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Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review☆

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ABSTRACT

Plastic pollution in the environment is currently receiving worldwide attention. Improper dumping of disused or abandoned plastic wastes leads to contamination of the environment. In particular, the disposal of municipal wastewater effluent, sewage sludge landfill, and plastic mulch from agricultural activities is a serious issue and of major concern regarding soil pollution. Compared to plastic pollution in the marine and freshwater ecosystems, that in the soil ecosystem has been relatively neglected. In this study, we discussed plastic pollution in the soil environment and investigated research on the effects of plastic wastes, especially microplastics, on the soil ecosystem. We found that earthworms have been predominantly used as the test species in investigating the effects of soil plastic pollution on organisms. Therefore, further research investigating the effects of plastic on other species models (invertebrates, plants, microorganisms, and insects) are required to understand the effects of plastic pollution on the overall soil ecosystem. In addition, we suggest other perspectives for future studies on plastic pollution and soil ecotoxicity of plastics wastes, providing a direction for such research.

1. Growing concerns on plastic pollution in the soil environment

Many organisms, including humans, depend on the soil for their survival, and therefore, soil pollution is a critical factor, even affecting food safety for humans (Akhtar, 2015; Micó et al., 2006; Li et al., 2014a). As industrial development has accelerated and the manufacture and disposal of plastics have increased, concerns on plastic pollution are growing. Recently, after Rillig (2012) pointed out the problem of microplastic (MP) pollution in soil and terrestrial ecosystems, people were encouraged to focus on this problem again. Researchers have paid attention to plastic wastes in the soil media and warned about the dangers of small plastics in the soil and terrestrial ecosystems (Liu et al., 2014; Rochman et al., 2015; Nizzetto et al., 2016a). Many researchers also pointed out the potential effects of widespread plastic contamination in the soil environment, emphasizing on the adverse effects of plastics and MPs in soils (Rillig, 2012; Liu et al., 2014; Nizzetto et al., 2016a, 2016b). Nevertheless, studies on the distribution, fate, and transformation of plastic wastes in the soil environment are still lacking (Fig. 1).

Several studies have estimated the concentrations of MPs in dry sludge dumped in landfills after wastewater treatment (Nizzetto et al., 2016a, 2016b; Talvitie et al., 2017). The development of techniques for the extraction and analysis of small plastics such as MPs from soil media have only begun recently (Fuller and Gautam, 2016; Scheurer and Bigalke, 2018; Zhang et al., 2018), compared to those from other media such as seawater and freshwater (Lenz et al., 2015; Mendoza and Jones, 2015), sediments (Crichton et al., 2017), beach sand (Lee et al., 2013; Hidalgo-Ruz and Thiel, 2013; Nel and Froneman et al., 2015), and even in living organisms (Claessens et al., 2013; Avio et al., 2015; Karami et al., 2017; Roch and Brinker, 2017) (Table 1). In previous studies, density difference of all media by separation with solutions from distilled water (1.0 g cm^{-3}) to NaCl, $CaCl_2$, or NaI (1.2–1.6 g cm^{-3}) was employed. In the digestion or extraction process, generally KOH, NaOH, or H_2O_2 have been widely used. Several researchers used various acids (H_2SO_4, HNO_3, or HCl), but these acids have the critical disadvantage of destroying several polymers (Scheurer and Bigalke, 2018). In addition, various filters with pore sizes of 0.45–300 μm have been used. Lastly, in the assessment process, Fourier Transformed Infrared Spectrometry (FTIR) and Raman spectroscopy have usually been applied for qualification, and microscopy, including scanning

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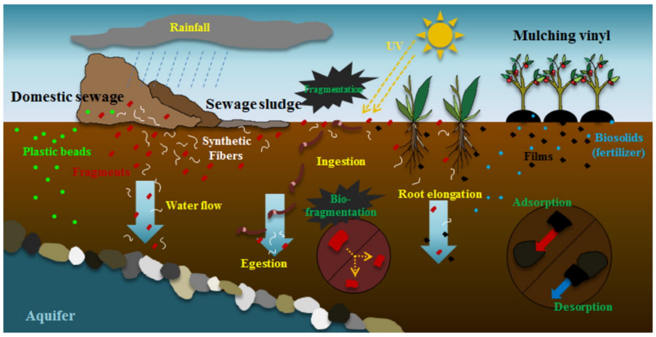

Fig. 1. Schematic of the flow of plastic wastes in the soil environment and their distributions and fate in soil. These plastic wastes enter the soil environment via various routes. These plastic wastes enter the soil ecosystem and they are distributed from the surface to deep soil layers. Water flows from the surface to deep soil layers and the activities of ingestion and egestion of organisms as well as root elongation of plants facilitate downward transport of small plastics. Plastics in deep soils can penetrate the aquifer. On the surface, large plastics can be broken into small plastics by UV radiation. In deep soils, plastic wastes can be fragmentized by feeding activities and digestive processes of organisms. Plastic wastes can be physically or chemically adsorbed on or desorbed from soil particles. Their fates vary according to the activities of organisms, water flow, physical and chemical characteristics, and weathering in soils.

electron microscope (SEM), has been used for quantification of microplastics, as shown in Table 1. Fuller and Gautam (2016) extracted and counted the number of microplastics in industrial soils from Sydney, Australia and found that the concentrations of microplastics widely varied (300–67,500 mg kg^{-1}) depending on the sites. In the study of Scheurer and Bigalke (2018), up to 55.5 mg kg^{-1} (593 particles kg^{-1}) of microplastics were found in soil samples from 26 floodplain sites in Switzerland. Overall, only few studies have investigated the concentrations or amount of MPs in soils to date, and therefore, further development in this field is still required.

2. Microplastic pollution in the soil environment

Diverse sources of plastics that contaminate environments have been reported (de Souza Machado et al., 2018). These include domestic sewage, containing fibers from clothing and microplastic beads from personal care products, biosolids (Carr et al., 2016; Mason et al., 2016; McCormick et al., 2016; Talvitie et al., 2017; Ziajahromi et al., 2017), fertilizers (Nizzetto et al., 2016a; Horton et al., 2017), landfills from urban and industrial centers (Nizzetto et al., 2016b), irrigation with wastewater, lake water flooding, littering roads and illegal waste dumping (Bläsing and Amelung, 2018), vinyl mulch used in agricultural activities (Kasirajan and Ngouajio, 2012; Li et al., 2014b; Farmer et al., 2017; Sintim and Flury, 2017), tire abrasion (Dubaish and Liebezeit, 2013; Foitzik et al., 2018; Wagner et al., 2018), and atmospheric particles transported over long distances (Dris et al., 2016). These various plastics enter the soil environment, settle on the surface, and penetrate into subsoils.

Several researchers have started to focus on these anthropogenic materials that enter the soil ecosystem from various routes. In 1998, Habib et al. focused on synthetic fibers from municipal wastewater; they found synthetic fibers derived from washing machines in the effluent water and sewage sludges, and observed the fibers using polarized light microscopy. They also reported that effluents from wastewater plants with final microfiltration steps contain less synthetic fibers than those from wastewater plants without microfiltration. Years later, Zubris and Richards (2005) conducted experiments simulating several test conditions, counted the number of fibers, and suggested composite images of synthetic fibers extracted from sludge products. They carried out a simple experiment on the extraction of fibers from the sludges. Both of these studies reported that the synthetic fibers can be transferred to the soil and can pollute soil environments via the application of the effluent to land. Interest in plastic pollution of the soil environment by small plastics has been continued even after these studies. After a lapse of several years, Rillig (2012) aroused the interest on microplastic contamination in the soil ecosystem again, and thus far, several studies have continued investigating and highlighting microplastics in the soil environment. In recent studies, the state of persistent plastic contamination in the soil environment has been suggested. Horton et al. (2017) suggested that the fragmentation of plastics can occur in the surface soil by UV radiation and elevated temperature. These fragmentized plastics can be MPs of small sizes (<5 mm). Rillig (2012) assumed that plastics on the soil surface can be incorporated into the deep soil by burrowing activities of earthworms. The combined fragmented plastics and MPs in surface soils can be further transported to deeper layers of the soil by the activities of soil organisms such as collembolans, insects, and plants (Maaß et al., 2017; Rillig et al., 2017a; Rillig et al., 2017b; de Souza Machado et al., 2018; Zhu et al., 2018a). Furthermore, although no study has revealed the transfer or existence of microplastics in groundwater, several researchers have warned of the potential distribution and transportation of MPs into groundwater and the hyporheic zone based on previous studies about MP transportation. Rillig et al. (2017) commented that microplastics can migrate through the soil profile and reach the groundwater. Bläsing and Amelung (2018) also warned of the potential of nanoplastics or colloids to pass through macropores and coarse soil. Scheurer and Bigalke (2018) suggested the probability of microplastics to be transferred to groundwater in areas with high groundwater table and coarse soils. Nevertheless, the mechanism is largely unknown because only few studies on plastic pollution in the soil environment have been conducted.

3. Impacts of microplastics on soil organisms

Currently, many researchers are focusing on the impacts of MPs in environments, and the toxicities and impacts of MPs have been extensively studied. However, most studies focus on MPs in the aquatic ecosystem because water pollution by MPs has been regarded as one of the most important and serious global concerns (Nizzetto et al., 2016a). Only few studies have focused on plastic pollution derived from landfill sludge and agricultural plastic mulch in soil ecosystems (Duis and Coors, 2016; Horton et al., 2017; Peng et al., 2017). MPs in soils can be ingested (Peng et al., 2017) and transferred (Nizzetto et al., 2016b) to soil organisms, leading to unwanted effects on their bodies (da Costa et al., 2016). To date, research on the toxic effects of MPs on soil organisms are very limited (Table 2, Fig. 2).

Gaylor et al. (2013) simulated the exposure of polybrominated diphenyl ether (PBDE) to earthworm *Eisenia fetida* with various exposure scenarios (biosolid or polyurethane foam microparticles that contain PBDEs). They found that PBDEs leached from polyurethane foam (<75 µm) were accumulated in the bodies of earthworms. This is a very important finding showing that chemicals derived from MPs can enter the soil ecosystem and be accumulated in soil invertebrate organisms. Additives or hazardous chemicals in MPs such as PBDEs can be transferred to other environments and organisms (Chen et al., 2013; Hong et al., 2017) not only in the marine ecosystem but also in the soil ecosystem. Huerta Lwanga *et al.* (2016) exposed earthworm *Lumbricus terrestris* to low density polyethylene (LDPE) MPs (<150 µm) for 60 days, and investigated their mortality, growth, tunnel formation, position in mesocosm, and MP ingestion after 14 and 60 days of exposure. In addition, the mortality, growth rate, ingestion rate, and accumulation were investigated after 4 days of exposure. The authors suggested several possibilities from their results: i) the health of earthworms was affected when they were exposed to high concentrations of MPs (28, 45, and 60% w/w microplastics in litter), ii) MPs have the potential of being preferentially retained in the earthworms and transferred to other organisms in the soil ecosystem through the food chain, and iii) MPs concentrated by earthworms could be transported to deeper layers of the soil and leached to groundwater.

In another study by Huerta Lwanga *et al.* (2017a), similar experiments were conducted using *L. terrestris* for 2 weeks. The burrowing activities of the earthworms and distributions of MPs in the soil were analyzed. A mesocosm study was conducted for 14 days using LDPE with sizes of $\leq$50 μm (40%) and 63–150 μm (60%) based on previous aquatic studies and representativeness in soil (Huerta Lwanga et al., 2016). *L. terrestris* was exposed to MPs with dried *Populus nigra* under dark conditions. After exposure, earthworms and soil were frozen, and the biomass of earthworm, burrow formation, and the amount of MPs in the burrow walls were analyzed. The results showed that MPs were transported into the burrows via the movement of earthworms and the authors explained that this may cause the pollution of groundwater by MPs and affect other organisms in the soil ecosystem. Additionally, the concentration of organic matter within the burrows of soil with high concentration of MPs was also high and this may be related to the stress response of earthworms exposed to MPs. Hodson et al. (2017) prepared MPs using high density polyethylene (HDPE) bags and exposed them to *L. terrestris* with metal, zinc (Zn) for 28 days. Before exposure, the adsorption and desorption of Zn on MPs were analyzed. Zn was less adsorbed on the MPs compared to other soil particles (arable and woodland soil), whereas much more Zn was desorbed from MPs than from other soil particles. Therefore, MPs may serve as the pathway of bioavailable metals, including Zn, in the soil ecosystem. Nevertheless, they found no significant adverse effect on the survival and body weight of the earthworm and no preferential ingestion or avoidance of earthworms toward MPs. Huerta Lwanga *et al.* (2017b) conducted the first study on the trophic transfer of MPs in the terrestrial food chain, in which they investigated the concentrations of MPs in home garden soil, earthworm casts, and chicken (*Gallus gallus domesticus*) feces. The concentrations increased along the trophic levels and the highest concentration of MP was confirmed in chicken feces (129.8 $\pm$ 82.3 particles g^{-1}). In particular, chicken gizzards also contained MPs (10.2 $\pm$ 13.8 MPs per gizzard), and this suggests the evidence of transfer of MPs to humans through food because gizzards are used for human consumption in several countries. In this study, authors suggested an annual amount of consumed plastics as 840 plastic particles per person.

Maaß et al. (2017) used two collembolan species, *Folsomia candida* and *Proisotoma minuta*, and observed the transport of urea-formaldehyde particles (200–400 μm). The transport of particles was strongly dependent on the type of particle, size of particles, and size of organisms. However, the results may not represent real environmental conditions because these experiments were conducted using dried mixtures of plaster and activated charcoal. Nevertheless, the authors confirmed the horizontal transport of plastic particles by soil microarthropods. Rillig et al. (2017a) also studied the transport of MPs by soil organisms but they used earthworms as test species in real soil media. *L. terrestris* was put into soils covered with 750 mg of various sizes of PE MPs (710–850, 1180–1400, 1700–2000, and 2360–2800 μm). After 21 days of exposure, MPs were detected in the middle and bottom layers of soils and the smallest particles (710–850 μm) reached the deepest soil layer. The authors did not define the mechanisms of plastic transport in soil, but they suggested that MPs might be transported through the activities of earthworms such as ingestion/egestion, burrowing, adherence, and making casts in the soils. Rodriguez-Seijo et al. (2017) investigated the effects of PE MPs (250–1000 μm) on the survival, growth, reproduction, histopathological damages, and immune system response of *Eisenia andrei*. In their study, MPs did not affect the survival, growth, and reproduction of earthworms but histopathological damages and immune system responses of earthworms were observed. MPs were also observed in the gut and middle intestinal tract of the earthworms. Increases in the contents of proteins, lipids, and polysaccharides in earthworms were also observed via Fourier Transformed Infrared Spectrometry with Attenuated Total Reflectance (FTIR-ATR). They confirmed that these increases of nutrients are caused by multiple stress-response mechanisms of the immune system of *E. andrei* to MP exposure.

Kokalj et al. (2018) exposed isopods (*Porcellio scaber*) to MPs produced from plastic bag films and particles from a facial cleanser with food pellets on filter paper for 14 days of test duration. However, they reported that MPs do not affect the feeding rate, body mass, and energy reserves in digestive glands of isopods. Authors suggested longer-term experiments and assessment of the effect of other polymers on isopods excluding the PE used in this study. Zhu et al. (2018a) investigated the transport of commercial polyvinyl chloride (PVC) MPs using relationships of predator (*Hypoaspis aculeifer*) and prey (*F. candida*). In this study, the authors confirmed that MPs are transported longer when predators and preys exist together than when they exist alone. That is, movements of MPs in soils can be influenced depending on soil biota including different trophic levels or food chains. In another research, Zhu et al. (2018b) investigated the growth, reproduction, isotope composition, and gut microbiota of *F. candida* after exposure to PVC MPs for 56 days. The indicators (bacterial diversity, microbiota in the gut, growth, reproduction, and isotope composition) were affected by MP exposure. These results indicate that MP can impact non-target species in soil biota.

In summary, only eleven studies have been conducted on the adverse effects of various MPs on soil organisms and their findings were very limited. Among these studies, three studies used collembolans as the test species, and poultry (*G. gallus domesticus*), isopod (*P. scaber*), and mite (*H. aculeifer*) have only been used once each as test species. The other studies used earthworm (*L. terrestris* in four studies, *E. fetida* in one study, *E. andrei* in one study, and unknown earthworm species in one study). Earthworms are very appropriate test species for investigating the pollution and impact of MPs in soil ecosystems because they can ingest small-sized plastics, generate secondary MPs in their body (Rillig, 2012; Huerta Lwanga et al., 2016), and transport MPs in soil through their burrowing activities (Anderson, 1988). Their activities such as ingestion of soils and excretion of casts may be the main mechanism behind the transport of MPs in the soil ecosystem (Huerta Lwanga et al., 2016). In addition, several end points such as the distributions of MPs in soil by the activities of earthworms (Huerta Lwanga et al., 2016; Rillig et al., 2017a), bioaccumulation in earthworm bodies (Gaylor et al., 2013), and sub-lethal effects on the growth, biomass, reproduction, and immune system response of earthworms (Huerta Lwanga et al., 2016; Hodson et al., 2017; Huerta Lwanga et al., 2017a; Rodriguez-Seijo et al., 2017) are suitable for evaluating the adverse effects of MPs on soil organisms and ecosystems. However, as mentioned above, to evaluate the overall impacts of MPs on soil ecosystems, various other organisms should be considered as test species in future studies.

PE was the most dominantly used test material in the above-mentioned studies. Among six studies that used PE, two studies used LDPE, one used HDPE from plastic carrier bags, two used

Table 1
Plastic extraction methods for various environmental samples from previous studies

Media	Pretreatment				Assessment		Methodology	Result	Ref.
	Separation	Digestion	Filtering	Dry	Qualification	Quantification			
Dry sludge	–	–	Filter mesh (300, 100 and 20 μm)	–	Fourier Transform infrared spectrometer (FTIRi)	Stereomicroscope	Removal of microlitter from wastewater during different treatment steps of mechanical, chemical and biological treatment and biologically active filter in a large advanced WWTP was examined	Twenty percent of the microlitter removed from the process was recycled back with the reject water, and eighty percent of the microlitter was contained in the dried sludge	Talvitie et al., 2017
Seawater and freshwater	–	–	Filter mesh (300 and 10 μm)	–	Raman spectrometer	Optical microscope	MPs (≥10 μm diameter) were filtered from below the sea surface and identified	Sixty-eight percent of visually counted MPs were spectroscopically confirmed as MPs and fibers with a higher success rate than other particles	Lenz et al., 2015
	–	–	0.7 μm GF/F glass microfiber filter	450 °C for 4 h	Fourier Transform infrared spectrometer (FTIR)	Dissection microscope, scanning electron microscope (SEM)	Plastic fragments less than 1 cm across were collected using a small net and a manta trawl	The most common synthetic polymers were found to be PP and PE.	Mendoza and Jones, 2015
Sediment	Settlement, oil layer separation sodium iodide (NaI) extraction, calcium chloride ($CaCl_2$) extraction	Enzyme blend for 60 h at 45 °C, 30% H_2O_2	1 μm pore polycarbonate membrane	–	Fourier transform infrared spectroscopy (FTIR)	Microscope	Sediment samples were collected at three local beaches; the first 5 cm of sediments was removed, and 250 ml of sediments was collected below this	Suggested alternative to density-based approaches by taking advantage of the oleophilic properties of MPs	Crichton et al., 2017
Beach sand/ sediment	–	–	–	–	–	Microscope	Collecting plastic debris on the beach: (i) identification of the sampling area, (ii) marking of the sampling quadrat, and (iii) sorting and counting of small plastic debris	The high abundance could be explained mainly by the transport of plastic debris via surface currents	Hidalgo-Ruz and Thiel, 2013
	Saturated saline solution (density-separation)	–	65 μm mesh	–	–	Microscope	Sediment and water samples were collected along the south-eastern coastline of South Africa	MP densities in beach sediments ranged between 688.9 ± 348.2 and 3308 ± 1449 particles·m^{-2}, while those in the water column varied between 257.9 ± 53.36 and 1215 ± 276.7 particles·m^{-3}	Nel and Froneman et al., 2015
Living organisms	–	Nitric acid, hydrogen peroxide, sodium hydroxide, HNO_3 with hypochloric acid or H_2O_2 in a 3:1 v/v ratio	0.8 μm membrane filter, 5 μm cellulose nitrate membrane filter	60 °C for 24 h	–	Dissection microscope	Evaluated the efficiency of techniques for extracting microplastics from invertebrate tissue	Extraction of MP yielded high efficiencies (94–98%), and efficiencies for fibers were highly variable (0–98%) depending on polymer type.	Claessens et al., 2013
	Hypersaline NaCl solution	30% stabilized hydrogen peroxide (H_2O_2), nitric acid, H_2O_2 solution	Cellulose nitrate membrane (8 μm\ pore size)	Dried	FTIR spectrometer	Stereomicroscope	Compared the efficacy of some existing approaches and optimized a new protocol	The new protocol afforded extraction yields of MPs from fish tissues ranging between 78% and 98%, depending on the polymer size	Avio et al., 2015
	NaI solution	KOH, H_2O_2, NaOH, HCl, HNO_3, NaClO solution,	8 μm pore size	–	Raman spectroscopy	Scanning electron microscope (SEM)	Measured the efficiency of different oxidative agents, bases, and acids in digesting	Treating biological materials with a 10% KOH solution and incubating at 40 °C	Karami et al., 2017

Table 1 (*continued*)

Media	Pretreatment				Assessment		Methodology	Result	Ref.
	Separation	Digestion	Filtering	Dry	Qualification	Quantification			
							fish tissues at various temperature	was both time and cost-effective, and thus efficient in digesting biological materials	
	NaI solution	NaOH, HNO_3	Cellulose nitrate filter (8 μm pore size)	Dried at room temperature	Fourier transform infrared spectroscopy (FTIR)	Digital microscope	Suggestion of a new extraction technique using NaOH, HNO_3, and NaI solutions	The novel approach could accelerate digestion using NaOH and HNO_3 that digest all organic materials within 1 h and an additional separation step using NaI could reduce mineral residues in samples	Roch and Brinker, 2017
Soil media	–	Methanol, hexane and dichloromethane	Glass fiber filter	–	FTIR-ATR mode	Microscopy	Suggestion of pressurized fluid extraction (PFE) that can measure MPs in environmental samples	Field soil samples were found to contain 0.03%–6.7% of MPs	Fuller and Gautam, 2016
	NaCl, $CaCl_2$ solutions	KClO, NaOH, H_2SO_4, HNO_3, and H_2O_2	0.45 μm filter	–	FT-IR microscope, raman spectroscopy	FT-IR microscope	Developed a method for identifying, quantifying, and measuring the sizes of most commonly produced MPs in soil by FT-IR microscopy	Ninety percent of Swiss floodplain soils contain MPs and highest MP concentrations were associated with the concentration of mesoplastics	Scheurer and Bigalke, 2018
	Distilled water	–	Filter paper (<3 μm)	60 °C		Microscope	Suggestion of a simple and cost-saving method to extract, distinguish and quantify light density MPs of PE and PP in soi	A heating method (3–5 s at 130 °C) and microscopy were effective in extracting MPs from soils (recovery rates of approximately 90%.)	Zhang et al., 2018

purchased PE, and one used produced PE from plastic bags and facial cleanser. In the remaining five studies, polyurethane was used for one study, urea-formaldehyde for one study, PVC for two studies, and uncharacterized plastic for one study. PE is one of the most common plastics in soil because of landfill with sewage sludge containing primary MPs from personal care products (McCormick et al., 2016; Talvitie et al., 2017) and PE vinyl mulch from agricultural activities (Kasirajan and Ngouajio, 2012; Li et al., 2014b; Sintim and Flury, 2017). Therefore, investigating the impacts and effects of PE on the soil ecosystem is an important and urgent task that requires further research.

Most of the abovementioned research can be summarized as follows: i) MPs may have adverse effects on and can be accumulated in soil organisms (Huerta Lwanga et al., 2016), ii) additives derived from MPs can be accumulated in soil organisms (Gaylor et al., 2013), iii) MPs can cause changes in the chemical contents of soil organisms (Rodriguez-Seijo et al., 2017), iv) responses of soil organisms exposed to MPs can cause changes in soil characteristics (Huerta Lwanga et al., 2017a), v) chemicals adsorbed on MPs can enter the soil ecosystem (Hodson et al., 2017), and vi) MPs can move horizontally (Maaß et al., 2017) and vertically (Huerta Lwanga et al., 2017a; Rillig et al., 2017a). However, among the abovementioned previous studies, several did not find any impact of MPs on soil organisms, and therefore, the authors suggested advanced future studies.

Overall, the amount and progress of research on the ecotoxicity of plastic wastes in the soil ecosystem are still very limited. Therefore, advancing research in this field is necessary to protect the soil environment and human health from serious plastic pollution, which threatens food, groundwater, and ecosystem safety.

4. Perspectives for future studies

Plastic pollution in the soil ecosystem has received attention and active studies on plastic pollution have been conducted only recently. Because of the unique characteristics of soil media, investigating the pollution and adverse effects of plastic wastes on soil environments is quite difficult. To promote research on plastic pollution in the soil ecosystem, two tasks are necessary. The first is to develop advanced techniques and methodologies for the sampling, extraction and detection of plastic wastes in soil media. Recently, several studies have developed methods for extracting and sorting out plastic wastes from soil media (Fuller and Gautam, 2016; Bläsing and Amelung, 2018; Scheurer and Bigalke, 2018; Zhang et al., 2018). However, several limitations still remain: limitation on size detection (Zhang et al., 2018), difficulties on analysis of small plastics with high density or disintegration during the oxidation of organic matter (Scheurer and Bigalke, 2018), absence of standard protocol, and high cost (Bläsing and Amelung, 2018). Additionally, there is no sampling strategy that can represent the average concentrations of microplastic in soils compared to those in water samples (Lusher et al., 2014; Song et al., 2014). The second task is to recognize the present state and condition of plastic

Table 2
Previous studies on microplastics that investigated and assessed their impacts on soil organisms

Materials			Test species	Exposure conditions			Methodology	Assessment point	Result	Note	Ref.
Polymer type	Options and details	Size		Conc.	Media	Duration					
Polyurethane (PU)	Commercial product	<75 µm	*Eisenia fetida*	PU 1:2000 w/w ΣPBDEs83 mg kg^{-1} dw	Artificial soil	7, 14 and 28 days	Direct exposure to PU and PBDE contaminated soil in the jar and evaluation of bioaccumulation	Bioaccumulation	PBDEs accumulate in organisms ingesting soils containing biosolids or waste plastics	Combined effect	Gaylor et al., 2013
Light-density Polyethylene (LDPE)	Produced	200 - 300 µm	*Lumbricus terrestris*	1, 5, 10 and 15% v/v	Sandy soil	4, 14 and 60 days	Direct exposure to LDPE contaminated litter and investigation of assessment points	Plastic ingestion, mortality, growth, reproduction, tunnel formation, position of the worms,	Growth rate was reduced and microplastics were concentrated in casts	Mesocosm study	Huerta Lwanga et al., 2016
High-density Polyethylene (HDPE)	Produced (from plastic carrier bag)	0.92 ± 1.09 mm^2	*Lumbricus terrestris*	HDPE 236, 1261, and 4505 mg kg^{-1} Zn 0.6, 3.4 and 12 mg kg^{-1}	Arable and woodland soil	28 days	Direct exposure to HDPE bags and zinc in soils and investigation of zinc bioaccumulation and HDPE retention time	Adsorption/ desorption, biomass, ingestion	No evidence of Zn accumulation, mortality, or weight change, and no retention of HDPE in earthworm gut	Combined effect	Hodson et al., 2017
Light-density Polyethylene (LDPE)	Produced	200 - 300 µm	*Lumbricus terrestris*	7, 28, 45 and 60% w/w,	Sandy soil	14 days	Direct exposure to HDPE in mesocosm and the burrows and evaluation of bioturbation efficiency ratio	Biomass, burrowing characteristic, Transport of MP	Highest burrows and MP bioturbation efficiency ratio were found in 7% LDPE treatment	Mesocosm study	Huerta Lwanga et al., 2017a
–	Plastic wastes from home garden	–	Earthworm, *Gallus gallus domesticus*	–	Field soil (home garden)	5 - 8 months	Evaluation of MP bioaccumulation in garden soil, earthworm casts, chicken feces, crops, and chicken gizzard	Bioaccumulation,	MP concentrations increased from soil, to earthworm casts, to chicken feces	Food chain, Field study	Huerta Lwanga et al., 2017b
Urea-formaldehyde microplastic	Purchased	<100 and 100–200 µm	*Folsomia candida, Proisotoma minuta*	5 mg of the 100–200 µm fraction and 2.5 mg of the <100 µm fraction,	Plaster of Paris and activated charcoal (3:1) in petri dish	7 days	Direct exposure of two collembolan species to MPs and evaluation of the horizontal transport of MPs	Transport of MP	*F. candida* could transport larger particles further and faster than *P. minuta*	Not soil test	Maaβ et al., 2017
Polyethylene (PE)	Purchased	710 - 850, 1180–1400, 1700–2000 and 2360–2800 µm	*Lumbricus terrestris*	750 mg per 2.5 kg soil (added on the soil surface) (2625, 424, 203 and 75 particles per 2.5 kg soil)	Albic Luvisol	21 days	Direct exposure of earthworm to PE and investigation of the vertical transport of PE particles	Transport of MP	Earthworms can transport MPs in soils via casts, burrows (affecting soil hydraulics), egestion, and adherence to the earthworm exterior	No ecological effects	Rillig et al., 2017
Polyethylene (PE)	Purchased	250 < MP < 1000 µm	*Eisenia andrei*	62.5,125, 250, 500,1000 mg MP / kg soil dw	OECD artificial soil	28 and 56 days	Direct exposure of earthworm to PE MPs in soil and reproduction, survival and investigation of the growth of adults, growth, histopathological analysis, and immune system response	Survival, number of juveniles, weight, histopathological analysis, damages, immune system response	No effect on survival, number of juveniles and, in the final weight of adult earthworms, but damages and immune system responses were confirmed	No effect on reproduction	Rodriguez-Seijo et al., 2017
Plastic bag film and particles from a facial cleanser (PE)	Produced	183 ± 93 (cleanser) and 137 ± 51 (film) µm	*Porcellio scaber*	4 mg g^{-1} dry weight	Filter paper in petri dish	14 days	Direct exposure of isopod on filter paper and evaluation of the effects of MP derived from plastic bag film and particles from a facial cleanser	Feeding rate, defecation fate, energy reserves	No effects on either end-point	Not soil test	Kokalj et al., 2018
	Purchased	80 - 250 µm				7 days		Transport of MP		Food chain	

Polyvinyl chloride (PVC)			*Folsomia candida, Hypoaspis aculeifer*	5000 microplastic particles in each petri dish	plaster of Paris mixed with activated charcoal (9:1 w/w) in petri dish		Direct exposure of collembolan and mite to PVC particles on petri dish and assessment of several endpoints		Soil microarthropods transported MP particles		Zhu et al., 2018a
Polyvinyl chloride (PVC)	Purchased	80 - 250 μm	*Folsomia candida*	1 g microplastics kg^{-1} dry soil	Natural soil	28 and 56 days	Direct exposure of collembolans to PVC MPs in soil and evaluation of the effects	Growth, reproduction, isotope composition, gut microbiota	Exposure to MP enhanced bacterial diversity, altered the microbiota in the collembolan gut, and significantly inhibited collembolan growth and reproduction	–	Zhu et al., 2018b

pollution in soils. Recently, several researchers could measure the concentrations of microplastics in soils from an industrial site in Australia (Fuller and Gautam, 2016) and Swiss floodplain soils (Scheurer and Bigalke, 2018). However, only limited information has been obtained thus far. To suggest effective solutions for overcome current problems related to plastic pollution, understanding the current state of plastic pollution in the soil environment is currently the most important task.

We suggest several future missions particularly considering soil ecotoxicity derived from plastic pollution. To investigate and understand the impact of plastic pollution on organisms in the soil environment, future studies must also consider these following topics.

- To date, only earthworms have been predominantly used as the test species. Earthworms are model organisms of the soil ecosystems and there are many advantages from using earthworms as test species: they are sufficiently large for easy identification, convenient for conducting experiments, provide sufficient endpoints to assess the effects of test materials, and there are established guidelines for using them as test species (Ma and Bodt, 1993; Paoletti, 1999). They also directly ingest plastic wastes in the soil media and the adverse effects of ingesting these plastic wastes can be easily assessed. The soil ecosystem, however, as described above, is a very complex ecosystem with numerous physical, chemical and biological factors, and includes a wide variety of organisms (Oades, 1988; Phillips, 1998; Arias-Estévez et al., 2008). Therefore, more organisms such as plants, invertebrates, insects, and microorganisms need to be urgently considered in investigating the impact of plastic pollution on the soil environment. This will aid in understanding the mechanisms (ingestion and egestion, ecological impact, transfer, etc.) of plastic wastes on each soil organism and overall effect of plastic pollution on the entire soil ecosystem.
- Recent studies have focused on PE fragments and spheres but effluents from wastewater treatment plants contain numerous varieties of polyester and polyacrylic fibers (Browne et al., 2011; Napper and Thompson, 2016; Pirc et al., 2016; Talvitie et al., 2017). These various kinds of polymers have potential for being transported into soil environment in the process of sludge dumping. Furthermore, plastic mulch used in agricultural activities do not exist in the form of spheres but irregular fragments or films. Using spherical microplastics in experiments is convenient and provides basic understanding of the toxicity of plastic in the soil environment, but using only these materials in laboratory experiment is not applicable to real environments. To simulate practical and realistic situations, various sizes, shapes, compositions, and origins of plastics are needed.
- Future research should consider various scenarios that can occur in real environments, such as trophic transfer and generational effect. In real environments, interactions between each organism can occur via the food chain and the reproductive system may be affected by long-term exposure to plastic wastes. These are very important in the environment and ecosystem because food chains and trophic transfers can determine and play important roles for community structure, population dynamics, and individual performance of higher trophic levels (Loreau, 1996; Kagata and Ohgushi, 2006). In the case of generational effects or aspects, these are related to species richness and diversity (Johnson et al., 2012) or ecological distributions of species (Sultan, 2001). In previous studies, researchers have found that micro- and nano-plastics can be transported between organisms, namely preys and predators in aquatic ecosystems (Cedervall et al., 2012; Farrell and Nelson, 2013; Mattsson et al., 2014; Setälä et al., 2014; Gutow et al., 2015). Only two studies

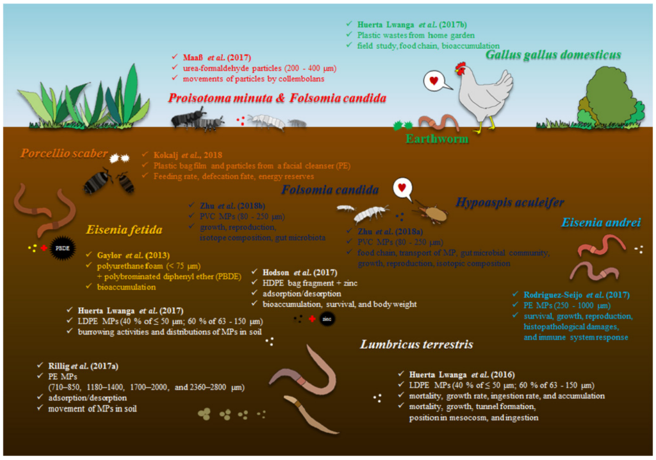

Fig. 2. Studies on the effect and impact of microplastics on soil organisms (*Eisenia andrei, Eisenia fetida, Lumbricus terrestris, Folsomia candida, Proisotoma minuta, Gallus gallus domesticus, Porcellio scaber,* and *Hypoaspis aculeifer*).

have investigated the transport of microplastics through the food chain in the soil media (Huerta Lwanga et al., 2017b; Zhu et al., 2018a). Few studies have investigated the generational effects of microplastics in aquatic ecosystems (Besseling et al., 2014; Au et al., 2015; Sussarellu et al., 2016) and there are no such studies considering the soil ecosystem. If plastic wastes are transferred via the food chain and their effects reach next generations, these impacts could affect populations and communities, and further affect the entire ecosystem.

- Further research should also consider additives of plastic products (plasticizers, retardant, antioxidants, and photo-stabilizers) and adsorbed chemicals in the soil environment. Only Gaylor et al. (2013) and Hodson et al. (2017) conducted such studies using added PBDE and adsorbed Zn, respectively (Gaylor et al., 2013; Hodson et al., 2017). Several similar studies have been conducted in marine and freshwater environments (Hong et al., 2017; Rochman et al., 2013; Ziccardi et al., 2016; Wardrop et al., 2016). The soil contains many organic and inorganic materials, such as minerals, metals, nutrients, and other contaminants (Swift, 1996; Bolan and Duraisamy, 2003; Gerhardt et al., 2009), and they could be adsorbed on plastics, desorbed from plastics, and aggregate with plastics as investigated in previous studies. The roles of plastic wastes as a vector or carrier for chemical transport in the soil environment are also important and further research on this topic is required.

The increasing amount of plastic wastes in the environment and their threat to ecosystems and human health cannot be ignored anymore. Therefore, it is time to focus on plastic pollution in the soil environment as a serious issue. For this purpose, the findings of previous studies on plastic pollution in marine and freshwater environments can be applied to future research.

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