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Microplastic as a vector of heavy metals and chemicals in aquatic ecosystems

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ABSTRACT
Microplastics (MPs) have become a symbol of modern life and their fate in the environment is an issue of great concern. MPs have attracted attention for their widespread distribution, especially in the aquatic ecosystems. MPs can act as a vector of various heavy metals in the environment and pose a threat to marine and freshwater organisms as well as human health. The MP surfaces play a defining role in the adsorption of heavy metal. Aged or biofouled MPs further induce the adsorption of metals. Particular microplastic (MPs) polymers have a higher tendency for adsorption of some metals specifically. Evidence shows that MPs are vectors for persistent organic pollutants (POPs), pharmaceuticals, and especially heavy metals. MP surfaces can retain chemical contaminants over six-fold higher than the surrounding environment. Since plastic materials offer different surface characteristics, therefore chemical composition, functional groups, crystallinity, and carbon chains vary significantly. The differences between plastic materials determine how they interact and become vectors for chemicals in aquatic systems. MPs could be enriched with heavy metals such as cadmium (Cd), chromium (Cr), copper (Cu), Pb, Mn, etc. The biofilms developed on the MP surface can enhance the adsorption capacities of heavy metals. It is urgent to understand the pattern of interactions of MPs with heavy metals in various aquatic systems. This allows us to understand the severity of ecotoxic effects which in turn helps regulate these pollutants. The adsorption of heavy metals on MPs increases their bioaccumulation. In this paper, we summarize the occurrence of MPs in a given aquatic ecosystem and patterns of interaction with heavy metals.

Keywords: Persistent organic pollutants POPs, Bioaccumulation, Trace metals, Aquatic ecosystem, MPs pollution.
Article type: Review Article.

INTRODUCTION
Since 1950, plastic production has increased rapidly around the world. The worldwide supply of plastic has been reported to be 8.3 billion tons (1 billion tons of synthetic fibers and 7.3 billion tons of non-fiber) by 2015 (Geyer *et al.* 2017). About 353 million tons of plastic waste was generated in 2019, of which 6.1 million tons were discharged into aquatic ecosystems such as rivers and oceans (1.7 million tons into the oceans) and 22 million tons into the environment. Plastic debris is classified based on its size into macro-plastics (retain their original shape), mesoplastics (fragments larger than 5 mm), and microplastics (MPs) which are smaller than 5 mm in size. Plastic debris is not biodegradable, but exposure to ultraviolet light, oxidation, or physical forces by wind and wave actions degrade plastics into micro- and mesoplastics (Andrady 2011; Cole *et al.* 2011). Owing to their robustness, plastics stay in the environment for extended periods (Bergmann *et al.* 2017; Brahney *et al.* 2021). It has been estimated that some > 24.4 trillion MPs floating currently in the world's ocean surface waters (Isobe *et al.* 2021). The discovery of plastics and their corresponding industrial development have simplified human lives enormously but have also damaged the environment in return. Every piece of plastic product produced since the 1950s still exists in the earth's environment today since plastics last for 400 to 1000 years (Fowler 1987). Many of them have come into the ocean through different pathways (Carpenter & Smith 1972). The situation has received intensive attention lately.

Microplastics (MPs)

Microplastic particles of 0.3-5 mm in diameter have a great influence on the ecosystem we are living in, because of their similarity to zooplankton or young fish. Animals from zooplankton to giant blue whales in the ocean eat plastic fragments as baits, which will pass through the food chain to human dining tables. The ratio between the floating MPs and zooplankton mass has been reported as high as 6:1 in the North Pacific, and can be up to 30:1 in some areas of the ocean (Moore *et al.* 2001). However, the studies of MPs in the oceans are based on very scarce data and are at the inventory level (Isobe *et al.* 2019). Very few processes of the MP distributions and concentrations are known at present. Plastic debris has received global recognition as an emerging environmental threat exacerbated by widespread production and inappropriate disposal (Andrady 2011). MPs have further concern worldwide owing to their omnipresent occurrence in terrestrial and aquatic environments and threats to organisms and humans. Plastics are extensively used in industrial and commercial products and municipal applications due to their robustness and affordability (Vaisakh *et al.* 2023). Since the mid-1950s the plastic industry has witnessed massive growth in production reaching 359 million tons in 2018 (Liu 2023) and is expected to surpass 33 billion tons by 2050 (Rochman *et al.* 2013a). The darker side is that over 8 million tons of plastic debris and litter are discharged into the freshwater and marine systems annually (Erni-Cassola *et al.* 2019). In comparison with common plastic wastes, the core characteristic of MPs is their somewhat small size, precisely defined as plastic fragments and particles with diameters less than 5 mm (Thompson *et al.* 2004). Two common forms of MPs have been defined as primary and secondary microplastics. Primary MPs are produced for several purposes, such as microbeads in cosmetics facial cleansers, or resins (Bayo *et al*. 2017; So *et al.* 2018). Secondary MPs vastly are produced from the decomposition of larger pieces of plastic wastes in certain processes such as biodegradation, weathering and aging (Gouin *et al.* 2011). Given their inactive nature, MPs might be accumulated in the environment (Wang *et al.* 2021a). Short- and long-term exposures to MPs result in adverse health issues with feeding behaviors and efficiency, reproduction accomplishment, antioxidant defense, and innate immunity disorders (Murphy & Quinn 2018; Wen *et al*. 2018a; Oliviero *et al.* 2019; Darabi *et al.* 2022).

Heavy metals

Another substantial threat to the environment and living resources is rooted in trace elements and heavy metals. By definition, heavy metals are elements with densities larger than 5 g cm^{-3} and high atomic mass (Alengebawy *et al.* 2021). Since these metals are not degradable, they are highly hazardous even in very low concentration (Zaynab *et al.* 2022). Bioaccumulation and biomagnification of heavy metals cause serious health risks to living things in the environment (Qin *et al.* 2021). Anthropogenic activities and products like mining, metal ores extraction, wastewater disposal from industries, and application of fertilizers and pesticides are among the most important sources of heavy metal pollution or contamination in the environment (Vaisakh *et al.* 2023). Like MPs, heavy metals are also widespread in nearly all sorts of habitats and environments and may incessantly enter aquatic ecosystems due to their non-degradable nature. These metals could be accumulated, magnified, and recycled in aquatic environments. MPs and heavy metals are known as persistent pollutants, though, their combined pollution poses a new and multidimensional hazard to a universal or global extent. MP maintains a somewhat great surface area, consequently traps and accumulates further toxic pollutants, and concentrates these toxic agents to very high levels. Heavy metals have been confirmed attached to MPs from the North Atlantic (Prunier *et al.* 2019), Brazil (Vedolin *et al.* 2018), southwest coasts of England (Massos & Turner 2017), and several other ecosystems in western Europe (Turner *et al.* 2019). Aquatic ecosystems hold a diverse array of decomposing microorganisms, with critical roles in several fundamental biogeochemical processes within the system which upsurges the complex nature of interactions between MPs and heavy metals. MPs develop microbial biofilm on their surface known as plastisphere that provides a plethora of small-scale ecological niches for the settlement of bacteria, fungi, protozoa, etc. (Mincer *et al.* 2016; Yang *et al.* 2020). This minute plastisphere creates space for colonization, settlement, and further growth of various types of microbial biofilms from immature to mature communities. These microplastic-associated biofilms alter the physical and chemical features of MPs and further affects the adsorption of various pollutants primarily heavy metals (Tu *et al.* 2020). Exposure to heavy metals influences biofilm formation and causes structural changes mostly on the polysaccharide matrix of biofilm, which additionally affects the adsorption and accumulation of heavy metals (de Araújo & de Oliveira 2020). Although the role played by biofilms has become a focus in the MP studies, their impact on the destiny of MPs and heavy metals remains less well known. In general, a lot of studies have tried to analyze the color, type, shape, size, and load of MPs to elucidate the source and fate of MPs in the environment. Meanwhile, various types of heavy metals have been recorded on the surface of MPs, which confirms MPs as vectors and carriers of heavy metals. A Large array of microbes live in aquatic systems that are possibly as a crucial biotic component in aquatic systems. Microbes may also play a key role in controlling the interaction between heavy metals and MPs. To date, comprehensive review papers on the interactions between these two components of the aquatic systems are not sufficient given the immensity of their roles in the system.

Sources and stability of heavy metals in MPs

Different hypotheses have been suggested to describe the sources of heavy metals that occur on immensity in the environment of which two make more sense. The first is that heavy metals and their different compounds are incorporated into plastics during their synthesis to improve the flexibility, performance, and longevity of the products both pristine and secondary products following modification of disposed waste plastics (Mao *et al.* 2020). These plastic fillers generally act as reinforcement and modify the properties of the product, followed by facilitating the processing activities (Shrivastava 2018). In addition, heavy metals and compounds have long been used in these processes (Turner 2016).

Table 1. Some important functions of plastic additives.

Types	Specific functions	Heavy metal species	Main purpose
Fillers and reinforcement	Mineral fillers	Barium sulfate ($BaSO_4$)	Thermoplastics: fiber composite, platelet composite Metallic fillers
	Metallic fillers	Al, Ni, Cu, Ag, metallized glass, metallic fillers	Electrical and electronic applications, communication, and computer devices
Property modifiers	Colorants	TiO_2, ZnS, Fe_3O_4, CrO_4^{2-}, Cd, Cr_2O_3, mixed metal oxides	Variety of colored plastic products
	biocides and antimicrobial agents	Ag-ion-based inorganic compounds	Medical devices, toys, sports equipment, appliances, food processing machinery, kitchen utensils, bathroom products, garbage bins, and electronic devices
	Antioxidants and light stabilizers	TiO_2 and zinc oxide (ZnO)	Various resins, UV absorbers

As shown in Table 1, heavy metals, such as cadmium (Cd) and zinc (Zn), are commonly used in plastic products at the rate of up to 1% and 10% respectively (Town *et al*. 2018). The second hypothesis suggests that MPs may absorb heavy metals directly from their immediate vicinity in the environment (Ashton *et al*. 2010; Holmes *et al*. 2012; Holmes *et al.* 2014; Turner & Holmes 2015; Brennecke *et al.* 2016; Nizzetto *et al*. 2016; Hodson *et al*. 2017). The mean concentration of these heavy metals settled on MPs should vary spatially and temporally (Guo & Wang 2019). In general, those heavy metals or metallic compounds added to plastics during the production process are in the liquid phase, therefore are more stable and show with lower tendency to migrate. However, when they go through degradation by physical abrasion, chemical oxidation, or biological processes they break apart into tiny fragments or pieces (Song *et al.* 2017; Hurley *et al.* 2018) then there is a high potential for metals to migrate toward the surface layers of MPs (Browne *et al.* 2013) and leak into the environment with subsequent impacts on the ecosystem well-being. Waste plastic recycling especially electronic waste plastics carries the risk of overloading heavy metals into the environment. Studies have proved that MPs possess high affinity in the environment to heavy metals in their aqueous phase (Rios *et al*. 2007; Ashton *et al.* 2010; Brennecke *et al*. 2016) and absorb heavy metals rapidly from their immediate vicinity (Brennecke *et al.* 2016). In a study, the concentrations of heavy metals on beached pellets were low, but in relatively similar magnitude as the extraneous solid materials (Ashton *et al.* 2010). In another study, the concentrations of heavy metals on beached pellets were higher than on the adjacent estuarine sediment (Holmes *et al*. 2012). Brennecke *et al.* (2016) reported that the concentrations of Cu and Zn adsorbed by the Polyvinyl chloride (PVC) fragments and Polystyrene (PS) beads were 32–163 times higher than their on seawater concentrations (Brennecke *et al*. 2016). Another study has shown that there is a close correlation between the concentrations of some heavy metals including Cd, Pb, Mn, and Hg on the MPs and levels of heavy metal in the same soil environment (Zhou *et al*. 2019a). It is critical to add that heavy metals are easily desorbed from MPs (Wang *et al*. 2019a) which postures a significant threat to organisms consuming MPs accidentally or deliberately instead of their favorite food items.

Interaction between MP and heavy metals

Direct interaction

The direct interaction between MPs and heavy metals normally occurs in liquid medium. These interactions include 3 pathways shown in Fig. 1.

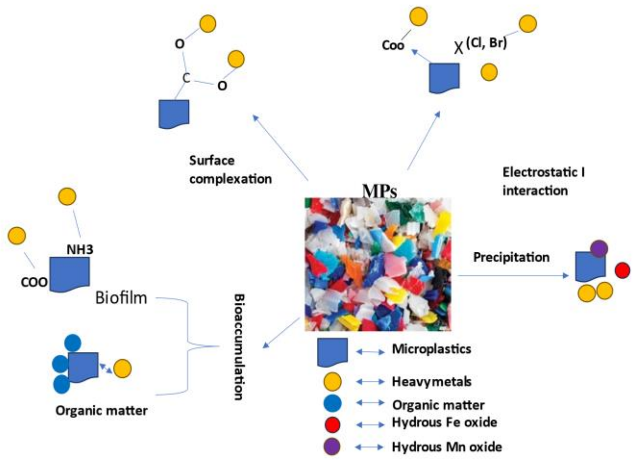

Fig. 1. Schematic pathways of 3 main interactions between different MPs and heavy metals.

These pathways include electrostatic interaction and surface complexation which are one of the most important adsorption mechanisms of heavy metal ions by MPs (Liao & Yang 2019). At First, heavy metals interact with the polar surface of the MPs (Zhang *et al.* 2019a). The polarity of the MP surface probably is a result of its physical and chemical characteristics (for instance chlorine is present in PVC and CPE), or the presence of charged additives and polluting agents such as hexabromocyclododecane (HBCD) which is a brominated flame retardant (Holmes *et al*. 2012; Lin *et al.* 2020a). Furthermore, weathering, e.g. photo-oxidative degradation produces C_C, C\\O, and -OH adsorption bands (Bandow *et al*. 2017) which further boosts the polarity of the involved polymer and induces charged surface (Mato *et al.* 2001). Secondly, MPs form new complexes through sorption and/or bioaccumulation with natural organic matter (NOM) and biofilms (Artham *et al.* 2009; Rochman *et al*. 2014b; Yu *et al*. 2020; Ateia *et al*. 2020) which in turn results in changed surface area (Edwards & Kjellerup 2013). In a study by Rochman *et al*. (2014b) all types of plastics placed in seawater accumulated almost similar concentrations of metals, exhibiting that aggregation or accumulation of heavy metals to a given plastic particle might be mediated by developed biofilms and the functional groups settled on the biofilms creating -COOH, and -NH2 bands, hence enhancing the adsorption (Hong & Brown 2008; Guan *et al*. 2020; Qi *et al.* 2021). Finally, interactions involving precipitation/coprecipitation play a role in the interaction of heavy metals and MPs. Heavy metal ions or complexes precipitate simultaneously with Fe and Mn hydrous oxides (Ashton *et al.* 2010). MPs due to their large surface area, degradation level, or aging and functional groups they host, can simply act as carriers of several heavy metals and transport them to different environmental setups (Holmes *et al*. 2014; (Zhou *et al*. 2019a). The adsorption progression is primarily affected by the types and properties of the plastics involved, the chemical features of heavy metals coupled with key environmental parameters such as pH, salinity, O_2, NOM, and background pollutant concentration (Fig. 2).

Influence of MP characteristics

The common MPs involved in the adsorption of heavy metals are PP, PE, PS and PVC. The extent of influence is a function of polymer type and largely the specific surface area and settled functional groups on the biofilms. For instance, Guo *et al*. (2019) examined 4 types of MPs and their adsorption capacity for Cd. The adsorption order was: PE < PP < PS < PVC, which unsurprisingly was consistent with their surface area (0.173 < 0.348 < 0.508 < 0.836 $mm^3\ g^{-1}$), implying the presence of a strong correlation among the adsorption capacity of MPs and their corresponding surface areas. Nevertheless, results from Lin *et al.* (2021) showed a different adsorption order: PS (128.5 μg g^{-1}) < PE (416.7 μg g^{-1}) < PVC (483.1 μg g^{-1}). In another study, Brennecke *et al*. (2016) compared the accumulation of Cu on the PVC and PS particles and reported that the accumulation of Cu in PVC particles was much higher than in PS particles apparently due to the higher surface area and also polarity of PVC-containing chlorine. Gao *et al.* (2019) reported some similar results. Thus, PVC adsorbed higher concentrations of Pb^{2+}, Cu^{2+}, and Cd^{2+} heavy metals, compared to PA, PE, and POM. Likewise, plastic additives also have been reported to change the adsorption of MPs (Hüffer *et al.* 2018; Ateia *et al.* 2020).

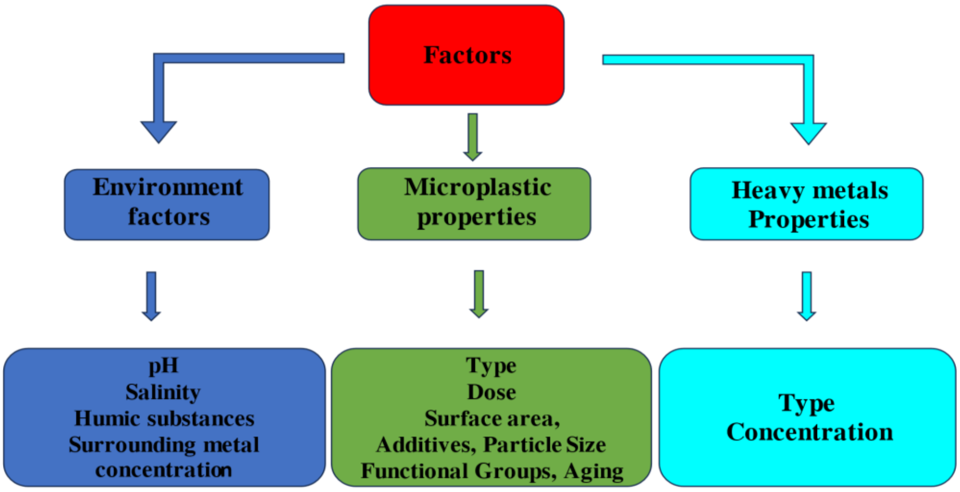

Fig. 2. Factors influencing the adsorption of heavy metals by MPs types are PP, PE, PS, PVC, PA and POM.

Influence of heavy metal chemical properties

The atomic number plus surface valence and the type of heavy metals affect their adsorption. It is known that certain synergistic or competitive effects play a role among metals. In a study on Pb, Cu, and Cd-coexisting solutions (0.05 mg L^{-1}), the adsorption single metallic solution was higher than that of mixed ones (Gao *et al.* 2019), implying a competitive adsorption. In a study, it was reported that the affinity of PA to Pb was stronger in the solution with the Cu and Pb coexisting than in a single solution. Fu *et al.* (2019a) reported that the coexistence of Zn^{2+} improved the adsorption of Cu^{2+} on PS. Several studies have reached similar conclusions. In a study, plastic pellets adsorbed Ag, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn in the range of 0.0004-2.78 μg g^{-1} at 20 μg L^{-1} (Holmes *et al.* 2012, 2014; Turner & Holmes 2015). However, when the concentration of Zn increased to 102-105 μg L^{-1}, the adsorption capacity reached 236-7171 μg g^{-1} (Hodson *et al.* 2017; Guo & Wang 2019a).

Combined effects of MPs and heavy metals on organisms and humans

As noted above, heavy metals and contaminants in general show certain levels of synergistic or competitive effects in their interaction which alter their toxicity to the biota. MPs combined with metallic contaminants can alter the toxicity of both to the target organism, regardless of the type of aquatic ecosystem (Bhagat *et al*. 2020), which is extremely important in comprehending the behavior of plastic particles in the environment (Sendra *et al.* 2021) (Fig. 3). It is known that both MPs and heavy metals can be toxic on organisms, however, their combined effects are tri-dimensional. These three categories of effects are synergistic, antagonistic, and potentiating (Bhagat *et al*. 2020). By definition, the synergistic effect is that the combined effect of two toxicants or chemicals is far greater than the effects exerted by each chemical individually (Bhagat *et al*. 2020).

In the case of antagonistic effect, studies have shown that MPs act as carriers of heavy metals, therefore, they decrease the heavy metal concentrations in the medium through adsorption. As a result, they also reduce the biological toxicity of heavy metals in the environment (Bhagat *et al.* 2020). Finally, the potentiating effect is observed or occurs when a nontoxic chemical substance (not known to be toxic) is added to another one, and change it to get much more toxic than it used to be (Bhagat *et al*. 2020). Undoubtedly, the first two effects are very common criteria in aquatic environments.

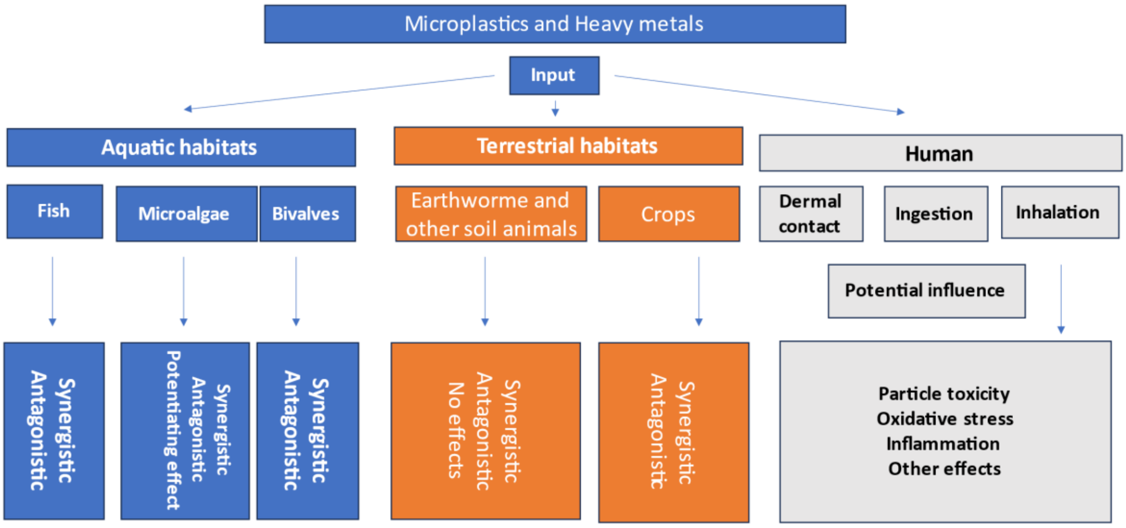

Fig. 3. Combined effects of MPs and heavy metals on organisms and humans. Synergistic or antagonistic effects are observed when organisms are co-exposed to certain MPs and heavy metals, hence, the combined toxicities of MPs and heavy metals on organisms might be chemical-specific and species-specific (Huang *et al*. 2020).

Effects on organism

A plethora of studies have shown that aquatic and terrestrial organisms can easily uptake MPs which potentially affects their physiology, reproduction success, mortality, and survival (Lwanga *et al*. 2016; Hodson *et al*. 2017; Imhof *et al.* 2017; Prendergast-Miller *et al*. 2019). In the meantime, being carriers, MPs readily transport the adsorbed heavy metals into the organisms where the adsorbed contaminants could be desorbed within the digestive systems (Hodson *et al*. 2017; Zhou *et al*. 2020c). Besides, the interaction between MPs and heavy metals may alter the surface properties of plastics. This in turn alters the uptake capacity and accumulation of plastics and/or heavy metals or other contaminants in the organisms (Barboza *et al.* 2018a; Bhagat *et al*. 2020; Zhou *et al.* 2020a). Even though the occurrence of heavy metals on the surface of MPs is a very well-known fact, however, few studies have addressed the issue of joint toxicity of MPs together with heavy metals on organisms (Abbasi *et al*. 2020; Bhagat *et al*. 2020).

Effects on the aquatic environment

In general, the mean size of MPs in an aquatic system ranges between 10–20 μm which almost perfectly matches the size of a large array of plankton (Strom *et al*. 2019; Zhang *et al*. 2020b). Consequently, MPs could be easily ingested by numerous aquatic organisms such as mussels, bivalves, and zooplankton, and further flow through the food chain towards higher levels in the hierarchy of organisms in the aquatic system, enter into organisms like fish, birds, mammals, and finally human (Santillo *et al.* 2017; Karami *et al*. 2018; Zhang *et al*. 2020b). Phytoplankton, invertebrates, and some fish have been subjected to studies on the joint effects of heavy metals and MP particles. Among plastics, PS and PE have been more frequently used in such investigations (Huang *et al*. 2021). There are three types of control in an ecosystem. The control from below to the top is known as the bottom-up one. The opposite is control from the top to the lower levels in the food chain known as the top-down one, while the third type is control exerted from the intermediate trophic level known as the wasp-waist one. Microalgae are the primary producers and though rest at the base of an aquatic food web, hence they are fundamental in a range of ecosystem functions (Harris 1986; Nava & Leoni 2021). The tiniest disturbances on microalgae populations have devastating impacts on food webs (Nava & Leoni 2021). Several studies have reported that MPs alone hinder microalgal growth, photosynthesis, and their chlorophyll contents (Zhang *et al*. 2017; Prata *et al*. 2019b; Tunali *et al*. 2020). The combined toxicity will produce a much worse outcome. There are always exceptions in nature. So, in a study, the toxicity of heavy metals on *Tetraselmis chuii* was not altered at the presence or absence of MPs (while on another occasion, the co-existence of MPs and heavy metals have benefited the algae in one way or another). It has been reported that polyacrylonitrile polymer (PAN) to some extent alleviates the toxicity of Cu^{2+} to *Chlorella pyrenoidos* (Lin *et al*. 2020b) and a combination of aged PVC (10 mg L^{-1}) and Cu (0.5 mg L^{-1}) boosted the growth performance and reproduction of *Chlorella vulgaris* (Fu *et* *al*. 2019b). The combination of metals and small-sized PS (0.5 μm) significantly inhibited the growth and chlorophyll-a concentration of microalgae than the PS alone (Tunali *et al.* 2020). MP 2–4 μm in size combined with Cd was more toxic to *Moina monogolica* than the Cd-free MP (Wang *et al.* 2020d). Filter-feeder organisms in general and invertebrates in particular are highly susceptible groups of organisms in aquatic systems to MPs ingestion (Fernández *et al*. 2020) and bivalves as an important commercial aquatic species are consumed by humans, although levels of pollutants accumulated in their tissue seem to be much higher than in other organisms and are in correlation with pollutant availability in their surrounding environment. Therefore, bivalves are bioindicator organisms and are used for biomonitoring of their environment (Briant *et al*. 2016). One of the most toxic metals in the environment is mercury (Hg), especially in the form of methylmercury. It has the potential to accumulate and be biomagnified in marine food chains with extremely high toxic effects (Bjørklund *et al*. 2017; Skdokur *et al*. 2020). MPs have shown synergistic and antagonistic effects on the mercury absorption by bivalves. It was reported that high-density polyethylene MPs facilitate the adsorption of Hg by the mussel, *Mytilus galloprovincialis* (Fernández *et al*. 2020). On the other hand, contaminated polyethylene MPs weakly influenced mercury bioaccumulation in *Ruditapes philippinarum* clams (Skdokur *et al.* 2020). As aforementioned, antagonistic interaction was also been observed between mercury and MPs. The co-exposure of MPs induced Hg elimination and reduced postexposure filtration rate, in addition to cholinesterase and S-transferase enzymes, along with the lipid peroxidation levels as biomarkers in *Corbicula fluminea* and its mercury uptake (Oliveira *et al*. 2018; Fernández *et al*. 2020; Skdokur *et al*. 2020). The zebrafish, *Danio rerio* is a typical model organism for toxicity studies in vertebrates specially in early developmental stages, since 87% of its genes are similar to human gene (Mak *et al*. 2019; Qiu *et al.* 2019). In the case of zebrafish, the presence of polystyrene MPs elevated the toxicity caused by Cd and Cu. Combined exposure resulted in oxidative damage and inflammation in *Danio rerio* tissues (Lu *et al.* 2018; Qiao *et al.* 2019b) since the *D. rerio* embryos are more sensitive to pollutants than their adults. The prevalence of Cd in aquatic environments as well as the combined toxicity of MPs and Cd have attracted more attention from researchers. Zhang *et al*. (2020b) and Cheng *et al*. (2021) concluded (although inconsistent with each other) that the synergistic or antagonistic toxicities caused by MPs might be associated with the concentrations and forms (fibers or granular MPs) of the corresponding microplastic. The inconsistency in their conclusion might have been due to differences in size and types of MPs (i.e., PET and PS) used for the experiment (Zhang *et al.* 2020b; Cheng *et al*. 2021, Cao *et al.* 2021). Several other studies have shown that the instantaneous exposure to MPs and Hg may alter behavioral responses and swimming velocity in European seabass, *Dicentrarchus labrax* (Barboza *et al*. 2018b), and influence the Hg bioconcentration in its gills and bioaccumulation in the liver (Barboza *et al*. 2018a). A combination of PS microplastics and Cd, Pb, and Zn did not fortify the risk to the gonad development of medaka, *Oryzias melastigma* (Yan *et al.* 2020). To date, studies on higher organisms such as fish in their aquatic environment are limited, although due to edibility, they are in close vicinity with humans and may be an outstanding model organism for such studies to explore combined toxicity and fate of toxicants during their food chain transfer.

Effects on human health

Human exposure to MPs under high concentration or excessive individual vulnerability might induce inflammation, particle toxicity, and oxidative stress. Their persistent nature delays their removal from the organisms and the result is chronic inflammation and risk of neoplasia in biological systems (Prata *et al*. 2019a). Nowadays MPs are present in almost all resources used by humans such as air, water, food, beverages, plastic bags, and materials which increases the possibility of contamination (Digka *et al*. 2018; Rist *et al.* 2018; Chen *et al*. 2019; Koelmans *et al*. 2019; Mortensen *et al*. 2021). The annual MP uptake or consumption is estimated about 74,000–121,000 particles via food and inhalation (Cox *et al*. 2019). Accumulation of MPs may exert localized toxicity through induced or enhanced immune response (Wright & Kelly 2017). Numerous studies have confirmed particle toxicity of plastics in the size range of microns with adverse effects on human health (Rist *et al.* 2018; Cheng *et al.* 2021). The heavy metals adsorbed on or in MPs might be transported into the human body through ingestion, inhalation, and direct contact (Liao & Yang 2019; Prata *et al*. 2019a; Rahman *et al.* 2021). Bulk of studies have related the MPs toxicity primarily to exposure concentration, particle properties, dose of adsorbed contaminants, target organs, and individual vulnerability (Rahman *et al.* 2021). Therefore, understanding the critical dosage entered the systemic circulation and its bioavailability and bio-accessibility, hence possible adverse effects should be carefully assessed (Semple *et al.* 2004; Rahman *et al*. 2021). To estimate the combined effects of MPs and heavy metals, measurements of cumulative exposure dosage of both pollutants should be determined (Rahman *et al*. 2021). However, the current knowledge on combined toxicity of MPs and heavy metals to humans is still inadequate, and further studies should explore the dose-dependent toxicity of MPs and heavy metals combined on human health.

Concluding remarks and future outlook

Evidence has shown the ubiquitous presence of MPs and heavy metals in aquatic environments almost all over the world. This paper reviewed some aspects of the interactions between MPs and heavy metals. Certain parts were elaborated on further in detail. The MP and heavy metal issue requires special attention from decision-makers. Unless countries define and place effective measures on plastic waste management. A steady upsurge in the amount of plastic waste will be apparent by an increase in human activities. The bottleneck is that MPs and heavy metals are both persistent pollutants, so their degradation and complete removal from the environment is very slow or rather impossible and their cumulative threats to humans should and could not be neglected or be overlooked any longer. In this review paper, various potential and actual interaction mechanisms and causative factors between MPs and heavy metals were elaborated. We noticed that exposure to MPs and heavy metals in combination may induce synergistic, antagonistic, and potentiating impacts on organisms. Since evaluation of genuine hazards from exposure to a combination of MPs and heavy metals to humans is not extremely tough, consequently their actual effects on humans are yet to be unraveled. Considering the body of existing literature few suggestions are made for future studies:

(1) Large number of literature and evidence show that MPs adsorb heavy metals but the mechanisms involved in this process in different environmental setups are not fully recognized (Zou *et al.* 2020). Large amounts of the existing evidence have been derived from short-term studies, thus long-term effects are not known, and further studies are inevitable (Wang *et al.* 2020b).

(2) The interaction between heavy metals and MPs in the aquatic phase has been studied in some detail however most of these studies have utilized pure or virgin polymers (Alimi *et al*. 2018), while in real-world MPs contain plenty of other components such as pigments, filler plasticizers, stabilizers, solvents and many more additives with potential to interfere in adsorption processes (Ateia *et al*. 2020; Lin *et al*. 2020a). Studies on the effects of synthetic polymers alone and incorporated additives and environmentally absorbed chemicals on the same polymer are necessary. Thus, future studies should take into account the interaction between aged and real MPs, and heavy metals, in addition to the ecotoxicological effects expected from inherent/absorbed heavy metals to aquatic biota.

(3) Most of the previous studies have examined the effects of a single MP and heavy metal on certain organisms. The properties (specific sizes, shapes, or types) of MPs that enhances or mitigate the effects of heavy metals on model organisms are yet to be understood (Huang *et al.* 2021). Therefore, further investigation is required on conditions and the underlying mechanism responsible for the antagonistic or synergistic effects of these two contaminants.

(4) The impacts of exposure to both MPs and heavy metals on ecological diversity is well unknown. MPs transport heavy metals through the food chain which amplifies the toxicity of these metals with adverse effects on organisms. MPs may transfer to progenies during reproduction. Exposure to MPs and heavy metals combined will have significant impacts on populations, communities, and the whole ecosystem (Chae & An 2018). Therefore, the impacts of exposure to MPs and heavy metals on the food chain should be determined.

REFERENCES

Abbasi, S, Moore, F, Keshavarzi, B, Hopke, PK, Karimi, J 2020, PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. *Science of the Total Environment*, 744: 140984.

Alengebawy, A, Abdelkhalek, S, Sundas, R, Qureshi & Wang, MQ 2021, Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications, *Toxics*, 9: 42. https://doi.org/10.3390/toxics9030042.

Alimi, OS, Budarz, JF, Hernandez, LL & Tufenkji, N 2018, Microplastics and nano plastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. *Environmental Science & Technology*, 52: 1704-1724.

Artham, T, Sudhakar, M, Venkatesan, R, Nair, CM, Murty, KVGK, Doble, M 2009. Biofouling and stability of synthetic polymers in seawater. *International Biodeterioration and Biodegradation*, 63: 884-890.

Ashton, K, Holmes, L & Turner, A 2010, Association of metals with plastic production pellets in the marine environment. *Marine Pollution Bulletin,* 60 (11): 2050-2055.

Ateia, M, Zheng, T, Calace, S, Tharayil, N, Attia, MF 2020, Sorption behavior of real microplastics (MPs): insights for organic micropollutants adsorption on a large set of well-characterized MPs. *Science of The Total Environment,* 720: 137634.

Bandow, N, Will, V, Wachtendorf, V & Simon, FG 2017, Contaminant release from aged microplastic. *Environmental Chemistry*, 14 (6): 394-405.

Barboza, LGA, Vieira, LR, Guilhermino, L 2018b, Single and combined effects of microplastics and mercury on juveniles of the European seabass (*Dicentrarchus labrax*): Changes in behavioral responses and reduction of swimming velocity and resistance time. *Environmental Pollution*, 236: 1014-1019.

Bayo, J, Martinez, A, Guillen, M, Olmos, S, Roca, M & Alcolea, A 2017, Microbeads in commercial facial cleansers: Threatening the environment. Clean (Weinh) 45:16006837. DOI: 10.1002/clen.201600683.

Bergmann, M, Tekman, MB & Gutow, L 2017, Sea change for plastic pollution. *Nature,* 544.

Bhagat, J, Nishimura, N, Shimada, Y 2020, Toxicological interactions of microplastics/ nanoplastics and environmental contaminants: current knowledge and future perspectives. *Journal of Hazardous Materials,* 405: 123913.

Brahney, J, Mahowald, N, Prank, M, Cornwell, G, Klimont, Z, Matsui, H, Prather, KA 2021, Constraining the atmospheric limb of the plastic cycle. *Proceedings of the National Academy of Sciences (PNAS) USA*, 118 (16): e2020719118. https://doi.org/10.1073/pnas.2020719118.

Brennecke, D, Duarte, B, Paiva, F, Caçdor, I, Canning-Clode, J 2016, Microplastics as vector for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science*, 178: 189-195.

Briant, N, Chouvelon, T, Martinez, L, Brach-Papa, C, Chiffoleau, JF, Savoye, N, Sonke, J, Konery, J 2016, Spatial and temporal distribution of mercury and methylmercury in bivalves from the French coastline. *Marine Pollution Bulletin*, 114: 1096-1102.

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. *Current Biology*, 23: 2388-2392.

Cao, Yanxiao, Mengjie Zhao, Xianying Ma, Yongwei Song, Shihan Zuo, Honghu Li, Wenzhuo Deng 2021, A critical review on the interactions of microplastics with heavy metals: Mechanism and their combined effect on organisms and humans. *Science of the Total Environment*, 788: 147620

Carpenter, EJ & Smith, KL 1972, Plastics on the Sargasso Sea surface. *Science* 175: 1240-1241.

Chae, Y & An, YJ 2018, Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environmental Pollution*, 240: 387-395.

Cheng, H, Feng, Y, Duan, Z, Duan, X, Wang, L 2021, Toxicities of microplastic fibers and communications concerning human health aspects of microplastics. Sci. Total Environ, 626: 720-726.

Cheng, H, Feng, Y, Duan, Z, Duan, X, Wang, L 2021, Toxicities of microplastic fibers and granules on the development of zebrafish embryos and their combined effects with cadmium. *Chemosphere* 269: 128677. doi: 10.1016/j.chemosphere.2020.128677.

Cole, M, Lindeque, P, Halsband, C, Galloway, TS 2011, Microplastics as contaminants in the marine environment: A review. *Marine Pollution Bulletin*, 62 (12): 2588-2597. https://doi. org/10.1016/j.marpolbul.2011.09.025.

Cox, KD, Covernton, GA, Davies, HL, Dower, JF, Juanes, F, Dudas, SE 2019, Human consumption of microplastics. *Environmental Science & Technology,* 53: 7068-7074.

Darabi, H, Baradaran, A, Ebrahimpour, K 2022, Subacute toxic effects of polyvinyl chloride microplastics (PVC-MPs) in juvenile common carp, *Cyprinus carpio* (Pisces: Cyprinidae). *Caspian Journal of Environmental Sciences,* 20: 233-242.

de Araújo, LCA & de Oliveira, MBM 2020, Effect of heavy metals on the biofilm formed by microorganisms from impacted aquatic environments. In Bacterial Biofilms, S, Dincer, MS, Özdenefe & A, Arkut (eds.) (London: IntechOpen). DOI: 10.5772/intechopen.89545.

Digka, N, Tsangaris, C, Torre, M, Anastasopoulou, A, Zeri, C 2018, Microplastics in mussels and fish from the Northern Ionian Sea. 135:30-40. DOI: 10.1016/j.marpolbul.2018.06.063.

Edwards, SJ, Kjellerup, BV 2013, Applications of biofilms in bioremediation and biotransformation of persistent organic pollutants, pharmaceuticals/personal care products, and heavy metals. *Applied Microbiology and Biotechnology,* 97 (23): 9909-9921.

Fowler, CW 1987, Marine debris and northern fur seals: a case study. *Marine Pollution Bulletin*, 18: 326-335.

Fu, DD, Zhang, QJ, Fan, ZQ, Qi, HY, Wang, ZZ, Peng, LC 2019a, Adsorption characteristics of copper on micron scale polystyrene. *Chinese Journal of Environmental Science*, 039 (011): 4769-4775 (In Chinese).

Gao, F, Li, J, Sun, C, Zhang, L, Jiang, F, Cao, W, Zheng, L 2019, Study on the capability and characteristics of heavy metals enriched on microplastics in marine environment. Marine Pollution Bulletin,144: 61-67.

Geyer, R, Jenna R. Jambeck, Kara Lavender Law 2017, Production, use, and fate of all plastics ever made. *Science Advances,* 3: e1700782

Gouin, T, Roche, N, Lohmann, R & Hodges, G 2011, A thermodynamic approach for assessing the environmental exposure of chemicals absorbed to microplastic. *Environmental Science & Technology*, 45: 1466-1472, DOI: 10.1021/es1032025.

Granules on the development of zebrafish embryos and their combined effects with cadmium. *Chemosphere,* 269: 128677.

Guan, J, Qi, K, Wang, J, Wang, W & Qu, J 2020, Microplastics as an emerging anthropogenic vector of trace metals in freshwater: significance of biofilms and comparison with natural substrates. *Water Resources*, 184: 116205.

Guo, F, Wang, W 2019c, A general kinetic model for adsorption: theoretical analysis and modeling. *Journal of Molecular Liquids*, 288 (15): 111100.

Guo, X, Hu, G, Fa, N, Jia, H 2019, Sorption properties of cadmium on microplastics: the common practice experiment and a two-dimensional correlation spectroscopic study. Ecotoxicol. Environ. Saf, 190: 110118.

Guo, X & Wang, JL 2019a, The chemical behaviors of microplastics in marine environment: A review. *Marine Pollution Bulletin,* 142: 1-14.

Harris, G 1986, Phytoplankton Ecology: Structure, Function and Fluctuation. Springer, Netherlands.

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. *Environmental Science & Technology*, 51 (8): 4714-4721.

Holmes, LA, Turner, A & Thompson, RC 2012, Adsorption of trace metals to plastic resin pellets in the marine environment. *Environmental Pollution*, 160: 42-48.

Holmes, LA, Turner, A & Thompson, RC 2014, Interactions between trace metals and plastic production pellets under estuarine conditions. *Marine Chemistry*, 167: 25-32.

Hong, Y & Brown, DG 2008, Electrostatic behavior of the charge-regulated bacterial cell surface. *Langmuir*, 24 (9): 5003-5009.

Huang, C, Ge, Y, Yue, S, Zhao, L & Qiao, Y 2021, Microplastics aggravate the joint toxicity to earthworm Eisenia fetida with cadmium by altering its availability. *Science of the Total Environment*, 753: 142042.

Hurley, R, Woodward, J & Rothwell, JJ 2018, Microplastic contamination of river beds significantly reduced by catchment-wide flooding. *Nature Geoscience*, 11: 251-257.

Imhof, HK, Rusek, J, Thiel, M, Wolinska, J, Laforsch, C 2017, Do microplastic particles affect Daphnia magna at the morphological, life history and molecular level. *PLoS One*, 12 (11): e0187590.

Isobe, A, Uchiyama-Matsumoto, K, Uchida, K, Tokai, T 2017, Microplastics in the Southern Ocean. *Marine Pollution Bulletin,* 114: 623-626, https://doi.org/10.1016/j. marpolbul.2016.09.037.

Karami, A, Golieskardi, A, Choo, CK, Larat, V, Karbalaei, S, Salamatinia, B 2018, Microplastic and mesoplastic contamination in canned sardines and sprats. Science of the Total Environment, 612: 1380-1386.

Koelmans, AA, Nor, NHM, Hermsen, E, Kooi, M, Mintenig, SM, France, JD 2019, Microplastics in freshwaters and drinking water: critical review and assessment of data quality. *Water Resources*, 155: 410-422.

LGA, Vieira, LR, Branco, V, Carvalho, C, Guilhermino, L 2018a, Microplastics increase mercury bioconcentration in gills and bioaccumulation in the liver and cause oxidative stress and damage in *Dicentrarchus labrax* juveniles. *Scientific Reports*, 8: 1-9.

Liao, YL, Yang, JY 2019, Microplastic serves as a potential vector for Cr in an in-vitro human digestive model. *Science of the Total Environment*, 703: 134805.

Lin, L, Tang, S, Wang, X, Sun, X & Yu, A 2020a, Hexabromocyclododecane alters malachite green and lead (II) adsorption behaviors onto polystyrene microplastics: interaction mechanism and competitive effect. *Chemosphere*, 265: 129079.

Lin, W, Su, F, Lin, M, Jin, M, Sun, X 2020b, Effect of microplastics pan polymer and/or Cu^{2+} pollution on the growth of *Chlorella pyrenoidosa*. *Environmental Pollution*, 265 (Part A): 114985.

Lin, ZKL, Hu, YW, Yuan, YJ, Hu, BW, Wang, BL 2021, Comparative analysis of kinetics and mechanisms for Pb (II) sorption onto three kinds of microplastics. *Ecotoxicology and Environmental Safety*, 208: 111451.

Liu, S, Huang, J, Zhang, W, Shi, L, Yi, K, Yu, H, Zhang, C, S, Li, J 2023, Microplastics as a vehicle of heavy metals in aquatic environments: A review of adsorption factors, mechanisms, and biological effects, *Journal of Environmental Management Part A*, 302: 113995, DOI: 10.1016/j.jenvman.2021.113995

Lu, K, Qiao, R, 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.

Lwanga, EH, Gertsen, H, Gooren, H, Peters, P, Salánki, T & Ploeg, MVD 2016, Microplastics in the terrestrial ecosystem: implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae). *Environmental Science & Technology*, 50 (5): 2685–2691.

Mak, CW, Yeung, KCF, Chan, KM 2019, Acute toxic effects of polyethylene microplastic on adult zebrafish. *Ecotoxicology and Environmental Safety*, 182: 109442.

Mao, R, Lang, M, Yu, X, Wu, R, Yang, X & Guo, X 2020, Aging mechanism of microplastics with UV irradiation and its effects on the adsorption of heavy metals. *Journal of Hazardous Materials*, 393: 122515. DOI: 10.1016/j.jhazmat.2020.122515.

Massos, A & Turner, A 2017, Cadmium, lead and bromine in beached microplastics. *Environmental Pollution*, 227: 139-145. DOI: 10.1016/j.envpol.2017.04.034.

Mato, Y, Isobe, T, Takada, H, Kanehiro, H, Ohtake, C, Kaminuma, T 2001, Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science & Technology*, 35: 318-324.

Mincer, TJ, Zettler, ER, & Amaral-Zettler, LA 2016, Biofilms on plastic debris and their influence on marine nutrient cycling, productivity, and hazardous chemical mobility. *The Handbook of Environmental Chemistry*, 78: 221-233, DOI: 10. 1007/698_2016_12.

Moore, CJ, Moore, SL, Leecaster, MK & Weisberg, SB 2001, A comparison of plastic and plankton in the North Pacific Central Gyrem. *Marine Pollution Bulletin*, 42: 1297-1300

Murphy, F & Quinn, B 2018, The effects of microplastic on freshwater *Hydra attenuata* feeding, morphology & reproduction. *Environmental Pollution*, 234: 487-494. DOI: 10.1016/j.envpol.2017.11.029

Nava, V & Leoni, B 2021, A critical review of interactions between microplastics, microalgae and aquatic ecosystem function. *Water Resources*, 188: 116476.

Nizzetto, L, Futter, M, Langaas, S 2016, Are agricultural soils dumps for microplastics of urban origin? *Environmental Science & Technology*, 50 (20): 10777-10779.

Oliviero, M, Tato, T, Schiavo, S, Fernandez, V, Manzo, S & Beiras R 2019, Leachates of micronized plastic toys provoke embryotoxic effects upon sea urchin *Paracentrotus lividus*. *Environmental Pollution*, 247: 706-715. DOI: 10.1016/j. envpol.2019.01.098.

Prata, JC, da Costa, João, P, Lopes, I, Duarte, AC, Rocha-Santos, T 2019a, Environmental exposure to microplastics: an overview on possible human health effects. *Science of the Total Environment*, 702: 134455.

Prendergast-Miller, MT, Katsiamides, A, Abbass, M, Sturzenbaum, SR, Thorpe, KL, Hodson, ME 2019, Polyester-derived microfiber impacts on the soil-dwelling earthworm *Lumbricus terrestris*. *Environmental Pollution*, 251: 453-459.

Prunier, J, Maurice, L, Perez, E, Gigault, J, Pierson-Wickmann, A, Davranche, M 2019, Trace metals in polyethylene debris from the North Atlantic subtropical gyre. *Environmental Pollution*, 245: 371-379, DOI: 10.1016/j.envpol.2018. 10.043.

Qi, K, Lu, N, Zhang, S, Wang, W, Guan, J 2021, Uptake of Pb (II) onto microplastic-associated biofilms in freshwater: adsorption and combined toxicity in comparison to natural solid substrates. *Journal of Hazardous Materials*, 411: 125115.

Qin, G, Niu, Z, Yu, J, Li, Z, Ma, J & Xiang, P 2021, Soil heavy metal pollution and food safety in China: Effects, sources and removing technology, Chemosphere Volume, 267: 129205. https://doi.org/10.1016/j.chemosphere.2020.129205

Qiu, H, Hu, J, Zhang, R, Gong, W, Gao, H 2019, The photocatalytic degradation of diesel by solar light-driven floating BiOI/EP composites. *Colloids and Surfaces A: Physicochemical and Engineering*, 583: 1-9.

Rahman, A, Sarkar, A, Yadav, OP, Achari, G & Slobodnik, J 2021, Potential human health risks due to environmental exposure to nano- and microplastics and knowledge gaps: a scoping review. *Science of the Total Environment*, 757: 143872. DOI: 10.1016/j.scitotenv.2020.143872.

Rist, S, Almroth, BC, Hartmann, NB, Karlsson, TM 2018, A critical perspective on early communications concerning human health aspects of microplastics. *Science of the Total Environment*, 626: 720-726.

Rochman, C, Hoh, E, Kurobe, T *et al.* Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Science Reports*, 3: 3263 (2013). https://doi.org/10.1038/srep03263.

Rochman, CM, Hentschel, BT, Teh, SJ 2014b, Long-term sorption of metals is similar among plastic types: implications for plastic debris in aquatic environments. *PLoS One*, 9 (1): e85433.

Santillo, D, Miller, K, Johnston, P 2017, Microplastics as contaminants in commercially important seafood species. Integr. Environ. Assess. Manag, 13 (3): 516–521.

Semple, KT, Doick, KJ, Jones, KC, Burauel, P, Craven, A, Harms, H 2004, Defining bioavailability and bioaccessibility of contaminated soil and sediment is complicated. *Environmental Science & Technology*, 38: 228A-231A.

Sendra, M, Sparaventi, E, Novoa, B, Figueras, A 2021, An overview of the internalization and effects of microplastics and nanoplastics as pollutants of emerging concern in bivalves. Science of the Total Environment, 753: 142024.

Shrivastava, A 2018, Introduction to plastics engineering introduction to plastics engineering. William Andrew Publishing, pp. 1-16.

Skdokur, E, Belivermi, M, Sezer, N, Pekmez, MKN 2020, Effects of microplastics and mercury on manila clam *Ruditapes philippinarum*: Feeding rate, immunomodulation, histopathology and oxidative stress. *Environmental Pollution*, 262: 114247.

So, WK, Chan, K & Not, C 2018, Abundance of plastic microbeads in Hong Kong coastal water. *Marine Pollution Bulletin*, 133: 500-505, DOI: 10.1016/j. marpolbul.2018.05.066.

Song, YK, Hong, SH, Jang, M, Han, GM, Jung, SW, Shim, WJ 2017, Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. *Environmental Science & Technology*, 51: 4368-4376.

Thompson, RC, Olsen, Y, Mitchell, RP, Davis, A, Rowland, SJ & John, AWG 2004, Lost at sea: Where is all the plastic? *Science*, 304: 838. DOI: 10.1126/science.1094559

Town, RM, van Leeuwen, HP, Blust, R 2018, Biochemodynamic features of metal ions bound by micro-and nano-plastics in aquatic media. *Frontiers in Chemistry*, 6: 627.

Tu, C, Chen, T, Zhou, Q, Liu, Y, Wei, J & Waniek, JJ 2020, Biofilm formation and its influences on the properties of microplastics as affected by exposure time and depth in the seawater. *Science of the Total Environment*, 734: 139237. DOI: 10.1016/j.scitotenv.2020.139237.

Tunali, M, Uzoefuna, EN, Tunali, MM & Yenigun, O 2020, Effect of microplastics and microplastic-metal combinations on growth and chlorophyll a concentration of *Chlorella vulgaris*. *Science of the Total Environment*, 743: 140479. microalgae and aquatic ecosystem function. Water Res. 188, 116476.

Turner, A 2016, Heavy metals, metalloids and other hazardous elements in marine plastic litter. *Marine Pollution Bulletin*, 111 (1–2): 136-142.

Turner, A, Holmes, LA 2015. Adsorption of trace metals by microplastic pellets in fresh water. *Environmental Chemistry*, 12: 600–610.

Turner, A, Wallerstein, C & Arnold, R 2019, Identification, origin and characteristics of bio-bead microplastics from beaches in western Europe. *Science of the Total Environment*, 664: 938-947. DOI: 10.1016/j.scitotenv.2019.01.281.

Vaisakh, PS, UK Adarsh, K Amrutha, AnishKumar, Warrier, VB Kartha, VK Unnikrishnn 2023, Integrated LIBS-Raman spectroscopy: A comprehensive approach to monitor microplastics and heavy metal contamination in water resources. *Environmental Research* Volume 231, Part 2, 15 August 2023, 116198

Vedolin, MC, Teophilo, CYS, Turra, A & Figueira, RCL 2018, Spatial variability in the concentrations of metals in beached microplastics. *Marine Pollution Bulletin*,129: 487-493, DOI: 10.1016/j.marpolbul.2017.10.019.

Wang, F, Yang, W, Cheng, P, Zhang, S, Zhang, S, Jiao, W, Sun, Y 2019a, Adsorption characteristics of cadmium on to microplastics from aqueous solutions. *Chemosphere*, 235: 1073-1080.

Wang, J, Li, J, Liu, S, Li, H, Chen, X & Peng, C 2021a, Distinct microplastic distributions in soils of different land-use types: a case study of Chinese farmlands. *Environmental Pollution*, 269: 116199. doi: 10.1016/j.envpol.2020.116199.

Wen, B, Jin, S, Chen, Z, Gao, J, Liu, Y, Liu, J 2018a, Single and combined effects of microplastics and cadmium on the cadmium accumulation, antioxidant defense and innate immunity of the discus fish (*Symphysodon aequifasciatus*). *Environmental Pollution*, 243: 462-471. DOI: 10.1016/j.envpol.2018.09. 029.

Yang, D, Shi, H, Li, L, Li, J, Jabeen, K, Kolandhasamy, P 2015, Microplastic pollution in table salts from China. *Environmental Science & Technology,* 49: 13622-13627.

Yang, Y, Liu, W, Zhang, Z, Grossart, H & Gadd, GM 2020, Microplastics provide new microbial niches in aquatic environments. *Applied Microbiology and Biotechnology*, 104: 6501-6511. DOI: 10.1007/s00253-020-10704-x.

Yu, H, Hou, JH, Dang, QL, Cui, DY, Xi, BD & Tan, WB 2020, Decrease in bioavailability of soil heavy metals caused by the presence of microplastics varies across aggregate levels. *Journal of Hazardous Materials*, 395: 122690.

Zaynab, M. AlYahyai, R, Ameen, A, Sharif, Y, Liaqat, A, Mahpara, F, Khalid, A & Shuangfei, Li 2022, Health and environmental effects of heavy metals, *Journal of King Saud University – Science*, 34: 101653.

Zhang, H, Pap, S, Taggart, MA, Boyd, KG, James, NA & Gibb, SW 2019a, A review of the potential utilization of plastic waste as adsorbent for removal of hazardous priority contaminants from aqueous environments. *Environmental Pollution*, 258: 113698.

Zhang, R, Wang, M, Chen, X, Yang, C & Wu, L 2020b, Combined toxicity of microplastics and cadmium on the zebrafish embryos (*Danio rerio*). *Science of the Total Environment*, 743: 140638.

Zhang, X, Zhang, M, He, J, Wang, Q, Li, D 2019c, The spatial-temporal characteristics of cultivated land and its influential factors in the Lowhilly region: a case study of Lishan town, Hubei Province, China. *Sustainability*, 11: (3810).

Zhang, Y, Wolosker, MB, Zhao, Y, Ren, H & Lemos, B 2020a, Exposure to microplastics cause gut damage, locomotor dysfunction, epigenetic silencing, and aggravate cadmium (Cd) toxicity in Drosophila. *Science of the Total Environment,* 744: 140979.

Zhou, Y, Liu, X & Wang, J 2019a, Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. *Science of the Total Environment*, 694: 133798.

Zou, J, Liu, X, Zhang, D & Yuan, X 2020, Adsorption of three bivalent metals by four chemicals distinct microplastics. *Chemosphere*, 248: 126064.