Interaction of Microplastics and Heavy Metals: Toxicity, Mechanisms, and Environmental Implications

Xiaofeng Jiang and Mei Li

Contents

Abstract With the wide use of plastic products in all aspects of life, more and more plastic ends up in the environment. Such plastic waste will gradually decompose, break up, and form smaller fragments through a series of physicochemical and biological processes. Among them, plastic fragments with particle size less than 5 mm are defined as microplastics (MPs). MPs have been reported to be widely distributed and to have the potential to adsorb other pollutants. Therefore, it is particularly important to evaluate the toxic effects of MPs in combination with other pollutants like metals. So far, studies on microplastic and metal toxicity have mainly focused on aquatic environments, while their impact on terrestrial ecosystems has been studied to a much lesser extent. In order to help our understanding of

---

X. Jiang and M. Li (✉)
State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing, China
e-mail: meili@nju.edu.cn

Defu He and Yongming Luo (eds.), *Microplastics in Terrestrial Environments - Emerging Contaminants and Major Challenges*,
Hdb Env Chem (2020) 95: 185–196, DOI 10.1007/698_2020_460,

the ecological risk of MP on soil ecosystems, this chapter reviewed the interaction of MPs and metals on soil organisms.

Keywords Combined exposure, Metals, MPs, Soil ecosystem, Toxic effects

1 Introduction

Microplastics can be divided into primary and secondary MPs. Primary MPs are plastic fragments or particles whose initial particle size is less than 5 mm when they are manufactured, mainly in textiles, drugs, and personal care products [1, 2]. The secondary MPs are plastic fragments shaped by environmental forces to a particle size less than 5 mm [3]. Up to now, most studies dealing with MPs and their toxicity have focused on the marine environment. Although freshwater and terrestrial environments have been considered the origin and transport route of plastics to the sea, there is still lack of research of MPs in these environments, especially in the soil environment.

In recent years, it has been found that MPs are widely detected in the soil environment. Fuller and Gautam have investigated the concentrations of MPs in industrial soils in Sydney, Australia, and found that it varies greatly among different sites, with a minimum concentration of 300 mg/kg, and the highest concentration of 6.75×10^4 mg/kg [4]. Scheurer and Bigalke reported the MP abundance of 26 floodplain sites in Switzerland. Their investigations showed that the highest MPs concentration could reach 55.5 mg/kg [5]. In addition, the toxicity of MPs to terrestrial organisms, such as earthworms, mice, and other, has also been conducted. It has been confirmed that MPs with particle size less than 1 mm are easily ingested by soil organisms [6]. Lwanga et al. found that MP exposure could affect the growth and movement of earthworm *Lumbricus terrestris* (*L. terrestris*). The results showed that microorganisms in the earthworm gut significantly decreased low density polyethylene (LDPE) particle size [7, 8]. Other studies have also shown the toxic effects of various MPs on other soil organisms [9, 10]. Furthermore, particle size is one of the most important characteristics of MPs toxicity [1]. For example, 1 μm is the most common size of filter food organ interception in crustaceans, so crustaceans prefer to ingest MPs with particle size less than 1 μm. Smaller particles have a greater possibility of biological intake than larger size particles, which may enter the cells through endocytosis. Although it has been assumed that the toxicity of MPs is significantly related to its particle size, there is no unified view on what kind of particle size MPs is more toxic. The toxic effects of 0.05 μm, 0.5 μm, and 6 μm MPs on rotifer *Brachionus koreanus* were compared, and it was concluded that small particle size MPs had more significant toxic effects. The antioxidant enzyme activity and mitogen-activated protein kinase (MAPK) signaling pathway in rotifer changed with different particle size of MPs [11, 12]. Likewise, another study found that MPs with particle size larger than 50 μm had no significant toxic effect on Grass shrimp (*Palaemonetes pugio*), while the fatality rate of acute toxicity test was higher when the size less than 50 μm. It was indicated that MPs have size-dependent effects on the same species [13].

The interaction between MPs and other pollutants is present in the environment. Therefore, in order to evaluate the ecological risk of MPs, the interaction between MPs and other pollutants should be considered, and the toxic effects of combined exposure on various organisms should be addressed. However, there is still lack of research on the toxic effects of MPs in combination with other pollutants, especially MPs and heavy metals [14–17]. There are only a few articles published that deal with the combined toxic effects of MPs and heavy metals. Combined exposure of Cr^{6+} and MPs enhanced the toxicity of the juveniles of common goby – *Pomatoschistus microps* and caused strong lipid peroxidation damage in larvae [18]. By contrast, another study has shown that the combined exposure of 1 μm MPs and Cu to microalgae did not show any toxicity [19]. These studies showed that the combined exposure of MPs and heavy metals is affected not only by the particle size but also by the selected biological species. Moreover, MPs can also interact with heavy metals in the soil environment [20, 21]. Hodson et al. studied the adsorption behavior of high density polyethylene (HDPE) on Zn^{2+} in soil. They found that HDPE had stronger adsorption capacity for Zn^{2+} in soil with more abundant organic matter. The adsorption behavior was in accordance with Langmuir and Freundlich equation [20]. The aged MPs in soil also had a significant effect on the adsorption of heavy metals. Nicole et al. exposed HDPE, polyvinyl chloride (PVC), and polystyrene to artificial aging conditions (2000 h, photo-oxidation and thermal oxidation) to simulate their aging process using a column percolation test. Their results showed that the aged MPs not only significantly increased the adsorption of TOC, Cl, Ca, Cu, and Zn but also weakened the desorption and release of heavy metals, which indicated that the aged MPs had stronger fixation ability to heavy metals [21]. In addition, the functional groups in the soil are adsorbed to the surface of the MPs and may change the adsorption capacity of heavy metals. Kim et al. investigated the adsorption of Ni by the functional group-coated polystyrene. Results showed that the functional groups change the surface hydrophobicity of the polystyrene microplastic and heavy metal and then alter the adsorption of the heavy metal [22]. Turner et al. also studied the adsorption properties of polyethylene microplastics (PE-MPs) for heavy metal ions (Ag, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn) [23]. The adsorption kinetics experiments showed that the adsorption efficiency of aged PE-MPs in river water was higher than that of original PE-MPs, which may be due to the change of the surface structure of aged PE-MPs to reach surface charge equilibrium. Holmes et al. also found that the adsorption capacity of aged polyethylene in seawater for heavy metals was stronger than that of the original polyethylene [24]. Therefore, once the MPs in the soil are weathered and aged, they can be effective carriers of heavy metal in the soil environment what can cause even greater damage to the health of the soil ecosystem.

2 Effects of Microplastics on Organisms

2.1 Individual Effects of Microplastics on Organisms

The ecotoxicity of MPs is mainly focused on smaller organisms. Organisms can directly ingest most MPs that can then cause physical damage, clog or wear ingestion organs and digestive tract, or reduce ingesting rate of organisms. Furthermore, sharp MPs can also cause damage to gills or intestinal tissues [25]. Mussel (*Mytilus edulis*) and herbivorous crab (*Carcinus maenas*) could ingest polyethylene (<80 μm) and polystyrene microspheres (10 μm) and ingested MPs could damage the intestinal tract [26, 27]. In addition, after organisms ingest MPs, they might cause the wrong sense of satiety, reduce the intake of food and act on the digestion process, resulting in energy loss, reduce growth as well as reproductive capacity, and ultimately lead to hunger and death [28].

MPs affect the individual growth, reproduction, and diversity of soil animals. Once MPs are taken up or accumulated by soil animals, in addition to causing physical damage, such as tearing of organs and tissues, the animal will also have an inflammatory response to invasive heterogenic substances [29]. In addition, the ingestion of MPs can also cause insufficient supply of nutrients and energy to soil organisms. Furthermore, the toxic substances released by MPs and the toxic effects of adsorbed pollutants can have varying degrees of adverse impacts on individual and species diversity [20, 30, 31].

The toxic effects of MPs on soil animals are related to particle size and concentration. Rillig showed that MPs with particle size less than 1 mm can be easily eaten by soil animals. After soil animals are fed with MPs, they can also remain in the body [32]. Another investigation showed that MPs are not only more likely to remain in the intestine than other ingested substances but can also pass through the intestinal wall and be transported to other tissues [33]. MPs with a particle size >1 mm remains in the intestinal tract or with the excreta while the small particles are more easily transferred, and can be accumulated by cells. It may relate to the limited space of intracellular phagocytosis of corpuscles [34]. Lwanga et al. studied the effects of different concentrations of MPs (polyethylene <150 μm) on the earthworm *Lumbricus terrestris*. It was found that the mortality rate was highest along with a negative growth rate, when the concentration of polyethylene reached 60% w/w [7, 35].

2.2 Combined Effects of Microplastics and Heavy Metals on Organisms

Heavy metals are widely distributed pollutants in the natural environment. Their toxic effects on aquatic organisms have been widely studied and they are considered to be high-risk pollutants. Heavy metals exist in various ion forms in the water environment. It has been reported that heavy metals can be enriched by aquatic organisms and have an adverse impact on the whole ecosystem [36, 37]. MPs have the potential to act as vectors for heavy metals and may change the toxicity of other contaminants [38, 39]. Therefore, it is of great significance to explore the interaction between MPs and heavy metals for the complete evaluation of the ecological effects. Barboza et al. found that MPs could absorb mercury from surrounding water and subsequently affect the accumulation of mercury in the European seabass (*Dicentrarchus labrax*) [40]. Khan et al. reported that exposure to aged MPs could increase the bioaccumulation of Ag in the intestine tissue of zebrafish (*Danio rerio*) [41]. Luís et al. found that MP exposure could affect the toxic effects of Cr (VI) on juvenile *P. microps* [18]. Lu et al. reported that exposure to MPs and Cd resulted in increase of Cd bioaccumulation in the zebrafish (*D. rerio*) tissues and showed increased toxic effects compared to exposure to Cd alone [42]. Wen et al. investigated the single and combined toxic effects between polystyrene MPs (0, 50 or 500 mg L^{-1}) and two concentrations of Cd (0 or 50 mg L^{-1}) on the discus fish (*Symphysodon aequifasciatus*) for 30 days. The results showed that there are no obvious effects on the survival and growth of juvenile *S. aequifasciatus*, indicating that the decreasing toxicity may be due to the antagonistic effects of Cd and MPs. However, co-exposure to high concentration of MPs (500 mg L^{-1}) and Cd led to elevated protein carboxyl content, suggesting a synergistic effect of MPs and Cd on the accumulation of protein oxidation products [43]. Lu et al. investigated the biochemical markers, histopathological changes, and functional gene expression of zebrafish (*D. rerio*), showing that the presence of 5 μm polystyrene microspheres enhanced the toxicity of Cd^{2+} to zebrafish and its combined exposure with Cd^{2+} could lead to oxidative damage and inflammation of zebrafish [25]. Nevertheless, the reports regarding combined effects of MPs and heavy metals on soil organisms are still limited. Hodson et al. studied the interactions between HPDE MPs particles and zinc (Zn) to understand the effect of MPs on earthworms' metal bioavailability. Their results showed that MPs could increase Zn bioavailability; however, Zn accumulation, mortality, or earthworms weight have not changed significantly [20].

Wang et al. exposed PVC MPs to earthworm *Metaphire californica* with arsenic (As (V)), for 28 days. The total arsenic concentration and arsenic species in the soil, the gut microbiome, and the tissues of earthworm were analyzed. The findings illustrated that arsenic could be bioaccumulated in the earthworm gut and tissues. Nevertheless, total arsenic concentrations in the earthworm gut and tissues were significantly decreased when earthworms were exposed to the combination of As (V) and MPs, which may explain that MPs can alleviate the adverse effect of arsenic on the gut microbiome due to MPs possibly by inhibiting the reduction of As (V) [44].

3 Potential Mechanism of Microplastics Toxicity

3.1 Uptake, Translocation, and Accumulation of Microplastics in Organisms

Microplastic particles will be transferred to higher organisms through the food chain [45, 46]. Lwanga et al. performed one study on the trophic transfer of MPs in the terrestrial food chain, in which the concentrations of MPs in gardening soil, earthworm casts, and chicken (*Gallus gallus domesticus*) feces were analyzed. The concentrations increased along the trophic levels, and the highest concentration of MP was confirmed in chicken feces. In particular, chicken gizzards also contained MPs, and this indicated that the evidence of transfer of MPs to humans is through food because gizzards are used for human consumption [35]. Maaß et al. 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. Nevertheless, the authors confirmed the horizontal transport of plastic particles by soil microarthropods [47]. Rillig et al. also studied the transport of PE-MP by soil organisms *L. terrestris*, which were cultured in 2.5 kg of soils covered with 750 mg of various sizes of PE-MPs particles. 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 layers of the soil. The mechanisms of plastic transport in soil were not demonstrated, but they suggested that MPs might be transported through the activities of earthworms such as ingestion/egestion, burrowing, adherence, and casts making [48].

So far, despite their ecological importance, the exposure of soil filter feeders such as nematodes, rotifers, and ciliates to MPs and nanoplastics has not yet been determined. Filter feeders in marine ecosystems have been shown to ingest microparticles [30, 49], while filter feeders in freshwater ecosystems, *Daphnia magma* and *Thamnocephalus platyurus*, have been shown to be sensitive to nanoplastics [50]. Organisms with other feeding modes are also susceptible to microplastic ingestion. Taylor et al. found synthetic microfibers on and inside six out of nine deep-sea organisms that belong to the phyla Cnidaria, Echinodermata and Arthropoda with predatory and feeding mechanisms [51]. As such, woodlice, snails, caecilians, and other soil organisms with similar feeding mechanisms would be subjects of interest in agroecosystems. Information about the bioavailability and bioaccumulation of MPs in soil organisms is generally lacking. We know that nanoplastics can enter cells, as fluorescent nanoplastic polymers have been used as molecular probes for a wide range of biological studies with mammalian cells, for example, to measure blood flow in tissue and as tracers for phagocytic processes [34]. The translocation of a range of microparticles by mammalian gut into the lymphatic system has been demonstrated in rabbits, dogs, and rodents. There is no experimental evidence of nanoplastics being transferred from invertebrates to vertebrates. However, there is evidence of the transfer of MPs from contaminated land to vertebrates and potentially from earthworm to chicken [35].

3.2 Molecular-Level Response

So far, there have been published only a few papers that focused on the molecular-level response of organisms to MPs exposure [10, 52, 53]. Prendergast-Miller et al. used metallothionein (*mt-2*), heat shock protein (*hsp70*), and superoxide dismutase (*SOD-1*) as the biomarker responses to evaluate the molecular-level response in *L. terrestris* exposed to polyester-derived microfiber (MF) with 0, 0.1, and 1.0%w/w for a period of 35 days [53]. Their results showed that *hsp70* expression was downregulated at the high MF exposure, which indicated that downregulation of *hsp70* is an index of stress when *L. terrestris* is exposed to MF. However, the activity of *mt* is not completely understood. It can be explained by the shortage of metal transcription factor (*MTF-1*) in *L. terrestris* compared to other higher organisms. Therefore it is necessary to determine the transcriptional response of the earthworm's response to MF [53]. Rodriguez-Seijo et al. also studied molecular changes of earthworms (*Eisenia andrei*) exposed to PE-MPs. They concluded that multiple stress-response mechanisms of the immune system of earthworms led to, involving a wide range of molecules/enzymes, the increased content in proteins, lipids, and polysaccharides [10]. In addition, the alterations of saturation fatty acid have also been considered as a biomarker for the response of soil organisms to stress [54]. The increase in saturated fatty acids makes membranes more viscous and less permeable, while saturation reduces the susceptibility of fatty acids to free radicals [55].

4 Environmental Implications and Future Prospective

4.1 Challenges About Toxicity Research Methodologies of Microplastics and Heavy Metals

MPs can act as a carrier of metals and combined they can cause toxicity to various organisms. However, it is difficult to determine the contribution of MPs and metals to overall toxic activity. Furthermore, contaminants carried by MPs may be transported along the food chain [56]. Among the chemical substances present in MPs are those added during their manufacture (additives) and those present in water that are adsorbed on the surface of MPs, such as persistent organic pollutants, pharmaceuticals, pesticides or herbicides. Among pollutants that MPs can absorb, metals have been widely studied [29, 33, 56]. In addition, some metals are frequently added as catalysts, pigments, and stabilizers during plastic manufacturing [57]. The toxicity of MPs and heavy metals should not be generalized by synergistic, antagonistic, additive or independent effect. Therefore, it is important that relevant standards and rules for toxicity research on MPs should be first determined so that data from different researches can be comparable and reliable.

4.2 Considerations for Assessing Ecological Risks of Microplastics and Heavy Metals

The widespread distribution and accumulation of MPs in the global environment has attracted attention on its sources, migration distribution, and ecotoxicological effects. The size, quantity, and shape of MPs entering the environment are uncertain, and the related research methods and classification criteria are not unified, what causes lack of consistency in the study of environmental behavior of MPs. There is also a lack of systematic analysis of the bioaccumulation and the transfer of MPs in the food chain. In addition, the interaction mechanism of micro-plastics and heavy metals, as well as the role of the MPs in their combined toxicity needs further study.

5 Summary

This chapter reviewed the interaction of MPs and heavy metals: toxicity, mechanisms, and environmental implications. However, most of the toxicity experiments of MPs are carried out in the laboratory on single species, the exposure time is short, and the dose is higher than the environmental concentrations. Therefore, it is necessary to provide comprehensive evaluation of the MP toxic effects according to the environmental conditions. Furthermore, new molecular biological techniques such as relevant omics should also be applied to study the toxic effects of MPs. The toxic mechanism of MPs and heavy metals on organisms, as well as the toxic effects on biodiversity, community structure, and ecosystem function, also need more detailed approach, which can provide basic data support for the determination of MPs in the environment and the establishment of standards.

Acknowledgments The authors gratefully acknowledge the financial support by the National Natural Science Foundation of China (Grant No. 41773115, 41571468) and Nanjing University Innovation and Creative Program for PhD candidate (Grant No. CXCY19-61).

References

1. Cole M, Lindeque P, Halsband C, Galloway TS (2011) Microplastics as contaminants in the marine environment: a review. Mar Pollut Bull 62:2588–2597
2. Browne MA, Niven SJ, Galloway TS, Rowland SJ, Thompson RC (2013) Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr Biol 23:2388–2392
3. Eriksen M, Mason S, Wilson S, Box C, Zellers A, Edwards W, Farley H, Amato S (2013) Microplastic pollution in the surface waters of the Laurentian Great Lakes. Mar Pollut Bull 77:177–182
4. Fuller S, Gautam A (2016) A procedure for measuring microplastics using pressurized fluid extraction. Environ Sci Technol 50:5774–5780

5. Scheurer M, Bigalke M (2018) Microplastics in Swiss floodplain soils. Environ Sci Technol 52:3591–3598
6. Peng J, Wang J, Cai L (2017) Current understanding of microplastics in the environment: occurrence, fate, risks, and what we should do. Integr Environ Assess 13:476–482
7. Lwanga HE, Gertsen H, Gooren H, Peters P, Salanki T, van der Ploeg M, Besseling E, Koelmans AA, Geissen V (2016) Microplastics in the terrestrial ecosystem: implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae). Environ Sci Technol 50:2685–2691
8. Lwanga HE, Thapa B, Yang X, Gertsen H, Salanki T, Geissen V, Garbeva P (2018) Decay of low-density polyethylene by bacteria extracted from earthworm's guts: a potential for soil restoration. Sci Total Environ 624:753–757
9. Zhu D, Chen QL, An XL, Yang XR, Christie P, Ke X, Wu LH, Zhu YG (2018) Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. Soil Biol Biochem 116:302–310
10. Rodriguez-Seijo A, Lourenco J, Rocha-Santos TAP, da Costa J, Duarte AC, Vala H, Pereira R (2017) Histopathological and molecular effects of microplastics in *Eisenia andrei* Bouche. Environ Pollut 220:495–503
11. Jeong CB, Won EJ, Kang HM, Lee MC, Hwang DS, Hwang UK, Zhou B, Souissi S, Lee SJ, Lee JS (2016) Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-p38 activation in the Monogonont Rotifer (*Brachionus koreanus*). Environ Sci Technol 50:8849–8857
12. Lei LL, Wu S, Lu S, Liu MT, Song Y, Fu Z, Shi HH, Raley-Susman KM, He DF (2018) Microplastic particles cause intestinal damage and other adverse effects in zebrafish (*Danio rerio*) and nematode *Caenorhabditis elegans*. Sci Total Environ 619:1–8
13. Gray AD, Weinstein JE (2017) Size- and shape-dependent effects of microplastic particles on adult daggerblade grass shrimp (*Palaemonetes pugio*). Environ Toxicol Chem 36:3074–3080
14. Oliveira M, Ribeiro A, Hylland K, Guilhermino L (2013) Single and combined effects of microplastics and pyrene on juveniles of the common goby *Pomatoschistus microps* (Teleostei, Gobiidae). Ecol Indic 34:641–647
15. Guven O, Bach L, Munk P, Dinh KV, Mariani P, Nielsen TG (2018) Microplastic does not magnify the acute effect of PAH pyrene on predatory performance of a tropical fish (*Lates calcarifer*). Aquat Toxicol 198:287–293
16. Rehse S, Kloas W, Zarfl C (2018) Microplastics reduce short-term effects of environmental contaminants. Part I: effects of bisphenol A on freshwater zooplankton are lower in presence of polyamide particles. Int J Environ Res Public Health 15:280. https://doi.org/10.3390/ijerph15020280
17. Lin W, Jiang RF, Xiong YX, Wu JY, Xu JQ, Zheng J, Zhu F, Ouyang GF (2019) Quantification of the combined toxic effect of polychlorinated biphenyls and nano-sized polystyrene on *Daphnia magna*. J Hazard Mater 364:531–536
18. Luís LG, Ferreira P, Fonte E, Oliveira M, Guilhermino L (2015) Does the presence of microplastics influence the acute toxicity of chromium (VI) to early juveniles of the common goby (*Pomatoschistus microps*)? A study with juveniles from two wild estuarine populations. Aquat Toxicol 164:163–174
19. Davarpanah E, Guilhermino L (2015) Single and combined effects of microplastics and copper on the population growth of the marine microalgae *Tetraselmis chuii*. Estuarine Estuar Coast Shelf Sci 167:269–275
20. Hodson ME, Duffus-Hodson CA, Clark A, Prendergast-Miller MT, Thorpe KL (2017) Plastic bag derived microplastics as a vector for metal exposure in terrestrial invertebrates. Environ Sci Technol 51:4714–4721
21. Nicole B, Verena W, Volker W, Franz-Georg S (2017) Contaminant release from aged microplastic. Environ Chem 14:394–405
22. Kim D, Chae Y, An YJ (2017) Mixture toxicity of nickel and microplastics with different functional groups on *Daphnia magna*. Environ Sci Technol 51:12852–12858
23. Turner A, Holmes LA (2015) Adsorption of trace metals by microplastic pellets in fresh water. Environ Chem 12:600–610

24. Holmes LA, Turner A, Thompson RC (2014) Interactions between trace metals and plastic production pellets under estuarine conditions. Mar Chem 167:25–32
25. Lu YF, Zhang Y, Deng YF, Jiang W, Zhao YP, Geng JJ, Ding LL, Ren HQ (2016) Uptake and accumulation of polystyrene microplastics in zebrafish (*Danio rerio*) and toxic effects in liver. Environ Sci Technol 50:4054–4060
26. Von Moos N, Burkhardt-Holm P, Köhler A (2012) Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. Environ Sci Technol 46:11327–11335
27. Watts AJ, Lewis C, Goodhead RM (2014) Uptake and retention of microplastics by the shore *crab Carcinusmaenas*. Environ Sci Technol 48:8823–8830
28. Talvitie J, Heinonen M, Pääkkönen JP (2015) Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal gulf of Finland, Baltic Sea. Water Sci Technol 72:1495–1504
29. Song Y, Cao CJ, Qiu R, Hu JN, Liu MT, Lu SB, Shi HH, Raley-Susman KM, He DF (2019) Uptake and adverse effects of polyethylene terephthalate microplastics fibers on terrestrial snails (*Achatina fulica*) after soil exposure. Environ Pollut 250:447–455
30. Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: a review. Environ Pollut 178:483–492
31. Von Moos N, Burkhardt-Holm P, Kohler A (2012) Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. Environ Sci Technol 46:11327–11335
32. Rillig MC (2012) Microplastic in terrestrial ecosystems and the soil? Environ Sci Technol 46:6453–6454
33. Farrell P, Nelson K (2013) Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ Pollut 177:1–3
34. Browne MA, Dissanayake A, Galloway TS, Lowe DM, Thompson RC (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). Environ Sci Technol 42:5026–5031
35. Lwanga HE, Gertsen H, Gooren H, Peters P, Salanki T, van der Ploeg M, Besseling E, Koelmans AA, Geissen V (2017) Incorporation of microplastics from litter into burrows of *Lumbricus terrestris*. Environ Pollut 220:523–531
36. Bing H, Wu Y, Nahm WH, Liu E (2013) Accumulation of heavy metals in the lacustrine sediment of Longgan Lake, middle reaches of Yangtze River, China. Environ Earth Sci 69:2679–2689
37. Brady JP, Ayoko GA, Martens WN, Goonetilleke A (2014) Enrichment, distribution and sources of heavy metals in the sediments of Deception Bay, Queensland, Australia. Mar Pollut Bull 81:248–255
38. Sleight VA, Bakir A, Thompson RC, Henry TB (2017) Assessment of microplastic-sorbed contaminant bioavailability through analysis of biomarker gene expression in larval zebrafish. Mar Pollut Bull 116:291–297
39. Brennecke D, Duarte B, Paiva F, Caçador I, Canning-Clode J (2016) Microplastics as vector for heavy metal contamination from the marine environment. Estuar Coast Shelf Sci 178:189–195
40. Barboza LGA, Vieira LR, Branco V, Figueiredo N, Carvalho F, Carvalho C, Guilhermino L (2018) Microplastics cause neurotoxicity, oxidative damage and energy-related changes and interact with the bioaccumulation of mercury in the European seabass, Dicentrarchus labrax (Linnaeus, 1758). Aquat Toxicol 195:49–57
41. Khan FR, Syberg K, Shashoua Y, Bury NR (2015) Influence of polyethylene microplastic beads on the uptake and localization of silver in zebrafish (*Danio rerio*). Environ Pollut 206:73–79
42. Lu K, Qiao RX, An H, Zhang Y (2018) Influence of microplastics on the accumulation and chronic toxic effects of cadmium in zebrafish (*Danio rerio*). Chemosphere 202:514–520
43. Wen B, Jin SR, Chen ZZ, Gao JZ, Liu YN, Liu JH, Feng XS (2018) Single and combined effects of microplastics and cadmium on the cadmium accumulation, antioxidant defence and innate immunity of the discus fish (*Symphysodon aequifasciatus*). Environ Pollut 243:462–471

44. Wang HT, Ding J, Xiong C, Zhu D, Li G, Jia XY, Zhu YG, Xue XM (2019) Exposure to microplastics lowers arsenic accumulation and alters gut bacterial communities of earthworm *Metaphire californica*. Environ Pollut 251:110–116
45. Yang D, Shi H, Li L, Li J, Jabeen K, Kolandhasamy P (2015) Microplastic pollution in table salts from China. Environ Sci Technol 49:13622–13627
46. Watts AJR, Lewis C, Goodhead RM, Beckett SJ, Moger J, Tyler CR, Galloway TS (2014) Uptake and retention of microplastics by the shore crab *Carcinus maenas*. Environ Sci Technol 48:8823–8830
47. Maaß S, Daphi D, Lehmann A, Rillig MC (2017) Transport of microplastics by two collembolan species. Environ Pollut 225:456–459
48. Rillig MC, Ziersch L, Hempel S (2017) Microplastic transport in soil by earthworms. Sci Rep 7:1362–1368
49. Van Cauwenberghe L, Janssen CR (2014) Microplastics in bivalves cultured for human consumption. Environ Pollut 193:65–70
50. Kiyama Y, Miyahara K, Ohshima Y (2012) Active uptake of artificial particles in the nematode *Caenorhabditis elegans*. J Exp Biol 215:1178–1183
51. Taylor ML, Gwinnett C, Robinson LF, Woodall LC (2016) Plastic microfibre ingestion by deep-sea organisms. Sci Rep 6:33997
52. Jiang XF, Chang YQ, Zhang T, Qiao Y, Klobučar G, Li M (2020) Toxicological effects of polystyrene microplastics on earthworm (*Eisenia fetida*). Environ Pollut 259:113896
53. Prendergast-Miller MT, Katsiamides A, Abbass M, Sturzenbaum SR, Thorpe KL, Hodson ME (2019) Polyester-derived microfibre impacts on the soil-dwelling earthworm *Lumbricus terrestris*. Environ Pollut 251:453–459
54. Antisari LV, Laudicina VA, Gatti A, Carbone S, Badalucco L, Vianello G (2014) Soil microbial biomass carbon and fatty acid composition of earthworm *Lumbricus rubellus* after exposure to engineered nanoparticles. Biol Fertil Soils 51:261–269
55. García JJ, Martínez-Ballarín E, Millan-Plano S, Allue JL, Albendea C, Fuentes L, Escanero JF (2005) Effects of trace elements on membrane fluidity. J Trace Elem Med Biol 19:19–22
56. Carbery M, O’Connor W, Thavamani P (2018) Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ Int 115:400–409
57. Fahrenfeld NL, Arbuckle-Keil G, Beni NN, Shannon L, Bartelt-Hunt L (2019) Source tracking microplastics in the freshwater environment. TrAC Trends Anal Chem 112:248–254