Environmental Pollution 240 (2018) 387–395

Contents lists available at ScienceDirect

Environmental Pollution

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

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

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ARTICLE INFO

Article history:

Keywords:
Plastic pollution
Microplastic
Soil pollution
Plastic waste
Terrestrial ecosystem

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

☆ This paper has been recommended for acceptance by Maria Cristina Fossi.

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https://doi.org/10.1016/j.envpol.2018.05.008
0269-7491/

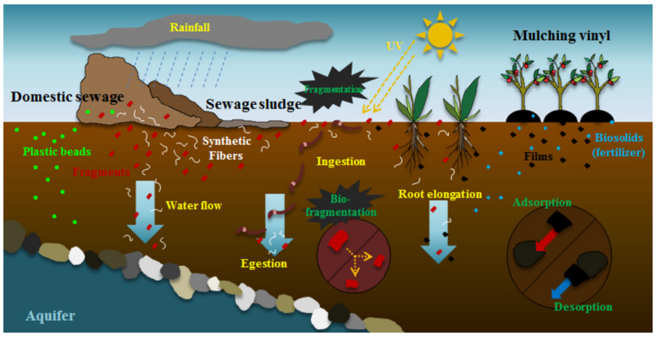

Fig. 1. Schematic of the flow of plastic wastes in the soil environment and their distributions and fate in soil. These plastic wastes enter the soil environment via various routes. These plastic wastes enter the soil ecosystem and they are distributed from the surface to deep soil layers. Water flows 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