Microbiol. 69, 1800–1809. https://doi.org/10.1128/

AEM.69.3.1800-1809.2003.
Groh, K.J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P.A., Lennquist, A., Leslie, H.A., Maffini, M., Slunge, D., Trasande, L., Warhurst, A.M., Muncke, J., 2019. Overview of known plastic packaging-associated chemicals and their hazards. Sci Total Environ. 651, 3253–3268. https://doi.org/10.1016/j.scitotenv.2018.10.015.
Gutierrez-Lopez, M., Salmon, S., Trigo, D., 2011. Movement response of Collembola to the excreta of two earthworm species: importance of ammonium content and nitrogen forms. Soil Biol. Biochem. 43, 55–62. https://doi.org/10.1016/j.soilbio.2010.09.010.
Gündoğdu, S., Çevik, C., Güzel, E., Kilercioğlu, S., 2018. Microplastics in municipal wastewater treatment plants in Turkey: a comparison of the influent and secondary effluent concentrations. Environ. Monit. Assess. 190, 626. https://doi.org/10.1007/s10661-018-7010-y.
Hahladakis, J.N., Iacovidou, E., 2018. Closing the loop on plastic packaging materials: what is quality and how does it affect their circularity? Sci. Total Environ. 630, 1394–1400. https://doi.org/10.1016/j.scitotenv.2018.02.330.
Hahladakis, J.N., Purnell, P., Iacovidou, E., Velis, C.A., Atseyinku, M., 2018a. Post-consumer plastic packaging waste in England: assessing the yield of multiple collection-recycling schemes. Waste Manage. 75, 149–159. https://doi.org/10.1016/j.wasman.2018.02.009.
Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018b. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. 344, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014.
Hartline, N.L., Bruce, N.J., Karba, S.N., Ruff, E.O., Sonar, S.U., Holden, P.A., 2016. Microfiber masses recovered from conventional machine washing of new or aged garments. Environ. Sci. Technol. 50 (21), 11532–11538. https://doi.org/10.1021/acs.est.6b03045.
Hays, H., Cormons, G., 1974. Plastic particles found in tern pellets, on coastal beaches and at factory sites. Mar. Pollut. Bull. 5, 44–46. https://doi.org/10.1016/0025-326X(74)90234-3.
He, L., Wu, D., Rong, H.F., Li, M., Tong, M.P., Kim, H., 2018. Influence of nano- and microplastic particles on the transport and deposition behaviors of bacteria in quartz sand. Environ. Sci. Technol. 52, 11555–11563. https://doi.org/10.1021/acs.est.8b01673.
He, P., Chen, L., Shao, L., Zhang, H., Lü, F., 2019. Municipal solid waste (MSW) landfill: a source of microplastics?-evidence of microplastics in landfill leachate. Water Res. 159, 38–45. https://doi.org/10.1016/j.watres.2019.04.060.
Hodson, M.E., Duffus-Hodson, C.A., Clark, A., Prendergast-Miller, M.T., Thorpe, K.L., 2017. Plastic bag derived-microplastics as a vector for metal exposure in terrestrial invertebrates. Environ. Sci. Technol. 51, 4714–4721. https://doi.org/10.1021/acs.est.7b00635.
Hoffman, M.J., Hittinger, E., 2017. Inventory and transport of plastic debris in the Laurentian great lakes. Mar. Pollut. Bull. 115, 273–281. https://doi.org/10.1016/j.marpolbul.2016.11.061.
Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190.
Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Sal Anki, T., Van, D.P.M., Besseling, E., Koelmans, A.A., Geissen, V., 2016. Microplastics in the terrestrial ecosystem: implications for Lumbricus terrestris (Oligochaeta, lumbricidae). Environ. Sci. Technol. 50, 2685–2691. https://doi.org/10.1021/acs.est.5b05478.
Huerta Lwanga, E., Vega, J.M., Quej, V.K., Chi, J.D.L.A., Cid, L.S.D., Chi, C., Segura, G.E., Gertsen, H., Salánki, T., van der Ploeg, Martine, Koelmans, A.A., Geissen, V., 2017a. Field evidence for transfer of plastic debris along a terrestrial food chain. Sci. Rep. 7, 1–7. https://doi.org/10.1038/s41598-017-14588-2.
Huerta Lwanga, E., Thapa, B., Yang, X., Gertsen, H., Salánki, T., Geissen, V., Garbeva, P., 2017b. Decay of low-density polyethylene by bacteria extracted from earthworm's guts: a potential for soil restoration. Sci. Total Environ. 624, 753–757. https://doi.org/10.1016/j.scitotenv.2017.12.144.
Hurley, R., Nizzetto, L., 2018. Fate and occurrence of micro(nano)plastics in soils: knowledge gaps and possible risks. Curr. Opin. Environ. Sci. Heal. 1, 6–11. https://doi.org/10.1016/j.coesh.2017.10.006.
Huang, Y., Zhao, Y., Wang, J., Zhang, M., Jia, W., Qin, X., 2019. LDPE microplastic films alter microbial community composition and enzymatic activities in soil. Environ. Pollut. 254, 112983. https://doi.org/10.1016/j.envpol.2019.112983.
Hüffer, T., Hofmann, T., 2016. Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous solution. Environ. Pollut. 214, 194–201. https://doi.org/10.1016/j.envpol.2016.04.018.
Hüffer, T., Metzelder, F., Sigmund, G., Slawek, S., Schmidt, T.C., Hofmann, T., 2019. Polyethylene microplastics influence the transport of organic contaminants in soil. Sci. Total Environ. 657, 242–247. https://doi.org/10.1016/j.scitotenv.2018.12.047.
Imhof, H.K., Sigl, R., Brauer, E., Feyl, S., Giesemann, P., Klink, S., Leupolz, K., LÃ¶der, M.G., LÃ¶schel, L.A., Missun, J., Muszynski, S., 2017. Spatial and temporal variation of macro-, meso-and microplastic abundance on a remote coral island of the Maldives. Indian Ocean. Mar. Pollut. Bull. 116 (1â€"2), 340–347. https://doi.org/10.1016/j.marpolbul.2017.01.010.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352.
Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobučar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. Environ. Pollut. 250, 831–838. https://doi.org/10.1016/j.envpol.2019.04.055.
Ju, H., Zhu, D., Qiao, M., 2019. Effects of polyethylene microplastics on the gut microbial community, reproduction and avoidance behaviors of the soil springtail, *Folsomia candida*. Environ. Pollut. 247, 890–897. https://doi.org/10.1016/j.envpol.2019.01.097.
Judy, J.D., Williams, M., Gregg, A., Oliver, D., Kumar, A., Kookana, R., Kirby, J.K., 2019. Microplastics in municipal mixed-waste organic outputs induce minimal short to long-term toxicity in key terrestrial biota. Environ. Pollut. 252, 522–531. https://doi.org/10.1016/j.envpol.2019.05.027.
Kasirajan, S., Ngouajio, M., 2012. Polyethylene and biodegradable mulches for agricultural applications: a review. Agron. Sustain. Dev. 32, 501–529. https://doi.org/10.1007/s13593-011-0068-3.
Kim, S.W., An, Y.J., 2019. Soil microplastics inhibit the movement of springtail species. Environ. Intern. 126, 699–706. https://doi.org/10.1016/j.envint.2019.02.067.
Koelmans, A.A., Besseling, E., Wegner, A., Foekema, E.M., 2013. Plastic as a carrier of POPs to aquatic organism: a model analysis. Environ. Sci. Technol. 47, 7812–7820. https://doi.org/10.1021/es401169n.
Koelmans, A.A., Bakir, A., Burton, G.A., Janssen, C.R., 2016. Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies. Environ. Sci. Technol. 50, 3315–3326. https://doi.org/10.1021/acs.est.5b06069.
Kole, P.J., Löhr, A.J., Van Belleghem, F., Ragas, A., 2017. Wear and tear of tyres: a stealthy source of microplastics in the environment. Int. J. Environ. Res. Public Health. 14 (10), 1265. https://doi.org/10.3390/ijerph14101265.
Laganà, P., Caruso, G., Corsi, I., Bergami, E., Venutid, V., Majolino, D., Ferla, R.L., Azzaro, M., Cappello, S., 2018. Do plastics serve as a possible vector for the spread of antibiotic resistance? First insights from bacteria associated to a polystyrene piece from King George Island (Antarctica). Int. J. Hy. Environ. Heal. 222, 89–100. https://doi.org/10.1016/j.ijheh.2018.08.009.
Lahive, E., Walton, A., Horton, A.A., Spurgeon, D.J., Svendsen, C., 2019. Microplastic particles reduce reproduction in the terrestrial worm *Enchytraeus crypticus* in a soil exposure. Environ. Pollut. 113174. https://doi.org/10.1016/j.envpol.2019.113174.
Lassen, C., Hansen, S.F., Magnusson, K., Hartmann, N.B., Rehne Jensen, P., Nielsen, T.G., Brinch, A., 2015. Microplastics: Occurrence, Effects and Sources of Releases to the Environment in Denmark, vol. 1793, 206. https://www2.mst.dk/Udgiv/publications/2015/10/978-87-93352-80-3.pdf.
Lehmann, A., Fitschen, K., Rillig, M.C., 2019. Abiotic and biotic factors influencing the effect of microplastic on soil aggregation. Soil Syst. 3 (1), 21. https://doi.org/10.3390/soilsystems3010021.
Li, X., Chen, L., Mei, Q., Dong, B., Dai, X., Ding, G., Zeng, E.Y., 2018a. Microplastics in sewage sludge from the wastewater treatment plants in China. Water Res. 142, 75. https://doi.org/10.1016/j.watres.2018.05.034.
Li, J., Zhang, K., Zhang, H., 2018b. Adsorption of antibiotics on microplastics. Environ. Pollut. 237, 460–467. https://doi.org/10.1016/j.envpol.2018.02.050.
Li, G., Khan, S., Ibrahim, M., Sun, T.R., Tang, J.F., Cotner, J.B., Xu, Y.Y., 2018c. Biochars induced modification of dissolved organic matter (DOM) in soil and its impact on mobility and bioaccumulation of arsenic and cadmium. J. Hazard. Mater. 348, 100–108. https://doi.org/10.1016/j.jhazmat.2018.01.031.
Liu, H., Yang, X., Liu, G., Liang, C., Xue, S., Chen, H., Ritsema, C.J., Geissen, V., 2017. Response of soil dissolved organic matter to microplastic addition in chinese loess soil. Chemosphere 185, 907–917. https://doi.org/10.1016/j.chemosphere.2017.07.064.
Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X., He, D., 2018. Microplastic and m esoplastic pollution in farmland soils in suburbs of Shanghai. China. Environ. Pollut. 242, 855–862. https://doi.org/10.1016/j.envpol.2018.07.051.
Liu, K., Wang, X.H., Fang, T., Xu, P., Zhu, L.X., Li, D.J., 2019. Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Sci. Total Environ. 675, 462–471. https://doi.org/10.1016/j.scitotenv.2019.04.110.
Lönnstedt, O.M., Eklöv, P., 2016. Environmentally relevant concentrations of microplastic particles influence larval fish ecology, ecotoxicology. Science 352, 1213–1216. https://doi.org/10.1126/science.aad8828.
Lu, L., Wan, Z., Luo, T., Fu, Z., Jin, Y., 2018. Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice. Sci. Total Environ. 631–632, 449–458. https://doi.org/10.1016/j.scitotenv.2018.03.051.
Luo, H.W., Yin, X., Jubb, A.M., Chen, H., Lu, X., Zhang, W., Lin, H., Yu, H.Q., Liang, L., Sheng, G.P., Gu, B., 2017. Photochemical reactions between mercury (Hg) and dissolved organic matter decrease Hg bioavailability and methylation. Environ. Pollut. 220, 1359–1365. https://doi.org/10.1016/j.envpol.2016.10.099.
Lusher, A.L., Tirell, V., O'Connor, I., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and subsurface samples. Sci. Rep. 5, 14947. https://doi.org/10.1038/srep14947.
Ma, X., Geiser-Lee, J., Deng, Y., Kolmakov, A., 2010. Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. Sci. Total Environ. 408, 3053–3061. https://doi.org/10.1016/j.scitotenv.2010.03.031.
Maaß, S., Daphi, D., Lehmann, A., Rillig, M.C., 2017. Transport of microplastics by two collembolan species. Environ. Pollut. 225, 456–459. https://doi.org/10.1016/j.envpol.2017.03.009.
Magnusson, K., Eliasson, K., Fråne, A., Haikonen, K., Hultén, J., Olshammar, M., Stadmark, J., Voisin, A., 2016. Swedish Sources and Pathways for Microplastics to the Marine Environment. IVL Svenska Miljöinstitutet, Stockholm, Sweden. http://www.ivl.se/download/18.7e136029152c7d48c205d8/1457342560947/C183+Sources+of+microplastic_160307_D.pdf.
Marschner, B., Kalbitz, K., 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. Geoderma 113, 211–235. https://doi.org/10.1016/S0016-7061(02)00362-2.
Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., Fink, P., Papazissimos, D., Rogers, D.L., 2016. Microplastic pollution is widely detected in us municipal wastewater treatment plant effluent. Environ. Pollut. 218, 1045–1054. https://doi.org/10.1016/j.envpol.2016.08.056.

McMahon, C.R., Holley, D., Robinson, S., 1999. The diet of itinerant male Hooker's sea lions, Phocarctos hookeri, at sub-Antarctic Macquarie Island. Wildl. Res. 26, 839–846. https://doi.org/10.1071/WR98079.
Mintenig, S.M., Int-Veen, I., Loder, M.G.J., Primpke, S., Gerdts, G., 2017. Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. Water Res. 108, 365–372. https://doi.org/10.1016/j.watres.2016.11.015.
Mor, R., Sivan, A., 2008. Biofilm formation and partial biodegradation of polystyrene by the actinomycetes Rhodococcus ruber. Biodegradation 19, 851–858. https://doi.org/10.1007/s10532-008-9188-0.
MST, 2018. http://www.most.gov.cn/kjbgz/201811/t20181101_142541.htm.
Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Mar. Pollut. Bull. 62, 1207–1217. https://doi.org/10.1016/j.marpolbul.2011.03.032.
Murugan, R., Beggi, F., Kumar, S., 2014. Belowground carbon allocation by trees, understory vegetation and soil type alter microbial community composition and nutrient cycling in tropical Eucalyptus plantations. Soil Biol. Biochem. 76, 257–267. https://doi.org/10.1016/j.soilbio.2014.05.022.
Muscolo, A., Panuccio, M.R., Mallamaci, C., Sidari, M., 2014. Biological indicators to assess short-term soil quality changes in forest ecosystems. Ecol. Indic. 45, 416–423. https://doi.org/10.1016/j.ecolind.2014.04.047.
Muscolo, A., Settineri, G., Attina, E., 2015. Early warning indicators of changes in soil ecosystem functioning. Ecol. Indic. 48, 542–549. https://doi.org/10.1016/j.ecolind.2014.09.017.
Naidoo, T., Glassom, D., Smit, A.J., 2015. Plastic pollution in five urban estuaries of KwaZulu-natal, south Africa. Mar. Pollut. Bull. 101, 473–480. https://doi.org/10.1016/j.marpolbul.2015.09.044.
Narayan, R., 1993. Biodegradation of polymeric materials (anthropogenic macromolecules) during composting. In: Hoitink, H.A.J., Keener, H.M. (Eds.), Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects. Renaissance Publishers, Washington, OH, pp. 339–362.
Naveed, M., Herath, L., Moldrup, P., Arthur, E., Nicolaisen, M., Norgaard, T., Ferre, T.P.A., de Jonge, L.W., 2016. Spatial variability of microbial richness and diversity and relationships with soil organic carbon, texture and structure across an agricultural field. Appl. Soil Ecol. 103, 44–55. https://doi.org/10.1016/j.apsoil.2016.03.004.
Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., Lindeque, P.K., 2018. Investigating microplastic trophic transfer in marine top predators. Environ. Pollut. 238, 999–1007. https://doi.org/10.1016/j.envpol.2018.02.016.
Ng, K.L., Obbard, J.P., 2006. Prevalence of microplastics in Singapore's coastal marine environment. Mar. Pollut. Bull. 52, 761–767. https://doi.org/10.1016/j.marpolbul.2005.11.017.
Ng, E.L., Lwanga, E.H., Eldridge, S.M., Johnston, P., Hu, H.W., Geissen, V., Chen, D., 2018. An overview of microplastic and nanoplastic pollution in agroecosystems. Sci. Total Environ. 627, 1377–1388. https://doi.org/10.1016/j.scitotenv.2018.01.341.
Nizzetto, L., Bussi, G., Futter, M.N., Butterfield, D., Whitehead, P.G., 2016a. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environ. Sci. Process. Imp. 18, 1050–1059. https://doi.org/10.1039/c6em00206d.
Nizzetto, L., Futter, M., Langaas, S., 2016b. Are agricultural soils dumps for microplastics of urban origin? Environ. Sci. Technol. 50, 10777–10779. https://doi.org/10.1021/acs.est.6b04140.
Nizzetto, L., Bussi, G., Futter, M.N., Butterfield, D., Whitehead, P.G., 2016c. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environ. Sci. Proc. Imp. 18 (8), 1050–1059. https://doi.org/10.1039/C6EM00206D.
Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Fut. 2, 315–320. https://doi.org/10.1002/2014EF000240.
Oßmann, B.E., Sarau, G., Holtmannspötter, H., Pischetsrieder, M., Christiansen, S.H., Dicke, W., 2018. Small-sized microplastics and pigmented particles in bottled mineral water. Water Res. 141, 307–316. https://doi.org/10.1016/j.watres.2018.05.027.
O'Connor, D., Pan, S., Shen, Z., Song, Y., Jin, Y., Wu, W.M., Hou, D., 2019. Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. Environ. Pollut. 249, 527–534. https://doi.org/10.1016/j.envpol.2019.03.092.
Ortega-Calvo, J.J., Tejeda-Agredano, M.C., Jimenez-Sanchez, C., Congiu, E., Sungthong, R., Niqui-Arroyo, J.L., Cantos, M., 2013. Is it possible to increase bioavailability but not environmental risk of PAHs in bioremediation? J. Hazard. Mater. 261, 733–745. https://doi.org/10.1016/j.jhazmat.2013.03.042.
Panebianco, A., Nalbone, L., Giarratana, F., Ziino, G., 2019. First discoveries of microplastics in terrestrial snails. Food Control 106722, 1–7. https://doi.org/10.1016/j.foodcont.2019.106722.
Peeken, I., Primpke, S., Beyer, B., GÃ¼termann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9 (1), 1505. https://doi.org/10.1038/s41467-018-03825-5.
Perminova, I.V., Grechishcheva, N.Y., Kovalevskii, D.V., Kudryavtsev, A.V., Petrosyan, V.S., Matorin, D.N., 2001. Quantification and prediction of the detoxifying properties of humic substances related to their chemical binding to polycyclic aromatic hydrocarbons. Environ. Sci. Technol. 35, 3841–3848. https://doi.org/10.1021/es001699b.
PlasticsEurope, 2017. Plastics - The Facts 2017: An analysis of European Plastic Production, Demand and Waste Data for 2017. Brussels, Belgium. https://www.plasticseurope.org/en/resources/publications/274-plastics-facts-2017.
Polubesova, T., Chefetz, B., 2014. DOM-affected transformation of contaminants on mineral surfaces: a review. Crit. Rev. Env. Sci. Tec. 44 (3), 223–254. https://doi.org/10.1080/10643389.2012.710455.
Prata, J.C., 2018. Airborne microplastics: consequences to human health? Environ. Pollut. 234, 115–126. https://doi.org/10.1016/j.envpol.2017.11.043.
Qi, Y.L., Yang, X.M., Pelaez, A.M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V., 2018. Macro- and micro- plastics in soil-plant system: effects of plastic mulch film residues on wheat (Triticum aestivum) growth. Sci. Total Environ. 645, 1048–1056. https://doi.org/10.1016/j.scitotenv.2018.07.229.
Ramos, L., Berenstein, G., Hughes, E.A., Zalts, A., Montserrat, J.M., 2015. Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. Sci. Total Environ. 523, 74–81. https://doi.org/10.1016/j.scitotenv.2015.03.142.
Reisser, J., Slat, B., Noble, K., du Plessis, K., Epp, M., Proietti, M.D., Epp, M., Proietti, M.C., Sonneville, J.D., Becker, T., Pattiaratchi, C., 2015. The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic gyre. Biogeosciences 12 (4), 1249–1256. https://doi.org/10.5194/bg-12-1249-2015.
Rezaei, M., Riksen, M.J., Sirjani, E., Sameni, A., Geissen, V., 2019. Wind erosion as a driver for transport of light density microplastics. Sci. Total Environ. 669, 273–281. https://doi.org/10.1016/j.scitotenv.2019.02.382.
Rillig, M.C., 2012. Microplastic in terrestrial ecosystems and the soil? Environ. Sci. Technol. 46, 6453–6454. https://doi.org/10.1021/es302011r.
Rillig, M.C., Ingraffia, R., de Souza, M., Anderson, A., 2017a. Microplastic incorporation into the soil in agroecosystems. Front. Plant Sci. 8. https://doi.org/10.3389/fpls.2017.01805.
Rillig, M.C., Muller, L.A.H., Lehmann, A., 2017b. Soil aggregates as massively concurrent evolutionary incubators. ISME J. 11, 1943–1948. https://doi.org/10.1038/ismej.2017.56.
Rillig, M.C., 2018. Microplastic disguising as soil carbon storage. Environ. Sci. Technol. 52, 6079–6080. https://doi.org/10.1021/acs.est.8b02338.
Rillig, M.C., Abel, D.S.M.A., Lehmann, A., Klümper, U., 2018. Evolutionary implications of microplastics for soil biota. Environ. Chem. https://www.publish.csiro.au/en/pdf/EN18118.
Rillig, M.C., Lehmann, A., de Souza Machado, A.A., Yang, G., 2019. Microplastic effects on plants. New Phytol. https://doi.org/10.1111/nph.15794.
Rocha-Santos, T., Duarte, A.C., 2015. A critical overview of the analytical approaches to the occurrence, the fate and the behavior of microplastics in the environment. Trend. Anal. Chem. 65, 47–53. https://doi.org/10.1016/j.trac.2014.10.011.
Rubol, S., Manzoni, S., Bellin, A., Porporato, A., 2013. Modeling soil moisture and oxygen effects on soil biogeochemical cycles including dissimilatory nitrate reduction to ammonium (DNRA). Adv. Water Resour. 62, 106–124. https://doi.org/10.1016/j.advwatres.2013.09.016.
Rodriguez-Seijo, A., Lourenço, J., Rocha-Santos, T.A.P., da Costa, J., Duarte, A.C., Vala, H., Pereira, R., 2017. Histopathological and molecular effects of microplastics in Eisenia andrei Bouche. Environ. Pollut. 220, 495–503. https://doi.org/10.1016/j.envpol.2016.09.092.
Rodríguez-Seijo, A., Santos, B., da Silva, E.F., Cachada, A., Pereira, R., 2019. Low-density polyethylene microplastics as a source and carriers of agrochemicals to soil and earthworms. Environ. Chem. 16 (1), 8–17. https://doi.org/10.1071/EN18162.
Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philos. T. R. Soc. B 364, 1999–2012. https://doi.org/10.1098/rstb.2008.0207.
Salmon, S., Ponge, J.F., 2001. Earthworm excreta attract soil spzonetails: laboratory experiments on Heteromurus nitidus (Collembola: entomobryidae). Soil Biol. Biochem. 33, 1959–1969. https://doi.org/10.1016/S0038-0717(01)00129-8.
Santana, M.F.M., Moreira, F.T., Turra, A., 2017. Trophic transference of microplastics under a low exposure scenario: insights on the likelihood of particle cascading along marine food-webs. Mar. Pollut. Bull. https://doi.org/10.1016/j.marpolbul.2017. 05.061.
Schnitzer, M., 2000. A lifetime perspective on the chemical of soil organic matter. Adv. Agron. 68 (08), 1–58. https://doi.org/10.1016/S0065-2113(08)60842-1.
Scheurer, M., Bigalke, M., 2018. Microplastics in swiss floodplain soils. Environ. Sci. Technol. 52, 3591–3598. https://doi.org/10.1021/acs.est.7b06003.
Schymanski, D., Goldbeck, C., Humpf, H.U., Fürst, P., 2018. Analysis of microplastics in water by micro-Raman spectroscopy: release of plastic particles from different packaging into mineral water. Water Res. 129, 154–162. https://doi.org/10.1016/j.watres.2017.11.011.
Sebille, E.V., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F., Law, K.L., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006. https://doi.org/10.1088/1748-9326/10/12/124006.
Setälä, O., Fleminglehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of microplastics in the planktonic food web. Environ. Pollut. 185, 77–83. https://doi.org/10.1016/j.envpol.2013.10.013.
Setälä, O., Norkko, J., Lehtiniemi, M., 2015. Feeding type affects microplastic ingestion in a coastal invertebrate community. Mar. Pollut. Bull. 102, 95–101. https://doi.org/10.1016/j.marpolbul.2015.11.053.
Shah, A.A., Hasan, F., Hameed, A., Ahmed, S., 2008. Biological degradation of plastics: a comprehensive review. Biotechnol. Adv. 26 (3), 246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005.
Sollins, P., Gregg, J.W., 2017. Soil organic matter accumulation in relation to changing soil volume, mass, and structure: concepts and calculations. Geoderma 301, 60–71. https://doi.org/10.1016/j.geoderma.2017.04.013.
Song, Y., Cao, C., Qiu, R., Hu, J., Liu, M., Lu, S., Shi, H.H., Raley-Susman, K.M., He, D., 2019. Uptake and adverse effects of polyethylene terephthalate microplastics fibers on terrestrial snails (*Achatina fulica*) after soil exposure. Environ. Pollut. 250, 447–455. https://doi.org/10.1016/j.envpol.2019.04.066.

Steinmetz, Z., Wollmann, C., Schaefer, M., Schaefer, M., Buchmann, C., David, J., Troger, J., Munoz, K., Foro, O., Schaumann, G.E., 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci. Total Environ. 550, 690–705. https://doi.org/10.1016/j.scitotenv.2016.01.153.

Sutherland, W.J., Clout, M., Isabelle, M., Daszak, C.P., Depledge, M.H., Fellman, L., Fleishman, E., Garthwaite, R., Gibbons, D.W., De Lurio, J., Impey, A.J., Lickorish, F., Lindenmayer, D., Madgwick, J., Margerison, C., Maynard, T., Peck, L.S., Pretty, J., Prior, S., Redford, K.H., Scharlemann, J.P.W., Spalding, M., Watkinson, A.R., 2010. A horizon scan of global conservation issues for 2010. Trends Ecol. Evol. 25 (1), 1–7. https://doi.org/10.1016/j.tree.2009.10.003.

Tang, J., Carroquino, M.J., Robertson, B.K., Alexander, M., 1998. Combined effect of sequestration and bioremediation in reducing the bioavailability of polycyclic aromatic hydrocarbons in soil. Environ. Sci. technol. 32 (22), 3586–3590. https://doi.org/10.1021/es9803512.

Thompson, Richard C., 2015. Microplastics in the marine environment: sources, consequences and solutions. In: Bergmann, Melanie, Gutow, Lars, Klages, Michael (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 185–200. http://link.springer.com/10.1007/978-3-319-16510-3_7https://doi.org/10.1007/978-3-319-16510-3_7.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838. https://doi.org/10.1126/science.1094559.

Trasar-Cepeda, C., Leiros, M.C., Gil-Sotres, F., 2008. Hydrolytic enzyme activities in agricultural and forest soils. some implications for their use as indicators of soil quality. Soil Biol. Biochem. 40, 2146–2155. https://doi.org/10.1016/j.soilbio.2008.03.015.

Veresoglou, S.D., Halley, J.M., Rillig, M.C., 2015. Extinction risk of soil biota. Nat. Commun. 6, 8862. https://doi.org/10.1038/NCOMMS9862.

UBA, 2015. Klärschlamm und Kompost. https://www.umweltbundesamt.de/themen/boden-landwirtschaft/umweltbelastungen-der-landwirtschaft/kompostklaerschlamm.

UNEP, 2014. UNEP Year Book 2014: Emerging issues in our global environment, pp. 50–53.

UNEP, 2015. Massive Online Open Course (MOOC) on Marine Litter, 2015. UNEP-University of the Netherlands, UNEP/GPML/GPA/OU/GUPES. marinelittermooc.org/learn/marine-litter-mooc-october-2015.

UNEP, 2018. Beat Plastic Pollution. http://www.worldenvironmentday.global/en/about/beat-plastic-pollution.

UNEP, 2018. How China's Ban of Plastic Wastes Imports Can help us Beat Pollution. https://www.unenvironment.org/news-and-stories/story/how-chinas-ban-plastic-waste-imports-can-help-us-beat-pollution.

van Velzen, E.T., Brouwer, M.T., Feil, A., 2019. Collection behaviour of lightweight packaging waste by individual households and implications for the analysis of collection schemes. Waste Manage. 89, 284–293. https://doi.org/10.1016/j.wasman.2019.04.021.

Wan, Y., Wu, C., Xue, Q., Hui, X., 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci. Total Environ. 654, 576–582. https://doi.org/10.1016/j.scitotenv.2018.11.123.

Wang, Z., Li, X., Shi, H., Sun, M., Ding, T., Wang, C., 2015a. Effects of residual plastic film on soil hydrodynamic parameters and soil structure. 140. Nongye Jixie Xuebao/Trans. Chin. Soc. Agric. Mach. 46, 101–106. https://doi.org/10.6041/j.issn.1000-1298.2015.05.015.

Wang, F., Shih, K.M., Li, X.Y., 2015b. The partition behavior of perfluorooctanesulfonate (PFOS) and perfluorooctanesulfonamide (FOSA) on microplastics. Chemosphere 119, 841–847.

Wang, F., Wong, C.S., Chen, D., Lu, X., Wang, F., Zeng, E.Y., 2018a. Interaction of toxic chemicals with microplastics: a critical review. Water Res. 139, 208–219. https://doi.org/10.1016/j.watres.2018.04.003.

Wang, J., Taylor, A., Xu, C.Y., Schlenk, D., Gan, J., 2018b. Evaluation of different methods for assessing bioavailability of DDT residues during soil remediation. Environ. Pollut. 238, 462–470. https://doi.org/10.1016/j.envpol.2018.02.082.

Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G., Zhang, P., 2019a. Microplastics as contaminants in the soil environment: a mini-review. Sci. Total Environ. 691, 848–859. https://doi.org/10.1016/j.scitotenv.2019.07.209.

Wang, J., Coffin, S., Sun, C., Schlenk, D., Gan, J., 2019b. Negligible effects of microplastics on animal fitness and HOC bioaccumulation in earthworm *Eisenia fetida* in soil. Environ. Pollut. 249, 776–784. https://doi.org/10.1016/j.envpol.2019.03.102.

Watts, A.J.R., Ceri, L., Goodhead, R.M., Beckett, S.J., Julian, M., Tyler, C.R., 2014. Uptake and retention of microplastics by the shore crab carcinus maenas. Environ. Sci. Technol. 48, 8823–8830. https://doi.org/10.1021/es501090e.

Weithmann, N., Möller, J.N., Löder, M.G.J., Piehl, S., Laforsch, C., Freitag, R., 2018. Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci. Adv. 4. https://doi.org/10.1126/sciadv.aap8060.

Wick, L.Y., Remer, R., Würz, B., Reichenbach, J., Braun, S., Schäfer, F., Harms, H., 2007. Effect of fungal hyphae on the access of bacteria to phenanthrene in soil. Environ. Sci. Technol. 41, 500–505. https://doi.org/10.1021/es061407s.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423.

Wu, J., Jiang, R., Lin, W., Ouyang, G., 2019. Effect of salinity and humic acid on the aggregation and toxicity of polystyrene nanoplastics with different functional groups and charges. Environ. Pollut. 245, 836–843. https://doi.org/10.1016/j.envpol.2018.11.055.

Yang, J., Yang, Y., Wu, W.M., Zhao, J., Jiang, L., 2014. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environ. Sci. Technol. 48, 13776–13784. https://doi.org/10.1021/es504038a.

Yang, Y., Yang, J., Wu, W.M., Zhao, J., Song, Y., Gao, L., Yang, R., Jiang, L., 2015a. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 1. Chemical and physical characterization and isotopic tests. Environ. Sci. Technol. 49, 12080–12086. https://doi.org/10.1021/acs.est.5b02661.

Yang, Y., Yang, J., Wu, W.M., Zhao, J., Song, Y., Gao, L., Yang, R., Jiang, L., 2015b. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 2. Role of gut microorganisms. Environ. Sci. Technol. 49, 12087–12093. https://doi.org/10.1021/acs.est.5b02663.

Yang, X., Bento, C.P., Chen, H., Zhang, H., Xue, S., Lwanga, E.H., Zomer, P., Ritsema, C.J., Geissen, V., 2018. Influence of microplastic addition on glyphosate decay and soil microbial activities in Chinese loess soil. Environ. Pollut. 242, 338–347. https://doi.org/10.1016/j.envpol.2018.07.006.

Yang, J., Cang, L., Sun, Q., Dong, G., Ata-Ul-Karim, S.T., Zhou, D., 2019a. Effects of soil environmental factors and UV aging on Cu 2+ adsorption on microplastics. Environ. Sci. Pollut. R. 1–10. https://doi.org/10.1007/s11356-019-05643-8.

Yang, Y.Y., Liu, G.H., Song, W.J., Ye, C., Lin, H., Li, Z., Liu, W.Z., 2019b. Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes. Environ. Int. 123, 79–86. https://doi.org/10.1016/j.envint.2018.11.061.

Yu, H., Huang, G.H., An, C.J., Wei, J., 2011. Combined effects of DOM extracted from site soil/compost and biosurfactant on the sorption and desorption of PAHs in a soil–-water system. J. Hazard. Mater. 190 (1–3), 883–890. https://doi.org/10.1016/j.jhazmat.2011.04.026.

Yu, H.Y., Liu, C., Zhu, J., Li, F., Deng, D.M., Wang, Q., Liu, C., 2016. Cadmium availability in rice paddy fields from a mining area: the effects of soil properties highlighting iron fractions and pH value. Environ. Pollut. 209, 38–45. https://doi.org/10.1016/j.envpol.2015.11.021.

Yurtsever, M., Kaya, A.T., 2018. A research on microplastic presence in outdoor air. Senem Çiftçi Bayraktar. 89–97. https://doi.org/10.1007/978-3-319-71279-6_13.

Zettler, E.R., Mincer, T.J., Amaral-Zettler, L.A., 2013. Life in the "plastisphere": microbial communities on plastic marine debris. Environ. Sci. Technol. 47, 7137–7146. https://doi.org/10.1021/es401288x.

Zhang, D., Liu, H.B., Ma, Z.M., Tang, W.X., Wei, T., Yang, H.D., Li, J.G., Wang, H.Y., 2017. Effect of residual plastic film on soil nutrient contents and microbial characteristics in the farmland. Sci. Agric. Sin. 50 (2), 310–319. https://doi.org/10.3864/j.issn.0578-1752.2017.02.010.

Zhang, G.S., Liu, Y.F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Sci. Total Environ. 642, 12–20. https://doi.org/10.1016/j.scitotenv.2018.06.004.

Zhang, G.S., Zhang, F.X., Li, X.T., 2019a. Effects of polyester microfibers on soil physical properties: perception from a field and a pot experiment. Sci. Total Environ. 670, 1–7. https://doi.org/10.1016/j.scitotenv.2019.03.149.

Zhang, M., Zhao, Y., Qin, X., Jia, W., Chai, L., Huang, M., Huang, Y., 2019b. Microplastics from mulching film is a distinct habitat for bacteria in farmland soil. Sci. Total Environ. 688, 470–478. https://doi.org/10.1016/j.scitotenv.2019.06.108.

Zhu, D., Bi, Q.F., Xiang, Q., Chen, Q.L., Christie, P., Ke, X., Wu, L.H., Zhu, Y.G., 2017. Trophic predator-prey relationships promote transport of microplastics compared with the single *Hypoaspis aculeifer*, and *Folsomia candida*. Environ. Pollut. 235, 150–154. https://doi.org/10.1016/j.envpol.2017.12.058.

Zhu, B.K., Fang, Y.M., Zhu, D., Christie, P., Ke, X., Zhu, Y.G., 2018a. Exposure to nanoplastics disturbs the gut microbiome in the soil oligochaete *Enchytraeus crypticus*. Environ. Pollut. 239, 408–415. https://doi.org/10.1016/j.envpol.2018.04.017.

Zhu, D., Chen, Q.L., An, X.L., Yang, X.R., Christie, P., Ke, X., Wu, L.H., Zhu, Y.G., 2018b. Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. Soil Biol. Biochem. 116, 302–310. https://doi.org/10.1016/j.soilbio.2017.10.027.

Zhu, F., Zhu, C., Wang, C., Gu, C., 2019. Occurrence and Ecological Impacts of Microplastics in Soil Systems: A Review. B. Environ. Contam. Tox. 102 (6), 741–749. https://doi.org/10.1007/s00128-019-02623-z.

Ziajahromi, S., Neale, P.A., Rintoul, L., Leusch, F.D., 2017. Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water Res. 112, 93–99. https://doi.org/10.1016/j.watres.2017.01.042.

Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2018. Environmentally relevant concentrations of polyethylene microplastics negatively impact the survival, growth and emergence of sediment-dwelling invertebrates. Environ. Pollut. 236, 425–431. https://doi.org/10.1016/j.envpol.2018.01.094.

Zitko, V., Hanlon, M., 1991. Another source of pollution by plastics—skin cleaners with plastic scrubbers. Mar. Pollut. Bull. 22, 41–42. https://doi.org/10.1016/0025-326X(91)90444-W.

Zubris, K.a.V, Richards, B.K., 2005. Synthetic fibers as an indicator of land application of sludge. Environ. Pollut. 138 (2), 201–211. https://doi.org/10.1016/j.envpol.2005.04.013.