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Interactions Between Microplastic and Heavy Metals in the Aquatic Environment: Implications for Toxicity and Mitigation Strategies

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Abstract Heavy metals (HMs) and microplastics (MPs) are toxic environmental pollutants that severely risk ecosystems and living organisms. The interactions of these pollutants in the aquatic environment can impact their bioavailability, toxicity, and bioaccumulation potential in organisms. Various factors, including temperature, pH, salinity, polymer type, particle size and microbial abundance, influence these interactions and are likely to increase their influence on aquatic biota and human beings. MPs have been recognized as heavy metal transporters in aquatic environments that exhibit various harmful effects. However, MP interactions with heavy metals are poorly understood. Hence, it is important to understand the detailed mechanism,

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mainly absorption vs ingestion, MPs degradation with metal fate and combined effects on living organisms. To tackle and reduce the harmful effects on biodiversity, it is essential to comprehend the underlying mechanisms (e.g. adsorption, desorption, biouptake, and synergistic effects). Also, more research is required to comprehend the intricate connections between MPs and HMs in an array of environmental situations, which could lead to innovative solutions for mitigating their detrimental environmental consequences. This review paper discusses microplastic's prevalence, concentration, adsorption, and dissociation characteristics concerning HMs in aquatic ecosystems that must be understood to reduce their deleterious effects on aquatic biodiversity. Understanding these complex interactions between MPs and HMs is critical to assessing the ecotoxic effects and preventing environmental pollution. This review paper also underscores the nature of environmental pollutants, including the interaction mechanisms of MPs and HMs, emphasizing the importance of multifaceted approaches that need to be adapted to mitigate their combined effects.

Keywords Microplastics · Heavy Metals · Micropollutants · Adsorption · Toxicity · Aquatic ecosystem

1 Introduction

Microplastics (MPs) have attracted significant interest on a global level due to their widespread environmental distribution and unidentified risks to living species. MPs are persistent organic pollutants (Vaisakh et al., 2023) defined as a particle of plastic sized lesser than 5 mm (Birch et al., 2020); or sizes from 100 nm to 5 mm (Sobhani et al., 2020). MPs may be classified into two discrete groups: primary and secondary (Lehtiniemi et al., 2018). Primary MPs are produced in significant quantities for a defined purpose and can be derived from specific sources, such as plastic pellets used in industrial manufacturing, microbeads found in cosmetics, and nylon fibers used in the textile sector. In contrast, secondary MPs are produced due to the fragmentation or degradation of larger plastic items, including macro-plastics (the term refers to relatively larger pieces of plastic debris typically greater than 5 mm such as plastic bottles) and meso-plastics (refer to smaller plastic particles ranging from 1 to 5 mm for instance microbeads) (Jeyasanta et al., 2020). Chemical and physical ageing, UV radiation (photo-oxidation), mechanical transformation, and biodegradation by microorganisms are all examples of degradation mechanisms (Rose et al. 2023b).

Each year, around 8 million metric tons of plastic enter the oceans, and by 2050, there will probably be more plastic by weight in the oceans than fish (Jambeck et al., 2015). The ubiquitous presence of MPs in many environmental matrices is attributable to their use in a variety of applications due to their affordability, toughness, and adjustable properties (Ahmed et al., 2023). As of 2016, estimates of the amount of plastic garbage released into rivers, lakes, and the ocean worldwide ranged from 9 to 23 million metric tons annually (Borrelle et al., 2020). The amount released into the terrestrial environment was estimated to be between 13 and 25 million metric tons annually (Lau et al., 2020). In the event that things go as estimated, these projected 2016 emission rates will nearly quadruple by 2025. Marine activities such as shipping and fishing contribute only 20% of the plastic in the water (Khalid et al., 2021b; Vedolin et al., 2018). The remaining amount of plastic being transported to marine environments comes from terrestrial sources. The atmosphere also contributes to transport of many suspended microplastic particles locally or globally (Camarero et al., 2017). According to a recent study, atmospheric MPs were the most dominant particles transferred to ocean surface air and isolated places in aquatic systems (Evangeliou et al., 2020). The atmospheric transport of MPs is yet to be revealed; however, the atmospheric MPs fallout has been reported in Paris, France ($110 \pm 96/m^2/d$) and Dungguan, China ($53 \pm 38/m^2/d$) (Wright et al., 2020).

In contrast, the terrestrial discharge contains a huge load of organic and inorganic pollutants, especially HMs, which are the major sources of toxicity, particularly cadmium (Cd) in aquatic ecosystems (Kakakhel et al., 2023b). HMs are inert and non-biodegradable inorganic pollutants with a density of > 5 g/cm^3 (Dixit et al., 2015; Musilova et al., 2016; Rose et al., 2023a). HMs pollution in the environment primarily originates from mining operations, industrial discharges, weathering processes, water cycles, oil refineries, untreated waste, automotive activities, paint and dye industries, domestic effluents, agricultural runoff, excessive water resource utilization, effluent discharges, and wastewater treatment plants (Thompson & Darwish, 2019). Toxic HMs, including lead (Pb), mercury (Hg), Cd, arsenic (As), and chromium (Cr), when deposited in the body, are likely to cause health issues ranging from developmental delays, neurological damage, and organ damage to increase risk of cancers (Kayiranga et al., 2023). HMs exhibit strong adsorption tendencies, and their interaction with microplastic causes them to bind microplastic's surface because of hydrophobicity, large surface area, electrostatic interactions, and chemical properties (Shi et al., 2023; Zhang et al., 2023). Consequently, MPs are responsible for dispersing hazardous metals across various environmental substrates (Liu et al., 2022b).

Aquatic animals' uptake microplastic using various mechanisms, including feeding, direct ingestion, and trophic transfer (da Costa Araujo & Malafaia, 2021). A study reported that MPs adhere to the surfaces of aquatic organisms such as crustaceans, molluscs and mammals with mucus bodies leading to ingestion and accumulation on external bodies (Amini-Birami et al., 2023). The absorption of MPs by numerous marine organisms like crabs, shrimp, fish, mussels and oysters has been extensively documented (Van Cauwenberghe et al., 2013). Experimental studies have suggested the inadvertent ingestion of MPs by a variety of planktonic organisms such as copepods during feeding (Setälä et al., 2014). Subsequently, large predators and fishes indirectly consume these MPs (Roch et al., 2020). Previous studies have demonstrated that MPs clubbed with HMs can have detrimental effects on the development and reproductive capabilities of aquatic organisms, including photosynthetic phytoplankton (Fu et al., 2019; Wang et al., 2020b). This observation illustrates the dire health risks that human health faces due to the potential propagation of heavy metal-associated MPs up the food chain.

Many studies are being conducted on toxicity of heavy metals and negative effects of microplastics. But the collective lethality needs to be studied upon. In this view, the current review article provides an in-depth overview and evaluation of research pertaining to the environmental consequences of MPs associated with HMs. The primary objective of this review is to address knowledge gaps while providing certain details by investigating the effects of toxic pollutants originating from MPs and HMs on aquatic organisms and humans. Additionally, the correlation mechanism between HMs and MPs, as well as potential influencing factors, have been explored. In addition to evaluating a range of mitigating strategies, the current study also proposes several potential directions for future research. This review article thus aims to improve our understanding of the origins, pathways, processes, and ecological risks that MPs and HMs collectively pose to human and environmental health.

2 Review Methodology

The methodology employed in this review paper on MPs and HMs followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, ensuring a rigorous and systematic approach. The study consisted of four main steps: 1: Identification, 2: Screening, 3: Eligibility, and 4: Inclusion criteria. These stages were accomplished in three sequential phases. The first phase involves searching for reliable literature using Scopus as a search engine by providing relevant keywords such as "microplastic", "Heavy Metals", and "microplastic and Heavy metals toxicity". A total of 2126 initial results were gathered and subsequently subjected to screening. The screening process applied various inclusion and exclusion criteria, i.e., the inclusion of articles published in journals in the English language and the exclusion of conference proceedings and book chapters, considering that journal articles provide a more comprehensive representation of research and in the field and English is a widely used language for scholarly communication. Articles within the specific subject areas relevant to the present study were also considered and categorized into different sub-areas.

Furthermore, any duplicate articles were removed, ensuring no overlap in the final dataset. The inclusion criteria focused on studies that specifically investigated the interaction, adsorption, or accumulation of HMs on MPs. Data extraction and synthesis were conducted to extract relevant information from the selected articles, including study design, sample characteristics, methodology, results, and conclusions. The extracted data was recruited to find the trends, and gaps in the MPs and HMs research. The search process utilized the appropriate use of Boolean operators to refine search queries and relevant results. As a result, a final dataset of 153 published articles from 2010 to 2023 was selected for the present review.

3 Interactions of Microplastics and Heavy Metals: Environmental and Health Concerns

Microplastics and HMs pose a significant environmental and health concern to humans and other organisms (Lin et al., 2021). The occurrences of HMs on microplastic surfaces can intensify the toxicity and ecological risks through synergistic interactions (Vaisakh et al., 2023). HMs concentrations on plastic (polyethylene) pellets after 8 weeks of suspension in a harbor showed HMs concentration in the following order: silver (Ag), iron (Fe), aluminum (Al), manganese (Mn), Pb, copper (Cu), and zinc (Zn). The plastic pellets absorbed the metal through co-precipitation, direct adsorption of cations or complexes onto charged sites or neutral regions of the plastic surface, and adsorption onto Fe and Mn hydrous oxides (Ashton et al., 2010). The age of the MPs significantly influences the accumulation of HMs. Santos-Echeandia et al. (2020) investigated Hg accumulation on plastics on the Spanish Mediterranean coast and reported a significant relation between the accumulation of Hg and the age of the MPs. There are four mechanisms by which the plastic-degradation takes place, including hydrolytic, bio-degradation, thermal-degradation, and photodegradation (Yao et al., 2022). Aghilinasrollahabadi et al. (2021) showed that weathered polyethylene terephthalate MPs had higher Pb adsorption than recently introduced polyethylene MPs and low Zn uptake in either condition. When exposed to rainwater, low-density polyethylene MPs released Pb and Zn. HMs can influence MPs adsorption characteristics and processes in the natural environment. To fully comprehend the environmental effects of MPs, it is vital to investigate the interactions between MPs and these co-existing pollutants, as given in Table 1.

3.1 Interactions in Aquatic Environments

While, multiple research studies have documented the abundance of organic contaminants in plastic debris (Karapanagioti & Rios-Mendoza, 2022), the occurrence of metals on plastic debris, either through adsorption, adhesion or as additives in the plastic itself, has only been more recently acknowledged and investigated (Attaelmanan et al., 2023; Vaisakh et al., 2023). Polyethylene, polyethylene terephthalate, high-density polyethylene, polystyrene, polyvinyl chloride, polyoxymethylene, polypropylene, polybutylene adipate terephthalate, low-density polyethylene, and polyacetic acid are different plastics found in aquatic environments (Pandiyan et al., 2013). While plastics are disposed of into the environment, it would attract and absorb potential pollutants from their surroundings and serve as reservoirs for toxic substances. Research based examinations and laboratory studies have unequivocally exhibited the occurrences and testimony of heavy metals onto these MPs (Xuan Guo & Wang, 2019). HMs such as Cr, Cd, and Fe are predominantly discharged into the environment through industrial effluents, often finding their way into water bodies (Khalid et al., 2021a; Zhou et al., 2020). These effluents are carelessly discharged into water bodies in developing countries without proper treatment. Furthermore, automotive emissions are a common source of Pb, Cd, Zn, and Fe, contaminate roadside soil and reach water sources during rainstorms (Guan et al., 2020). The spread and breaking down of antifouling coatings (biocide based coatings and silicon-based coatings), as well as the combustion of fuel, induces heavy metal contamination in marine environments, particularly in harbors, waterways, and bays (Abbasi et al., 2020). Recent studies have shown MPs propensity to attract and interact with HMs, suggesting their possible contribution to the dynamics of heavy metal pollution. Despite the uptake of HMs from the surrounding environment, MPs also act as a carrier source of HMs deposition. Hazardous metals have been obtained from plastic surfaces in ocean floors. This indicates the ocean litter is a potential "pathway" to pollution of the beach environment climate because of their deposition in oceanside soil for a long time. The total mass of Pb that could leach from polyvinyl chloride plastic litter over a year onto Ookushi Beach, Goto Islands, Japan was estimated to be 0.6 ± 0.6 g/year (Nakashima et al., 2012). In another study, (Imhof et al., 2016) reported different types of HMs including Fe (23.64 µg/g), Cr (4.06 to 456.25 µg/g), Zn (0.76 to 89.75 µg/g), Pb (219.70 to 227.02 µg/g) and Ti (1046.01 to 175,513.36 µg/g) associated with paint particles in Lake Garda, Italy. Previously, Massos and Turner (2017) examined sandy beaches in southwest England and reported the presence of Cd (3390 µg/g), Pb (5330 µg/g), and beryllium (13,300 µg/g) on MP pellets and fragments in water bodies. Additionally, Zn (2.39), Cd (17.56), Pb (131.1), Fe (500.6), and Ti (38,823.7) adsorption

Table 1 The relation between microplastics and various types of heavy metals in different countries

Country	Area	Dominant microplastics detected	Microplastics sampling technique	Dominant adsorbed heavy metals	Characterization technique	References
United Arab Emirates	Dubai beaches	Polyethylene, Polypropylene	-	Titanium (Ti), Cr, Mn, Fe, nickel (Ni), Fe, Zn, Pb, cesium, Cd, Co	FTIR, X-ray fluorescence spectroscopy (XRF)	(Attaelmanan et al., 2023)
India	Swarna River near Kalmadi (Malpe) in Udupi district, and River Netravathi in Mangalore, Dakshina Kannada	Polypropylene, Polyethylene, Polyethylene terephthalate	Stainless steel sieve with a 1 mm mesh size	Cd, Zn, Fe, Mn, Cr	LIBS- Raman system, Inductive coupled plasma optical emission spectroscopy (ICP-OES)	(Vaisakh et al., 2023)
Thailand	Chao Phraya River	Polypropylene, Polyethylene	Point sampling with a Manta trawl net of 300 m aperture size	Cr, Fe, Cd, Pb, Zn, Ti	FTIR, Scanning electron microscope (SEM), ICP-OES	(Ta & Babel, 2023)
China	Pearl River Estuary	Expanded polystyrene	Stainless steel sieve with 0.03 mm pore size	Cd, Cr, Fe, Zn, Pb, Mn, Fe, Cd, Cd	SEM, µ-FTIR, ICP-MS	(Xie et al., 2021)
India	East Kolkata Wetland	Polyethylene, Polyethylene terephthalate	Samples were collected using a grab and transferred to a steel bucket, followed by immediate sieving using a mesh sieve (63 µm)	Cd, Cd, Cr, Fe, Zn, Pb, Zn	Optical microscopy, fluorescence microscopy, FTIR	(Sarkar et al., 2021)
China	Hong Kong	Polyethylene, Polypropylene, Polystyrene	Sieved with a 0.5 mm pore size	Cd, Zn, Cd, Zn, Fe, Mn, Fe	FTIR, ICP-OES	(Li et al., 2020)
China	Jinjiang River	Polyethylene terephthalate, Polyethylene, Polypropylene	Samples were collected using stainless shovels and transferred into aluminum foil bags	Cr, Zn, Fe, Zn, Pb, Cd, Cd	SEM–EDS, Raman, FTIR, Inductive coupled plasma mass spectrometry (ICP-MS)	(Deng et al., 2020)
Indonesia	Musi River, South Sumatera Province	Polypropylene, Polyethylene, Polyether sulfone, Polyvinyl chloride, Nylon	Sampling was done using a Neuston net with a mesh size of 300 µm and an aperture diameter of 50 cm across a 1.5 m length	Pb, Fe	AAS, stereomicroscope, FTIR	(Purwiyanto et al., 2020)

Table 1 (continued)

Country	Area	Dominant microplastics detected	Microplastics sampling technique	Dominant adsorbed heavy metals	Characterization technique	References
China	Beijing River	Polyethylene, Polypropylene	The samples were taken with stainless-steel and then put in a bag made of Cd foil to keep them preserved	Zn, Cd, Pb, Fe, Ti	µ-FTIR, SEM	(Jiang et al., 2019)
Croatia	Zaglav Beach and Milna Beach on island of Vis	Plastic pellets	Sieved using a 1 mm sieve	Cd, Cr, Fe, Fe, Mn, Zn, Pb, Zn	Atomic Absorption spectroscopy (AAS), FTIR	(Maršić-Lučić et al., 2018)
Iran	Persian Gulf in Bushehr	Plastic debris	Samples were collected with tweezers followed by sieving with different mesh sizes	Cd, Fe, Mn, Cd, Cr, Zn, Pb, Fe	Epifluorescence microscopy, FTIR, ICP-OES	(Dobaradaran et al., 2018)
Brazil	Beaches along the Coast of São Paulo State	Polyethylene, Polypropylene resin pellets	Pellets were hand-collected and kept in plastic bags	Cd, Cr, Fe, Fe, Mn, selenium, Ti, Zn	FTIR, ICP-OES	(Vedolin et al., 2018)
England	Plymouth and the Kingsbridge estuary	Polyethylene pellets	Samples were collected using plastic tweezers and polypropylene centrifuge tubes	Fe, Zn, Pb, Cd, Cd, Cr, cobalt (Co), molybdenum, uranium	FTIR, Energy Dispersive Spectroscopy (EDS)	(Ashton et al., 2010)

were determined on polypropylene and polyethylene particles in the Beijing River in China (Wang et al. 2021a). The occurrence of HMs (maximum concentration) such as Cd (45 ± 9 mg/kg), Fe (1.0 ± 1 mg/kg), Fe (228.0 ± 142 mg/kg), Mn (9.0 ± 6 mg/kg), Zn (8.0 ± 9 mg/kg), and Ti (3.0 ± 0.4 mg/kg) in MPs (e.g., polypropylene, polyethylene, and high-density polyethylene) was reported along the coast of Sao Paulo State in southern Brazil (Vedolin et al., 2018). About 0.1 µg/g of Pb was adsorbed to the beach pellets, and its avian bio-accessibility was around 60 and 70% (Turner et al., 2020). Purwiyanto et al. (2020) reported the dominance of polypropylene followed by polyethylene, polyester, polyvinyl chlorine, and nylon, and the average concentration of Pb (0.470 mg/kg) was higher than Fe (0.0138 mg/kg) on MPs in the Musi River, South Sumatera Province, Indonesia. Ta and Babel (2020) reported the occurrence of polypropylene, polyethylene, and polystyrene MPs with high concentrations of Pb (17.61 µg/g) and Fe (13.02 µg/g) adsorbed on MPs in the Chao Phraya River at the Tha Pra Chan area of Bangkok, Thailand. In the wetlands of Eastern India, Sarkar et al. (2021) reported various HMs (wastewater canal, treatment plant, µg/g) such as Cd (4.51 µg/g), Cr (342.2 µg/g), Fe (119.5 µg/g), Zn (75.5 µg/g), and Pb (104.6 µg/g), which were adsorbed in MPs manufactured of polyethylene and polyethylene terephthalate.

The presence of MPs in food chains and food webs has raised concerns due to their potential interaction with HMs (Huang et al., 2021a, b). Initially, the pollutants are exposed to aquatic organisms by ingestion, or sorption by phytoplankton and zooplankton followed by transfer to higher trophic levels and deposition from water to sediments. MPs with attached HMs deposited in sediments are consumed by benthic organisms such as clams and polychaetas, which can subsequently be directly ingested by large vertebrates such as fish and the fish is further consumed by the human (Kakakhel et al., 2023a; Zaheer Ud Din et al., 2023). The widespread presence of MPs in aquatic habitats allows their absorption and subsequent accumulation in fish and other animals' digestive systems. MPs can interact with HMs, increasing the potential of hazardous chemicals such as persistent organic pollutants (POPs), phthalates, bisphenol A, flame retardants and antimicrobial agents, migrating into the aquatic food cycle. Some studies have investigated how MPs bioaccumulate and biomagnify in aquatic environments at various trophic levels. For instance, Chen et al. (2021) conducted a study on *Caenorhabditis elegans* and found transgenerational neurotoxicity induced by polystyrene MPs. Dimitriadi et al. (2021) observed significant decreases in heart function and swimming competence, oxidative stress and metabolic changes in zebrafish exposed to food-enriched particles ranging from 3 to 12 µm. Carrasco-Navarro et al. (2021) investigated the influence of polystyrene MPs and tire rubber MPs on *Chironomus riparius*. Results observed alterations in the expression of heat shock proteins and Mn superoxide dismutase genes. Aljaibachi et al. (2020) reported a significant decline in *Daphnia magna*, indicating stressful environmental conditions upon exposure to polystyrene MPs < 15 µm. Figure 1 illustrates the correlation in heavy metals and MPs in aquatic environments

4 Interaction Mechanism Between Microplastics and Heavy Metals: Isotherm Model and Sorption Mechanism

The interaction between MPs and HMs involves three primary mechanisms. The first mechanism involves electrostatic interaction and surface complexation, where HMs interact with polar or charged MPs by coulombic forces (Cao et al., 2021). Van der Waals refers to weak attractive forces between all molecules, including non-polar molecules like microplastics and metal ions (Ikai, 2017). These forces may aid in the adsorption of metal ions onto the microplastic's surfaces. The second process involves complex development by sorption and/or deposition by natural organic matter and biofilms, altering microplastic surface properties (He et al., 2022). The third mechanism includes precipitation and co-precipitation, where heavy metal ions or their complexes co-precipitate with hydrous oxides of Fe and Mn by adsorbing them onto them (Qasem et al., 2021; Yang et al., 2022). π-π interactions, which involve the overlapping of π-orbitals between aromatic or conjugated systems in plastic polymers and certain heavy metal ions, contribute to the binding and adsorption of HMs onto the microplastic's surface (Thakuria et al., 2019). The pore-filling mechanisms entail the HMs adsorbing into the microplastic pores, resulting in their subsequent retention and

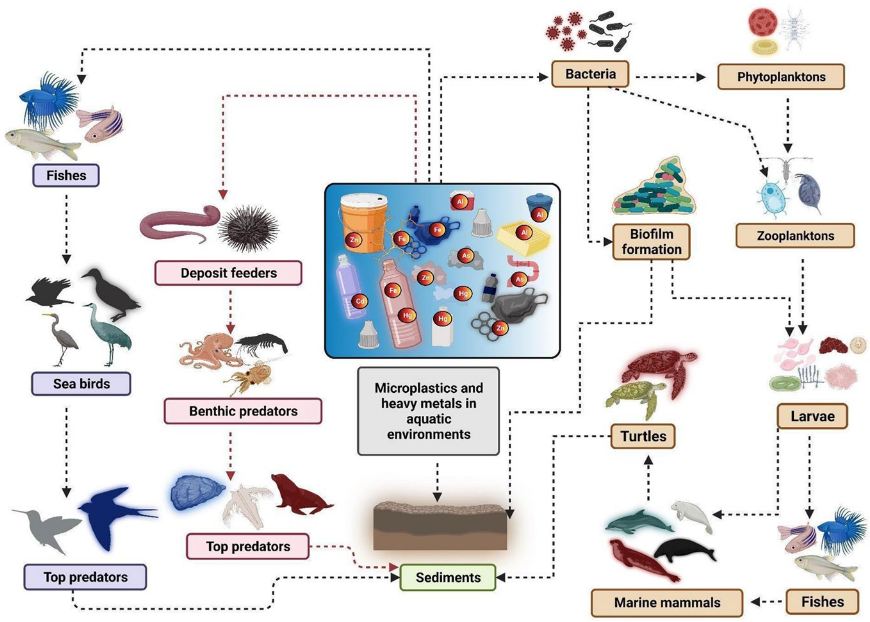

Fig. 1 Interaction between microplastics and heavy metals in aquatic environments

accumulation. Figure 2 illustrates the interaction mechanism between MPs and HMs through various sorption mechanisms such as H-bonding, π-π interactions, electrostatic interaction, hydrophobic interaction, pore filling and Van der Waals forces.

External diffusion, intra-particle diffusion, and adsorption are the three phases that comprise metal adsorption on MPs (Xuan Guo & Wang, 2019). External diffusion occurs when heavy metal ions rapidly permeate the water film that envelops the microplastic particles (Yu et al., 2020). Intraparticle diffusion pertains to the process by which HMs permeate on the surface of MPs; as sorption rate and available adsorption sites decrease, the intraparticle diffusion

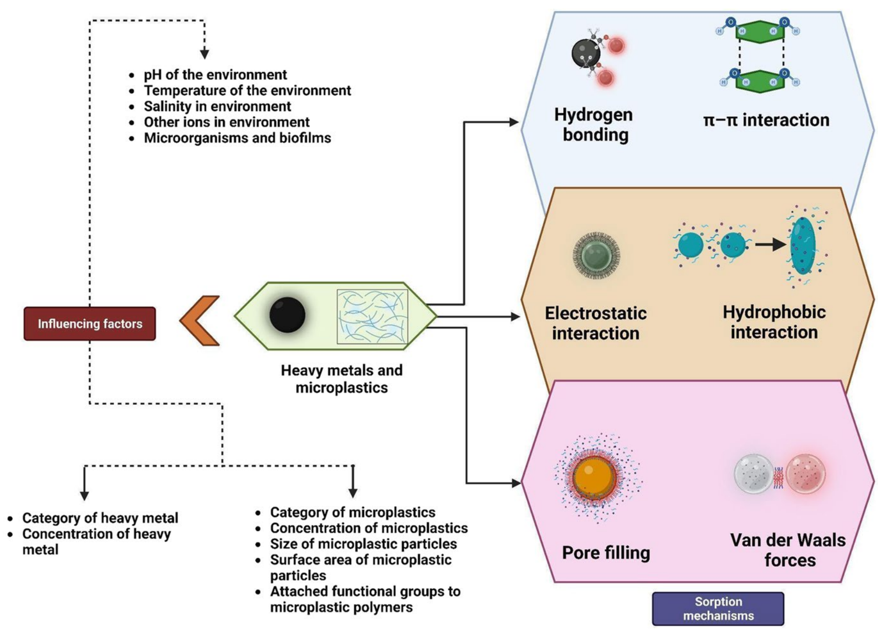

Fig. 2 Influencing factors and interaction mechanisms between microplastics and heavy metals

becomes apparent (Liu et al., 2022c). Adsorption depicts the final stage, in which the rate of adsorption decreases in tandem with the concentration of HMs and the limited number of adsorption sites that are accessible (Bai et al., 2023). Kinetic models, including the pseudo-second order model, are frequently employed to characterize the adsorption process. These models imply that the rate-limiting phase is the chemical adsorption step.

As stated by Wang et al., 2020a, 2020b, 2020c, 2020d, the common processes between the interaction of heavy metal and MPs include adsorption, desorption, and bioaccumulation. To comprehend, the adsorption process onto the surfaces of MPs has the potential to enhance the bioavailability and absorption of HMs (Yinghua Li et al., 2022). However, the efficiency of this adsorption process can be influenced by several factors such as particle size, dimensions, density, shape, and surface charge of the MPs' characteristics. (Hodson et al., 2017). Additionally, the desorption of HMs from MPs is influenced by salinity, temperature, and pH (Ji et al., 2021). During bioaccumulation, organisms tend to ingest MPs that have adsorbed HMs on their surface. Microplastic size, shape, content, and surface chemistry also affect heavy metal bioavailability.

Weathering and ageing processes, including long-term physical abrasion, photo-oxidation, and biodegradation are examples of how weathering and ageing can radically affect microplastic surface properties (Bai et al., 2023). However, numerous mechanisms are involved in the adsorption between MPs and HMs. The intermolecular interaction of the plastic polymer and the adsorbate is critical in determining the surface of heavy metal adsorption microplastic (Liu et al., 2022b). Despite MPs' property of being inert to metal ions in water, the breakdown of plastic polymers may increase metal ion adsorption on their surface (Binda et al., 2021). Multiple interactions, including hydrogen bonding, electrostatic interaction, liquid filling mechanisms, hydrophobic interaction, Van der Waals forces, and π-π interactions, could cause this interaction. Table 2 shows several studies on heavy metal adsorption on MPs

Small metal absorption by plastic resin pellets was investigated, with findings indicating that polar or charged plastic surfaces and non-specific interactions with metal–organic complexes could influence metal ingestion efficiency (Holmes et al., 2012). Another study, Ashton et al. (2010) reported that the co-precipitation of metallic HMs on hydrated Fe and Mn oxides is likely to be the reason for their accumulation, which signifies that the conjugation of these two pollutant could possible increase the toxicity level of water. In contrast, the absorption of HMs on the surface of MPs can decrease the contamination of HMs in aquatic ecosystems. An electrostatic interaction between divalent metal ions and carboxylate anions on the surface of MPs was shown in the study reported by Tang et al. (2021). It indicated that the strong electrostatic force found in carboxylate and divalent cations could bridge between microplastic, Pb to aggregate and are likely to bond together, potentially impacting the aquatic ecosystem by smothering benthic organisms. Prior research has investigated the adsorption of Fe by pure polyethylene, revealing that the highest level of adsorption was seen at a $pH > 5$. The increased electrostatic interaction between Fe ions and polyethylene is the reason behind this adsorption reaction (Wang et al., 2020a, b, c, d). A study on the effect of surfactants on Pb adsorption by different types of MPs revealed that the introduction of surfactants enhanced the MPs' hydrophilicity and negative charge, thereby enhancing their sorption capacity (Shen et al., 2021).

A recent study employed Fourier Transform Infrared Spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS) to assess the sorption of Cd onto various MPs. The process was found to involve cation-bonding interaction and oxygen functional groups, as indicated by the increased proportions of carbon–carbon and C-O bands in polyamide and acrylonitrile butadiene styrene (Zhou et al., 2020). The alteration in the absorption peak of the C-O bond upon adsorption of Pb onto nylon microplastic was also observed by Tang et al. (2020), suggesting the presence of a surface complex mechanism involving Pb and carboxylate anions (-COO-). Because the Pb ions interact with the amide carbonyl group upon absorption onto the surface of the nylon microplastic. For instance, the electron density distribution within the amide group can be altered when Pb^{2+} makes a coordinate bond with a lone pair of electrons localized on the O_2 atom (Ingham, 2022). Zou et al. (2020) investigate the chemical properties of polyvinyl chloride, chlorinated polyethylene, and polyethylene after adsorption of Pb, Fe, and Cd. Results showed changes in carbon–oxygen bonds and carbon-chlorine bonds

Table 2 Adsorption mechanisms of heavy metals by microplastics

Microplastics type	Heavy metals type	Best fit isotherm	Sorption mechanism	References
Polystyrene	Fe	Langmuir	-	(Chen et al., 2022)
Polyethene	Pb	Langmuir	Electrostatic force and complexation	(Fu et al., 2021)
Polypropylene	Cd	Henry model	Physical adsorption	(Shen et al., 2021)
Low-density Polyethylene	Fe, Fe, Pb, Mn, Zn	Freundlich	-	(Huang et al., 2020)
Polyethene	Fe	Langmuir	Intra-particle diffusion and electrostatic forces	(Wang et al., 2020a, c)
High degree Polyethylene	Cd	Langmuir	-	(Wang et al., 2020a, c)
Chlorinated Polyethylene	Fe, Pb, Cd	Freundlich (Fe, Pb), Langmuir (Cd)	Surface complexation and electrostatic interaction	(Zou et al., 2020)
Polystyrene	Cd	Henry model	π-π Interaction	(Xuetao Guo et al., 2020)
Polystyrene	Cd	Freundlich	Non-covalent interactions and electrostatic force	(Dong et al., 2020)
Polystyrene	Cd	Henry model	Electrostatic and π-π Interaction	(Zhou et al., 2019)
Polyethene	Strontium	Freundlich	Internal and external diffusion	(Xuan Guo & Wang, 2019)

(specifically, between chlorinated polyethylene and polyvinyl chloride). This demonstrated the correlation between metals and oxygen-containing functional groups on MPs, as well as electronegative chloride on chlorinated polyethylene and polyvinyl chloride. In another study, Xuetao Guo et al. (2020) identified that the adsorption process of polystyrene is significantly influenced by polar interactions arising from the benzene structure. Conversely, van der Waals forces originating from nonspecific functional groups serve as the primary mechanism by which Cd adsorbs onto polyethylene and polypropylene (Xuetao Guo et al., 2020).

Organic materials that are adhered to the surface of MPs can also impact the adsorption of metal ions onto them. Although biological communities also contribute significantly, heavy metal adsorption onto MPs is primarily influenced by their chemical and physical properties (Liu et al., 2022a). For instance, the microbial consortiums present in the water systems form biofilms that influence the surface properties and functional insights of MPs (Yuan et al., 2020). In 2020, University of Washington researchers investigated the mechanisms by which HMs adsorb onto MPs coated in biofilm within a reservoir. The biofilms' capacity to enhance the adsorption of HMs was governed by complexation with functional groups (phenyl-OH, amino, and carboxyl), cation exchange, and electrostatic interactions (Guan et al., 2020). The authors reported that the adsorption of HMs onto MPs covered by biofilms is the result of a complex combination of physical and chemical mechanisms, as illustrated in Fig. 3.

In a research study, Ahamed et al. (2020) illustrated that biofilms enhanced the adsorption of heavy metal ions through two mechanisms: (i) reducing the hydrophobicity of polyethylene and (ii) supplying functional groups that can interact with easily accessible metal ions. The kinetics of Pb, Cd, and Zn adsorption were studied on virgin polypropylene and polyethylene terephthalate coated with biofilm. The results of this study indicated that biofilm-coated polymeric materials exhibit improved metal-binding characteristics. Increased electrostatic interactions, oxide production, and a change in surface charge may all contribute to efficient metal removal as biofilms develop on MPs surfaces (Wang et al., 2020b); nevertheless, the rate of heavy metal adsorption on microplastic surfaces is accelerated by biofilm growth and maturation (Kalčíková et al., 2020).

5 Role of Environmental Factors

Adsorption of HMs to MPs is likely to be substantially influenced by salinity, pH, dissolved organic

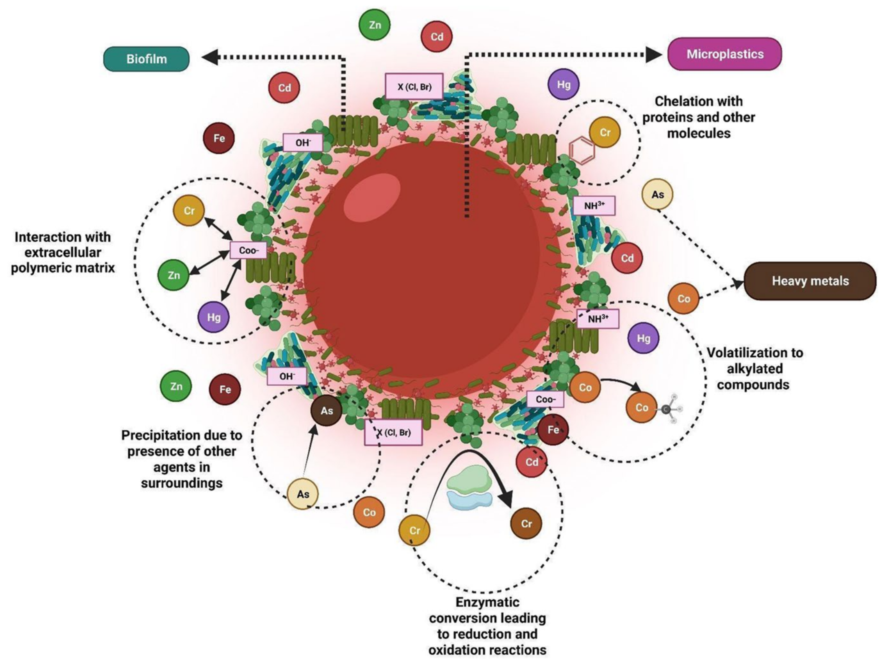

Fig. 3 The potential interaction between MPs, HMs and bacterial taxa in the environment describe the absorption mechanism, as the bacteria play a key role in the degradation of plastic. This mechanism could be an ecofriendly approach towards the degradation of MPs in the environment

matter (DOM), temperature, and particulate matter (Jardak et al., 2016).

5.1 pH Condition

pH plays an important role in the adsorption of HMs on MPs. The capacity of MPs to adsorb HMs can be enhanced by a rise in pH (Zou et al., 2020). As the pH decreases, cationic contaminant adsorption increases due to precipitation, stronger electrostatic forces, and reduced competition from H^+ in the solution, among other factors. Conversely, the sorption capacity for anionic pollutants reduces with increasing pH of the solution (Demiraj et al., 2018). According to Zou et al. (2020), the adsorption of Fe, Pb, and Cd by MPs increases as the pH (6.13) of the solution rises. However, Dong et al. (2019) observed the inverse pattern in the case of Arsenic (III) adsorption. Due to their comparatively lower zeta potential and consequently stronger electrostatic attraction towards metal cations, MPs exhibit this effect as the pH (3–7) of the surrounding environment rises. On the contrary, the adsorption of heavy metal ions may be impeded by passivation or precipitation occurring at elevated pH levels. Lin et al. (2021) noted that Pb exists in a cationic state at low pH values (2), whereas at high pH values (6), it can produce species such as $Pb(OH)^+$, $Pb(OH)_2$, and $Pb(OH)_{3-}$.

5.2 Temperature

Temperature significantly impacts the adsorption of HMs onto MPs in numerous ways. For instance, the adsorption of HMs is endothermic, whereby the capacity for adsorption escalates in tandem with elevated temperatures (Ahmad et al., 2014). In a study conducted by Wang et al. (2022), it was found that positive adsorption of Pb onto nylon MPs was endothermic and spontaneous across a wide temperature range, as evidenced by positive enthalpy change (ΔH) and negative Gibbs free energy (ΔG) values. Tang et al. (2021) observed findings regarding the adsorption of Zn, Fe, and Zn onto nylon MPs. This effect is accounted for by the chemisorption of cationic ions with nylon MPs. Higher temperatures facilitate the transfer of pollutants to the surface of MPs because of the increased energy accessibility (Inyang et al., 2016). However, elevated temperatures might have an adverse impact on the sorption of As (III). The research conducted by Dong et al. (2020) demonstrated that the sorption of As (III) onto polytetrafluoroethylene and polystyrene resulted in negative ΔH values. These values suggest that the processes involved are exothermic and advantageous when conducted at lower temperatures. Overall, it is apparent that the impact of temperature on the adsorption of HMs by MPs is contingent upon the microplastic polymer and the contaminants in consideration.

5.3 Salinity

The adsorption behavior of HMs by MPs in aqueous media is significantly influenced by salinity (Zou et al., 2020). A study conducted by Wang et al. (2019) discovered that Cd adsorption onto high-density polyethylene could be inhibited by the addition of sodium chloride (NaCl) at varying concentrations. Cd exchange and coexisting ions with salinity were identified to limit sorption capacity. The species distribution of HMs in solution exhibited a shift as the concentration of Cl increased. Additionally, as the concentration of Cl rose, bivalent ion adsorption onto MPs was observed to decrease (Tang et al., 2021). The impact of co-occurring saline ions on Fe adsorption was found to be property-dependent. Specifically, magnesium ions exhibited a substantial inhibitory effect on Fe sorption, as reported by Ivanets et al. (2016). Another study conducted by Tang et al. (2020) provided evidence that the sorption of Cd, Fe, and Pb by MPs is influenced by the concentration of NaCl (0% NaCl, Pb 1.07 q_e(mg/g)). During the sorption process, sodium, magnesium, and calcium ions engage in competition with HMs. Conversely, anions like chlorine facilitate the formation of complexes, which results in a reduction of sorption capacity (Gao et al., 2020). The aggregation of microplastic particles can be influenced by salinity, leading to a decrease in both surface area and sorption capacity (Tang et al., 2021).

5.4 Dissolved Organic Matter and Particulate Matter

The sorption behavior of HMs on MPs can be influenced by the presence of dissolved organic matter (Xu et al., 2018). Cd sorption by various MPs varied as the concentration of humic acid increased and decreased (Guo et al., 2022). In a study on competing sorption with MPs, Zhou et al. (2019) found that the affinity of negatively charged fulvic acid and humic acid with π-electrons and functional groups for these contaminants led to a reduction in the overall sorption capacity. On the contrary, certain MPs might absorb further humic or fulvic acids to enhance the electrostatic interactions with cationic contaminants (Guo et al., 2022). It has been demonstrated that DOM influences the sorption capabilities of bivalent metal ions in numerous ways (Tang et al., 2020). The complicated interactions between DOM, microplastic properties, and pollutant targets make assumptions about the effects of DOM on HMs/microplastic sorption challenging. The hydrophilic nature of MPs was observed to be enhanced by surfactants, thereby increasing their capacity to adsorb Pb from wastewater (Tang et al., 2020). Free chlorine and corrosion inhibitors in water distribution systems may minimize the amounts of HMs adsorbed by MPs due to oxidation and competition effects (Huang et al., 2021a, 2021b). However, the influence of co-occurring particulate matter on microplastic sorption behaviors in the natural environment remains unclear and requires further investigation (Wang et al., 2020d).

6 Toxic Effects

Combining MPs with pollutants can lead to changes in toxicity towards organisms (Sun et al., 2022). Khalid et al. (2020) developed considerable evidence that HMs and MPs are hazardous to numerous organisms. Jinhui et al. (2019) studied MPs and HMs for their harmful impact on organisms in aquatic environments. Direct intake of MPs and associated HMs by living bodies from their environment can result in metal accumulation in the organism's body (Zhu et al., 2018), possibly leading to reactive oxygen species (ROS) generation. HMs can indirectly enter organisms through the digestive system once MPs are consumed. Micro- and macro-algae are critical in marine environments because they act as a feed source from zooplankton to fish, turtles, crustaceans, mollusks, and larger species (Huang et al., 2020).

Bhattacharya et al. (2010) reported the accumulation of MPs in *Chlorella* sp. The findings of this study revealed the depletion in the algal photosynthesis process and enhancement of algal ROS, which could probably have implications on the sustainability of the aquatic food chain. In a lab-based experiment, Kalčíková et al. (2020) observed that MPs have significantly impacted duckweed's root growth. Similarly, Abbasi et al. (2020) examined interactions in the rhizosphere zone of wheat and found that polyethylene terephthalate MPs acted as carriers of HMs such as Pb, Zn, and Cd. A multitude of additional studies have examined the uptake of MPs by various organisms inhabiting aquatic ecosystems, including zooplankton, bivalve mollusks, and mussels. These investigations have also investigated the potential transfer of MPs to multicellular organisms, specifically fish (Karami et al., 2018; Santillo et al., 2017). Phytoplankton, fish, invertebrates, and algae are extensively studied organisms for the assessment of combined impacts of HMs and MPs, as these organisms are ultimately ingested by organisms at higher levels in the food chain (Huang et al., 2021a, 2021b). The effects of 100 µg/L polyethylene MPs on mosquito fish were examined in a recent study spanning a period of 14 days. According to the findings obtained from this study, MPs were found to be substantially accumulated in the liver, which increased the malondialdehyde ($p < 0.05$) level to 200 µg/L (Banaee et al., 2023).

6.1 Potential Effects on Aquatic Biota

Exposure to HMs and MPs is most likely to have detrimental effects on aquatic organisms, including stunted growth and development, decreased reproduction, elevated stress levels, altered behavior, and additional health issues (Cormier et al., 2022; Singh & Kalamdhad, 2011). Multiple laboratory investigations have yielded findings that support the notion that combined MPs and HMs may have harmful effects on organisms inhabiting freshwater and marine environments as shown in Fig. 4, (Arif et al., 2022; Cao et al., 2021). In a study conducted by Dercia Santos et al. (2021), *Danio rerio* was exposed to MPs (2 mg/L) and two non-lethal concentrations of Fe (60 and 125 µg/L) for a period of 14 days post fertilization. The findings indicated that *Danio rerio* larvae that were subjected to these conditions exhibited increased vulnerability to mortality and oxidative stress. Furthermore, it was observed that the larvae experienced neurotoxicity, confirmed by the inhibition of acetylcholinesterase activity and antioxidant enzyme activity. Another study attempted to assess the impact of Fe (25 µg/L) and MPs (2 mg/L) on zebrafish, for 30 days. According to the results obtained, the antioxidant system of the brain in zebrafish was modulated by the synergistic exposure of Fe HMs and MPs; glutathione peroxidase, however, was also inhibited by Fe and MPs (Yuan et al., 2023). Furthermore, the research findings of Dércia Santos et al. (2022) demonstrated that the concurrent application of Fe and microplastic resulted in the suppression of proliferating cell nuclear antigens in zebrafish. A similar study reported that zebrafish exposed to polystyrene MPs (6:2 chlorinated polyfluorinated ether sulfonate) exhibited an increase in oxidative stress and an intensified inflammatory response to *Danio rerio* larvae (Yuan et al., 2023).

The toxicity of HMs (Cd 10 µg/L, Pb 50 µg/L, and Zn 100 µg/L) and polystyrene MPs (100 µg/L, about 1×10^3 particles/mL 2.5 µm) was evaluated in marine medaka (*Oryzias melastigma*) for a duration of 30 days. Empty follicles, follicular atresia, and changes in gene expression involving the

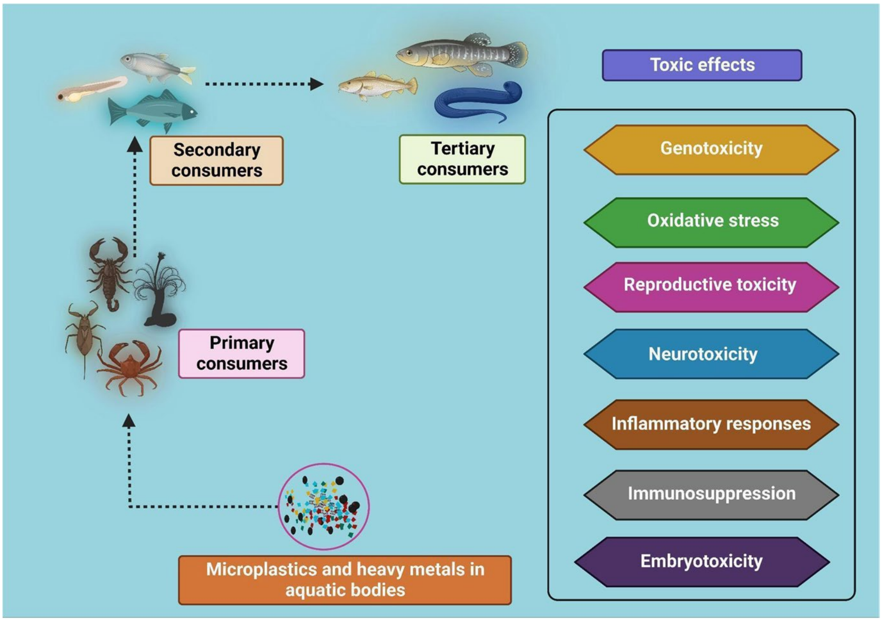

Fig. 4 The potential intoxication of aquatic organisms caused by heavy metals and microplastics

hypothalamic-pituitary–gonadal axis were among the adverse effects observed in the study (Yan et al., 2020). Additionally, a 45-day investigation was conducted to determine the effects of high-density polyethylene, Fe (0.05 mg/L), Cd (0.01 mg/L), and Pb (0.05 mg/L) on the yellow seahorse (*Hippocampus kuda*). The results found that growth and survival rates of seahorses decreased readily (Jinhui et al., 2019). The same authors also observed similar impacts in various species, including Shrimp scad (*Alepes djedaba*), Orange-spotted grouper (*Epinephelus coioides)*, Pickhandle barracuda (*Sphyraena jello*), and Bartail flathead (*Platycephalus indicus*) collected in natural environments. These species were found to contain MPs and HMs such as Hg, Cr, Zn, Mn, As, Fe, Se, Fe (Cu), Zn (Ni), vanadium (V), and Pb, which resulted in similar negative effects due to their accumulation inside their bodies (Jinhui et al., 2019). Fish can be considered model organisms for studying developmental toxicity in humans (Qiu et al., 2019). Despite limited research on higher organisms like fish in aquatic environments, they hold significant importance due to their position in the food chain and their edibility, making them a valuable model for studying combined toxicity and contaminant transformation through the food chain. Toxicity of HMs and MPs is given in Table 3.

6.2 Potential Effects on Human Beings

Digestive diseases, oxidative stress, DNA damage, immunological dysfunction, inflammation, neurological damage, cancer, cardiovascular disease, respiratory issues, dermatitis, and infertility are examples of HMs and MPs toxicity (Chang et al., 2020; Ijomone et al., 2020) as given in Fig. 5. These harmful compounds may enter the body through direct skin contact, ingesting contaminated food or water, and inhaling airborne particles (Engwa et al., 2019; Ijomone et al., 2020; Zheng et al., 2022). Additionally, MPs were found in various human consumption resources, including water, air, food, drink, and plastic (Jin et al., 2021). A study by Hwang et al. (2019) demonstrated the accumulation, which led to stimulation in the immune system and increased hypersensitivity to polypropylene MPs by the increasing cytokines and histamine levels in human HMC-1 cells. Therefore, the abundance of MPs and HMs in the environment raises concerns about the potential hazards of their co-exposure.

A study focusing on microplastic ingestion into human body was conducted by Liao et al. (2020) wherein it was concluded that microplastic consumption through a variety of dietary items, including sugar, salt, bottled water, alcohol, vegetables, fruits, and fish, has been identified as the primary route of microplastic penetration into the human body. These MPs have the potential to transport hazardous metals to human beings (Liao et al., 2020). The bio-accessibility and hazard quotients of MPs loaded with Cr(VI) and Cr(III) were investigated at several stages of digestion, including the mouth, stomach, small intestine, and large intestine. The Cr (VI) bio-accessibilities for polylactic acid were highest in the gastrointestinal, 15.6% in the small intestinal, and 3.9% in the large intestinal. The study also estimated that humans different age groups could absorb 0.50 to 1.18 g of Cr daily from microplastic use. Metal nanoparticles and MPs have also been shown to have cell-toxic effects on the human's brain, epithelial cells, and colon-rectal differentiated cells (Rahman et al., 2021). More research on the toxicity and impact of MPs and metals on human health is critical, even if the exact risks of human exposure remain poorly understood (Noventa et al., 2021).

Microplastics have been reported by several researchers and revealed that the MPs can have significant effects including oxidative stress, DNA damage, organs dysfunction, metabolic disorders, and immune response (Yue Li et al., 2023). It is generally believed that after entering the human body, the MPs would be extracted via gastrointestinal tract and biliary tract. However, scientists detected the MPs in human blood (Leslie et al., 2022). A recent study reported that MPs are transported to the whole body by blood circulation and effects spleen, liver, colon, lungs, placenta, and breastmilk (Kutralam-Muniasamy et al., 2023). In addition, the MPs act as carriers for the other contamination by adsorption processes which have adverse effects on the human body (Lee et al., 2023). Such as, the absorption of MPs and HMs in the human gut can have significant effects on good microbiota and cause dysbiosis (Fournier et al., 2023).

Table 3 Previous research based on the consequences of microplastics and heavy metals in aquatic organisms

Species	Microplastics	Microplastic size (µm)	Microplastics concentration (mg/L)	Heavy metal	Heavy metals concentration (mg/L)	Exposure time (hours)	Effects	References
Cyprinus caprio	Polyethylene	-	0.25; 0.5	Cd	0.01; 0.02	720	Immunotoxicity, reduction in plasma total protein, albumin, globulin levels. Activity of acetylcholinesterase and gamma-glutamyl-transferase reduction	(Banaee et al., 2023)
Danio rerio	Polystyrene	0.1; 20	0.02	Fe	0.05	72; 144	Accumulation in the liver and guts, oxidative stress	(Qiao et al., 2023)
Danio rerio	Polystyrene	1–5	2	Cd	0.025	720	DNA damage decreased SOD activity, increased oxidative stress	(Dércia Santos et al., 2022)
Clarias gariepinus	Polyamide 12, Polylactic acid	-	-	Fe, Pb	0.050 0.060	2190	Reduced immunity, oxidative stress, deposition in gill, liver and intestine	(Jang et al., 2022)
Danio rerio	Microspheres	1–5	2	Fe	0.06; 0.125	504	Induced oxidative stress and increased mortality in zebrafish larvae	(Dercia Santos et al., 2021)

Table 3 (continued)

Species	Microplastics	Microplastic size (µm)	Microplastics concentration (mg/L)	Heavy metal	Heavy metals concentration (mg/L)	Exposure time (hours)	Effects	References
Chlorella vulgaris	Polystyrene	0.5	1,5, 50, 100, 1000	Fe, Zn, Mn	0.25	432	The highest percentage with combinations of heavy metals and MPs was found to be 70.43% inhibition in growth and 64.09% in chlorophyll content. Lower concentrations of MPs did not show any effect	(Tunali et al., 2020)
Danio rerio	Polystyrene	0, 0.05, 0.1, 1, 5, 10	0.05, 0.1, 1, 5, 10	Cd	0, 0.01	8, 32, 96	Antagonistic toxicity on mortality, negative impacts on heart rate and survival	(Zhang et al., 2020)
Danio rerio	Polystyrene	0.1	0.02, 0.002	Pb	0.05	504	Cytotoxicity, oxidative stress, altered lipid metabolism, disturbed immunological responses	(Yu et al., 2020)
Ruditapes philippinarum	Polyethylene	10–45	0.025	Hg	0.01	96	Accumulation in the digestive system and gills, immune modulation, and oxidative stress	(Sıkdokur et al., 2020)
Daphnia magna	Polystyrene	10; 50	0, 0.01, 0.1, 1, 10, 100, 500, and 1000	Zn, Cd, Fe, Pb	10, 20, 30, 40, and 50	0, 1, 2, 4, 8, 12, 18, 24, 36, 48, 60, and 72	Antagonistic toxicity with more affinity of MPs to Pb > copper > Cd > Zn	(Yuan et al., 2020)

Table 3 (continued)

Species	Microplastics	Microplastic size (µm)	Microplastics concentration (mg/L)	Heavy metal	Heavy metals concentration (mg/L)	Exposure time (hours)	Effects	References
Euglena gracilis	Polystyrene	0.1; 5	1	Cd	0.5	96	Growth inhibition, oxidative damage, and lower pigment concentrations during photosynthesis	(Liao et al., 2020)
Prochilodus lineatus	Polyethylene	10–90	0.02	Fe	0.01	24, 96	DNA damage and decreased brain AChE activity, genotoxicity, decrease in lipid peroxidation, neurotoxicity, DNA damage in erythrocytes (96 h), and DNA damage in liver cells (24 and 96 h)	(Roda et al., 2020)
Hippocampus kuda Bleeker	High-density polyethylene	15–80	33.33	Fe, Cd, Pb	0.05 0.01 0.05	0.5, 1, 2, 4, 6, 8, 10, and 12	Reduced growth, decreased body weight, oxidative stress	(Jinhui et al., 2019)
Chlorella vulgaris	Polyvinyl chloride (UV- aged)	97–183	10	Fe	0.5	120, 240	Inhibited growth with a growth inhibition ratio of 35.26%, oxidative stress	(Fu et al., 2019)
Danio rerio	Polystyrene	5	20 & 200	Cd	0.01	72	Inflammation, ROS, increased deposition of Cd in organs including the liver, gut, gills	(Lu et al., 2018)
Mytilus galloprovincialis	High-density polyethylene	10–44	2	Hg	10	24, 48, 96 and 168	Accumulation in gills, translocation to glands	(Rivera-Hernández et al., 2019)

Table 3 (continued)

Species	Microplastics	Microplastic size (μm)	Microplastics concentration (mg/L)	Heavy metal	Heavy metals concentration (mg/L)	Exposure time (hours)	Effects	References
Pomatoschistus microps	Polyethylene	1–5	0.14	Cd	3, 6, 13, 25, 50	96	Lipid oxidative damage, neurotoxicity, reduced PEPP, and AChE activity	(Miranda et al., 2019)
Danio rerio	Polystyrene	0.05; 0.2; 0.5	100	Gold	0.05; 0.1; 0.5; 1; 2; 10	24	Mitochondrial damage, oxidative stress, embryotoxicity, reduced growth, accumulation in the whole body	(Lee et al., 2019)
Corbicula fluminea	Polymer microspheres	1–5	0.13	Hg	0.03	336	Accumulation in gills and digestive system, neurotoxicity, oxidative stress	(Oliveira et al., 2018)
Symphysodon aeqifasciatus	Polystyrene	32–40	0.05; 0.5	Cd	0.05	720	Oxidative stress and innate immunity stimulation	(Wen et al., 2018)
Daphnia magna	Polystyrene	0.194	1; 5; 10; 30	Zn	1; 2; 3; 4; 5	48	Accumulation in organs, toxicity	(Kim et al., 2017)
Tetraselmis chuii	Polyethylene	1–5	0.184–1.47	Fe	0.02; 0.04; 0.08; 0.16; 0.32 and 0.64	24, 48, 72, 96	Decreased growth	(Davarpanah & Guilhermino, 2015)
Danio rerio	Polyethylene	10–106	10, 100, 1000	Cd	0.001	4, 24	Accumulation in the intestine, gills, and body	(Khan et al., 2015)

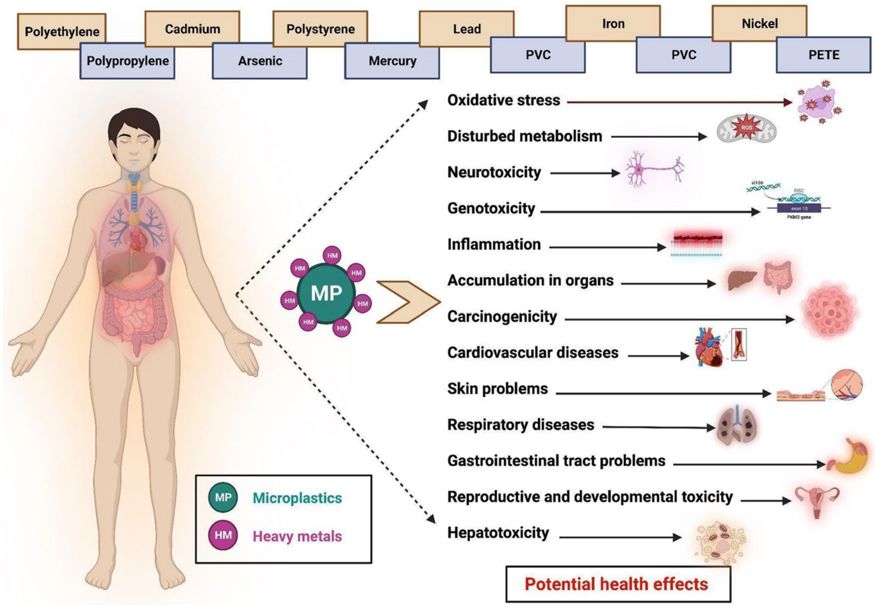

Fig. 5 Potential effects of microplastics and heavy metals on human beings

7 Future Recommendations and Perspectives

To tackle the intricate matter of interactions between MPs and HMs, it is crucial to explore numerous significant future avenues. Firstly, it is necessary to expand research efforts to encompass a broader range of environments, particularly terrestrial ecosystems, to better understand the extent and impact of these interactions beyond aquatic systems. This would probably help identify contamination hotspots and sources of exposure in different ecological settings. Additionally, long-term studies are worth assessing the influence of MPs and HMs on food chains and human health, including potential risks associated with consuming contaminated food. More research is required to understand the complex mechanism and correlation between MPs and HMs. This includes investigating the variables that influence interactions, such as environmental conditions and the types, sizes, and concentrations of MPs involved. Conduction of comprehensive toxicity assessments to investigate the interactions between MPs, HMs, and organisms at different stages of the food chain is equally essential. Evaluation of hazardous effects of HMs and MPs on ecosystems requires critical evaluation of both short-term and long-term exposures, likely affecting different trophic levels.

The mitigation strategies majorly focus on minimizing and inhibiting the MPs and HMs in the aquatic ecosystems, especially the marine environment. The promotion of sustainable alternatives to plastic products and the implementation of restrictions on industrial wastes is imperative. Physical, chemical, and biological remediation techniques are being used for solving the problem of heavy metals and microplastics. However, the physical methods like sedimentation, magnetic separation, centrifugation, and flotation are not very effective. Chemical methods like adsorption, advanced oxidation processes, and oxidation/ reduction reactions used in mitigating MPs and HMs are effective, but are a matter of concern and pose a significant environmental threat. Moreover, attention should be given to biological techniques such as bioremediation, microbial degradation and enzymatic treatment, as they are comparatively safer. Biological filtration, biofilms, biological aggregation and phytoremediation are significant eco-friendly techniques used to degrade or break down MPs and eliminate the HMs from water bodies. In addition, many plants like water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna minor*), and watercress (*Nasturtium officinale*) can absorb HMs using roots and bioaccumulation, which microorganisms further degrade. The beneficial microorganisms can also be used as a synergistic biofiltration system with chemicals to filter MPs and HMs from water bodies. Hence, attention should be given to biological sources to utilize them in mitigating HMs and MPs from the water.

Understanding the mechanisms of heavy metal adsorption onto MPs and their subsequent toxicity to aquatic organisms is an essential area of future research on the fate and toxic effects of HMs and MPs in aquatic environments. It is important to create procedures for monitoring and conducting research on these detrimental compounds. Additional safeguards against HMs and MPs should be enforced by legislation and regulatory frameworks. Beside all these, there are several limitations for the study "Interactions between microplastic and heavy metals in the aquatic environment" which could be the research bias, for instance, there may be differences in laboratory conditions and field studies. Secondly, the interactions of HMs and MPs may generate byproducts whose entities might not be known. Thirdly, the combined effects of both the pollutants (HMs and MPs) especially when human bodies and animal species are considered remains unclear. Fourthly, concentration of pollutants being very less in the environment, does not give uniformly generated data. Lastly, the units considered for the measurement of microplastics in water are very confusing like items/L, mg/L and items per unit area etc. Thus, it is important to study in depth interactions between MPs and HMs in-vitro and in-vivo conditions so as to assess the multiple levels at which the damage is being done.

8 Conclusions

This compiled literature study emphasizes the significance of HMs and microplastic interactions in aquatic ecosystems while focussing on the serious hazards they pose to the well-being of humans and the ecosystem. MPs will likely influence HMs absorption, toxicity, accumulation, and transport. Several factors influence sorption capabilities, including solution pH, temperature, salinity, surface properties, polymer type, exposure duration, size, concentration and other environmental conditions in the water. Higher temperatures favored high adsorption rates in maximum number of studies. Also, pH conditions are still a complex subject in terms of HM adsorption on MPs as it is dependent on surface charge, chemical speciation, competing reactions and hydrophobicity. Furthermore, altered surface morphology, crystallinity, and oxygen-containing functional groups of MPs due to degradation or ageing processes led to greater adsorption of HMs. Little is known about the variables influencing these interactions, even though the processes by which various HMs interact with certain MPs can be varied and complex. When MPs and/or HMs co-exist, the negative effects on organisms may be synergistically increased dose- or size-dependent. Aquatic animals are likely to suffer negative effects from HMs and microplastic exposure, including stunted growth, decreased reproduction, higher stress levels, altered behavior, and other health problems. However, further research studies are needed to develop effective remediation strategies for removing these pollutants. A novel approach, for instance, nanotechnology, including nanotubes and metallic nanomaterials, is likely to hold and has considerable potential for removing toxic materials from the ecosystem. It is important to fill the missing knowledge gaps between laboratory-scale studies and real-world water environments.

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Data Availability The dataset generated and analyzed during the current study are available from the corresponding authors on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interest.

References

Abbasi, S., Moore, F., Keshavarzi, B., Hopke, P. K., Naidu, R., Rahman, M. M., et al. (2020). PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. *Science of the Total Environment, 744*, 140984.

Aghilinasrollahabadi, K., Salehi, M., & Fujiwara, T. (2021). Investigate the influence of microplastics weathering on their heavy metals uptake in stormwater. *Journal of Hazardous Materials, 408*, 124439.

Ahamed, T., Brown, S. P., & Salehi, M. (2020). Investigate the role of biofilm and water chemistry on lead deposition onto and release from polyethylene: An implication for potable water pipes. *Journal of Hazardous Materials, 400*, 123253.

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., et al. (2014). Biochar as a sorbent for

contaminant management in soil and water: A review. *Chemosphere, 99*, 19–33.
Ahmed, F., Hasan, S., Rana, M. S., & Sharmin, N. (2023). A conceptual framework for zero waste management in Bangladesh. *International Journal of Environmental Science and Technology, 20*(2), 1887–1904.
Aljaibachi, R., Laird, W. B., Stevens, F., & Callaghan, A. (2020). Impacts of polystyrene microplastics on Daphnia magna: A laboratory and a mesocosm study. *Science of the Total Environment, 705*, 135800.
Amini-Birami, F., Keshavarzi, B., Esmaeili, H. R., Moore, F., Busquets, R., Saemi-Komsari, M., et al. (2023). Microplastics in aquatic species of Anzali wetland: An important freshwater biodiversity hotspot in Iran. *Environmental Pollution, 330*, 121762.
Arif, I., Shang, Y., Zhang, C., Khan, F. U., Tan, K. A., Waiho, K., et al. (2022). Combined effects of nanoplastics and heavy metal on antioxidant parameters of juvenile tri-spine horseshoe crabs. *Frontiers in Marine Science, 9*, 1005820.
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. https://doi.org/10.1016/j.marpolbul.2010.07.014
Attaelmanan, A. G., Aslam, H., Ali, T., & Dronjak, L. (2023). Mapping of heavy metal contamination associated to microplastics marine debris-A case study: Dubai, UAE. *Science of The Total Environment*, 164370.
Bai, B., Bai, F., Sun, C., Nie, Q., & Sun, S. (2023). Adsorption mechanism of shell powders on heavy metal ions Pb2+/Cd2+ and the purification efficiency for contaminated soils. *Frontiers in Earth Science, 10*, 1071228.
Banaee, M., Zeidi, A., Sinha, R., & Faggio, C. (2023). Individual and Combined Toxic Effects of Nano-ZnO and Polyethylene Microplastics on Mosquito Fish (Gambusia holbrooki). *Water, 15*(9), 1660.
Bhattacharya, P., Lin, S., Turner, J. P., & Ke, P. C. (2010). Physical adsorption of charged plastic nanoparticles affects algal photosynthesis. *The Journal of Physical Chemistry C, 114*(39), 16556–16561.
Binda, G., Spanu, D., Monticelli, D., Pozzi, A., Bellasi, A., Bettinetti, R., et al. (2021). Unfolding the interaction between microplastics and (trace) elements in water: A critical review. *Water Research, 204*, 117637.
Birch, Q. T., Potter, P. M., Pinto, P. X., Dionysiou, D. D., & Al-Abed, S. R. (2020). Sources, transport, measurement and impact of nano and microplastics in urban watersheds. *Reviews in Environmental Science and Bio/Technology, 19*, 275–336.
Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., ... & Rochman, C. M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*, *369*(6510), 1515–1518.
Camarero, L., Bacardit, M., de Diego, A., & Arana, G. (2017). Decadal trends in atmospheric deposition in a high elevation station: Effects of climate and pollution on the long-range flux of metals and trace elements over SW Europe. *Atmospheric Environment*, *167*, 542–552. https://doi.org/10.1016/j.atmosenv.2017.08.049
Cao, Y., Zhao, M., Ma, X., Song, Y., Zuo, S., Li, H., & Deng, W. (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.
Carrasco-Navarro, V., Muñiz-González, A.-B., Sorvari, J., & Martínez-Guitarte, J.-L. (2021). Altered gene expression in Chironomus riparius (insecta) in response to tire rubber and polystyrene microplastics. *Environmental Pollution*, *285*, 117462. https://doi.org/10.1016/j.envpol.2021.117462
Chang, X., Xue, Y., Li, J., Zou, L., & Tang, M. (2020). Potential health impact of environmental micro-and nanoplastics pollution. *Journal of Applied Toxicology, 40*(1), 4–15.
Chen, C., Wei, F., Ye, L., Wang, Y., Long, L., Xu, C., et al. (2022). Adsorption of Cu2+ by UV aged polystyrene in aqueous solution. *Ecotoxicology and Environmental Safety, 232*, 113292.
Chen, H., Hua, X., Li, H., Wang, C., Dang, Y., Ding, P., & Yu, Y. (2021). Transgenerational neurotoxicity of polystyrene microplastics induced by oxidative stress in Caenorhabditis elegans. *Chemosphere, 272*, 129642.
Cormier, B., Cachot, J., Blanc, M., Cabar, M., Clérandeau, C., Dubocq, F., et al. (2022). Environmental microplastics disrupt swimming activity in acute exposure in Danio rerio larvae and reduce growth and reproduction success in chronic exposure in D. rerio and Oryzias melastigma. *Environmental Pollution*, *308*, 119721.
da Costa Araujo, A. P., & Malafaia, G. (2021). Microplastic ingestion induces behavioral disorders in mice: A preliminary study on the trophic transfer effects via tadpoles and fish. *Journal of Hazardous Materials, 401*, 123263.
Davarpanah, E., & Guilhermino, L. (2015). Single and combined effects of microplastics and copper on the population growth of the marine microalgae Tetraselmis chuii. *Estuarine, Coastal and Shelf Science, 167*, 269–275.
Demiraj, E., Libutti, A., Malltezi, J., Rroço, E., Brahushi, F., Monteleone, M., & Sulçe, S. (2018). Effect of organic amendments on nitrate leaching mitigation in a sandy loam soil of Shkodra district. *Albania. Italian Journal of Agronomy, 13*(1), 93–102.
Deng, J., Guo, P., Zhang, X., Su, H., Zhang, Y., Wu, Y., & Li, Y. (2020). Microplastics and accumulated heavy metals in restored mangrove wetland surface sediments at Jinjiang Estuary (Fujian, China). *Marine Pollution Bulletin, 159*, 111482.
Dimitriadi, A., Papaefthimiou, C., Genizegkini, E., Sampsonidis, I., Kalogiannis, S., Feidantsis, K., et al. (2021). Adverse effects polystyrene microplastics exert on zebrafish heart–Molecular to individual level. *Journal of Hazardous Materials, 416*, 125969.
Dixit, R., Malaviya, D., Pandiyan, K., Singh, U. B., Sahu, A., Shukla, R., et al. (2015). Bioremediation of heavy metals from soil and aquatic environment: An overview of principles and criteria of fundamental processes. *Sustainability, 7*(2), 2189–2212.
Dobaradaran, S., Schmidt, T. C., Nabipour, I., Khajeahmadi, N., Tajbakhsh, S., Saeedi, R., et al. (2018). Characterization of plastic debris and association of metals with microplastics in coastline sediment along the Persian Gulf. *Waste Management*, *78*, 649–658. https://doi.org/10.1016/j.wasman.2018.06.037

Dong, Y., Gao, M., Song, Z., & Qiu, W. (2019). Adsorption mechanism of As (III) on polytetrafluoroethylene particles of different size. *Environmental Pollution, 254*, 112950.

Dong, Y., Gao, M., Song, Z., & Qiu, W. (2020). As (III) adsorption onto different-sized polystyrene microplastic particles and its mechanism. *Chemosphere, 239*, 124792.

Engwa, G. A., Ferdinand, P. U., Nwalo, F. N., & Unachukwu, M. N. (2019). Mechanism and health effects of heavy metal toxicity in humans. *Poisoning in the Modern World-New Tricks for an Old Dog, 10*, 70–90.

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., & Stohl, A. (2020). Atmospheric transport is a major pathway of microplastics to remote regions. *Nature Communications, 11*(1), 3381.

Fournier, E., Leveque, M., Ruiz, P., Ratel, J., Durif, C., Chalancon, S., et al. (2023). Microplastics: What happens in the human digestive tract? First evidences in adults using in vitro gut models. *Journal of Hazardous Materials, 442*, 130010.

Fu, D., Zhang, Q., Fan, Z., Qi, H., Wang, Z., & Peng, L. (2019). Aged microplastics polyvinyl chloride interact with copper and cause oxidative stress towards microalgae Chlorella vulgaris. *Aquatic Toxicology, 216*, 105319.

Guan, J., Qi, K., Wang, J., Wang, W., Wang, Z., Lu, N., & Qu, J. (2020). Microplastics as an emerging anthropogenic vector of trace metals in freshwater: Significance of biofilms and comparison with natural substrates. *Water Research, 184*, 116205.

Guo, X., Hu, G., Fan, X., & Jia, H. (2020). Sorption properties of cadmium on microplastics: The common practice experiment and a two-dimensional correlation spectroscopic study. *Ecotoxicology and Environmental Safety, 190*, 110118.

Guo, X., & Wang, J. (2019). The chemical behaviors of microplastics in marine environment: A review. *Marine Pollution Bulletin, 142*, 1–14.

Guo, Z., Li, P., Yang, X., Wang, Z., Lu, B., Chen, W., et al. (2022). Soil texture is an important factor determining how microplastics affect soil hydraulic characteristics. *Environment International, 165*, 107293.

He, S., Jia, M., Xiang, Y., Song, B., Xiong, W., Cao, J., et al. (2022). Biofilm on microplastics in aqueous environment: Physicochemical properties and environmental implications. *Journal of Hazardous Materials*, *424*, 127286. https://doi.org/10.1016/j.jhazmat.2021.127286

Hodson, M. E., Duffus-Hodson, C. A., Clark, A., Prendergast-Miller, M. T., & Thorpe, K. L. (2017). Plastic Bag Derived-Microplastics as a Vector for Metal Exposure in Terrestrial Invertebrates. *Environmental Science & Technology, 51*(8), 4714–4721. https://doi.org/10.1021/acs.est.7b00635

Holmes, L. A., Turner, A., & Thompson, R. C. (2012). Adsorption of trace metals to plastic resin pellets in the marine environment. *Environmental Pollution*, *160*, 42–48. https://doi.org/10.1016/j.envpol.2011.08.052

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

Huang, W., Song, B., Liang, J., Niu, Q., Zeng, G., Shen, M., et al. (2021b). Microplastics and associated contaminants in the aquatic environment: A review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. *Journal of Hazardous Materials, 405*, 124187.

Huang, X., Zemlyanov, D. Y., Diaz-Amaya, S., Salehi, M., Stanciu, L., & Whelton, A. J. (2020). Competitive heavy metal adsorption onto new and aged polyethylene under various drinking water conditions. *Journal of Hazardous Materials, 385*, 121585.

Hwang, J., Choi, D., Han, S., Choi, J., & Hong, J. (2019). An assessment of the toxicity of polypropylene microplastics in human derived cells. *Science of the Total Environment, 684*, 657–669.

Ijomone, O. M., Olung, N. F., Akingbade, G. T., Okoh, C. O. A., & Aschner, M. (2020). Environmental influence on neurodevelopmental disorders: Potential association of heavy metal exposure and autism. *Journal of Trace Elements in Medicine and Biology, 62*, 126638.

Ikai, A. (2017). Interaction Forces. In *The World of Nano-Biomechanics* (pp. 63–76). Elsevier.

Imhof, H. K., Laforsch, C., Wiesheu, A. C., Schmid, J., Anger, P. M., Niessner, R., & Ivleva, N. P. (2016). Pigments and plastic in limnetic ecosystems: A qualitative and quantitative study on microparticles of different size classes. *Water Research*, *98*, 64–74. https://doi.org/10.1016/j.watres.2016.03.015

Ingham, A. (2022). Lone pair activity, versatility, and charge: lessons from chelators designed for radiopharmaceuticals. University of British Columbia.

Inyang, M. I., Gao, B., Yao, Y., Xue, Y., Zimmerman, A., Mosa, A., et al. (2016). A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. *Critical Reviews in Environmental Science and Technology, 46*(4), 406–433.

Ivanets, A., Kitikova, N., Shashkova, I., Matrunchik, Y., & Kul'bitskaya, L., & Sillanpää, M. (2016). Non-acidic synthesis of phosphatized dolomite and its sorption behaviour towards Pb 2+, Zn2+, Cu2+, Cd2+, Ni2+, Sr2+ and Co2+ ions in multicomponent aqueous solution. *Environmental Technology & Innovation, 6*, 152–164.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science, 347*(6223), 768–771.

Jang, F. H., Wong, C., Choo, J., Sia, E. S. A., Mujahid, A., & Müller, M. (2022). Increased transfer of trace metals and Vibrio sp. from biodegradable microplastics to catfish Clarias gariepinus. *Environmental Pollution*, *298*, 118850.

Jardak, K., Drogui, P., & Daghrir, R. (2016). Surfactants in aquatic and terrestrial environment: Occurrence, behavior, and treatment processes. *Environmental Science and Pollution Research, 23*, 3195–3216.

Jeyasanta, K. I., Sathish, N., Patterson, J., & Edward, J. K. P. (2020). Macro-, meso-and microplastic debris in the beaches of Tuticorin district, Southeast coast of India. *Marine Pollution Bulletin, 154*, 111055.

Ji, C., Wu, D., Lu, J., Shan, C., Ren, Y., Li, T., et al. (2021). Temperature regulated adsorption and desorption of heavy metals to A-MIL-121: Mechanisms and the role of exchangeable protons. *Water Research*, *189*, 116599. https://doi.org/10.1016/j.watres.2020.116599

Jiang, C., Yin, L., Li, Z., Wen, X., Luo, X., Hu, S., et al. (2019). Microplastic pollution in the rivers of the Tibet Plateau. *Environmental Pollution, 249*, 91–98.

Jin, M., Wang, X., Ren, T., Wang, J., & Shan, J. (2021). Microplastics contamination in food and beverages: Direct exposure to humans. *Journal of Food Science, 86*(7), 2816–2837.

Jinhui, S., Sudong, X., Yan, N., Xia, P., Jiahao, Q., & Yongjian, X. (2019). Effects of microplastics and attached heavy metals on growth, immunity, and heavy metal accumulation in the yellow seahorse. *Hippocampus Kuda Bleeker. Marine Pollution Bulletin, 149*, 110510.

Kakakhel, M. A., Bibi, N., Mahboub, H. H., Wu, F., Sajjad, W., Din, S. Z. U., et al. (2023a). Influence of biosynthesized nanoparticles exposure on mortality, residual deposition, and intestinal bacterial dysbiosis in Cyprinus carpio. *Comparative Biochemistry and Physiology Part c: Toxicology & Pharmacology, 263*, 109473. https://doi.org/10.1016/j.cbpc.2022.109473

Kakakhel, M. A., Narwal, N., Kataria, N., Johari, S. A., Din, Z. U., S., Jiang, Z., et al. (2023b). Deciphering the dysbiosis caused in the fish microbiota by emerging contaminants and its mitigation strategies-A review. *Environmental Research, 237*, 117002. https://doi.org/10.1016/j.envres.2023.117002

Kalčíková, G., Skalar, T., Marolt, G., & Kokalj, A. J. (2020). An environmental concentration of aged microplastics with adsorbed silver significantly affects aquatic organisms. *Water Research, 175*, 115644.

Karami, A., Golieskardi, A., Choo, C. K., Larat, V., Karbalaei, S., & Salamatinia, B. (2018). Microplastic and mesoplastic contamination in canned sardines and sprats. *Science of the Total Environment, 612*, 1380–1386.

Karapanagioti, H. K., & Rios-Mendoza, L. M. (2022). Sorption of Pollutants on Microplastics. In *Handbook of Microplastics in the Environment* (pp. 517–529). Springer.

Kayiranga, A., Li, Z., Isabwe, A., Ke, X., Simbi, C. H., Ifon, B. E., et al. (2023). The Effects of Heavy Metal Pollution on Collembola in Urban Soils and Associated Recovery Using Biochar Remediation: A Review. *International Journal of Environmental Research and Public Health, 20*(4), 3077.

Khalid, N., Aqeel, M., & Noman, A. (2020). Microplastics could be a threat to plants in terrestrial systems directly or indirectly. *Environmental Pollution, 267*, 115653.

Khalid, N., Aqeel, M., Noman, A., Hashem, M., Mostafa, Y. S., Alhaithloul, H. A. S., & Alghanem, S. M. (2021a). Linking effects of microplastics to ecological impacts in marine environments. *Chemosphere, 264*, 128541.

Khalid, N., Rizvi, Z. F., Yousaf, N., Khan, S. M., Noman, A., Aqeel, M., et al. (2021b). Rising metals concentration in the environment: A response to effluents of leather industries in Sialkot. *Bulletin of Environmental Contamination and Toxicology, 106*, 493–500.

Khan, F. R., Syberg, K., Shashoua, Y., & Bury, N. R. (2015). Influence of polyethylene microplastic beads on the uptake and localization of silver in zebrafish (Danio rerio). *Environmental Pollution, 206*, 73–79.

Kim, D., Chae, Y., & An, Y.-J. (2017). Mixture toxicity of nickel and microplastics with different functional groups on Daphnia magna. *Environmental Science & Technology, 51*(21), 12852–12858.

Kutralam-Muniasamy, G., Shruti, V. C., Pérez-Guevara, F., & Roy, P. D. (2023). Microplastic diagnostics in humans:"The 3Ps" Progress, problems, and prospects. *Science of the Total Environment, 856*, 159164.

Lau, W. W., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., ... & Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. *Science, 369*(6510), 1455–1461.

Lee, W. S., Cho, H.-J., Kim, E., Huh, Y. H., Kim, H.-J., Kim, B., et al. (2019). Bioaccumulation of polystyrene nanoplastics and their effect on the toxicity of Au ions in zebrafish embryos. *Nanoscale, 11*(7), 3173–3185.

Lee, Y., Cho, J., Sohn, J., & Kim, C. (2023). Health effects of microplastic exposures: Current issues and perspectives in South Korea. *Yonsei Medical Journal, 64*(5), 301.

Lehtiniemi, M., Hartikainen, S., Näkki, P., Engström-Öst, J., Koistinen, A., & Setälä, O. (2018). Size matters more than shape: Ingestion of primary and secondary microplastics by small predators. *Food Webs, 17*, e00097.

Leslie, H. A., Van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International, 163*, 107199.

Li, W., Lo, H.-S., Wong, H.-M., Zhou, M., Wong, C.-Y., Tam, N.F.-Y., & Cheung, S.-G. (2020). Heavy metals contamination of sedimentary microplastics in Hong Kong. *Marine Pollution Bulletin, 153*, 110977.

Li, Y., Tao, L., Wang, Q., Wang, F., Li, G., & Song, M. (2023). Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects. *Environment & Health, 1*(4), 249–257. https://doi.org/10.1021/envhealth.3c00052

Li, Y., Zhang, Y., Su, F., Wang, Y., Peng, L., & Liu, D. (2022). Adsorption behaviour of microplastics on the heavy metal Cr (VI) before and after ageing. *Chemosphere, 302*, 134865.

Liao, Y., Jiang, X., Xiao, Y., & Li, M. (2020). Exposure of microalgae Euglena gracilis to polystyrene microbeads and cadmium: Perspective from the physiological and transcriptional responses. *Aquatic Toxicology, 228*, 105650.

Lin, Z., Hu, Y., Yuan, Y., Hu, B., & Wang, B. (2021). Comparative analysis of kinetics and mechanisms for Pb (II) sorption onto three kinds of microplastics. *Ecotoxicology and Environmental Safety, 208*, 111451.

Liu, Q., Wu, H., Chen, J., Guo, B., Zhao, X., Lin, H., et al. (2022a). Adsorption mechanism of trace heavy metals on microplastics and simulating their effect on microalgae in river. *Environmental Research, 214*, 113777.

Liu, S., Huang, J., Zhang, W., Shi, L., Yi, K., Yu, H., et al. (2022b). Microplastics as a vehicle of heavy metals in aquatic environments: A review of adsorption factors, mechanisms, and biological effects. *Journal of Environmental Management, 302*, 113995.

Liu, S., Huang, J., Zhang, W., Shi, L., Yi, K., Zhang, C., et al. (2022c). Investigation of the adsorption behavior of Pb (II) onto natural-aged microplastics as affected by salt ions. *Journal of Hazardous Materials, 431*, 128643.

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.

Maršić-Lučić, J., Lušić, J., Tutman, P., Bojanić Varezić, D., Šiljić, J., & Pribudić, J. (2018). Levels of trace metals on microplastic particles in beach sediments of the island of Vis, Adriatic Sea, Croatia. *Marine Pollution Bulletin*, *137*, 231–236. https://doi.org/10.1016/j.marpolbul.2018.10.027

Massos, A., & Turner, A. (2017). Cadmium, lead and bromine in beached microplastics. *Environmental Pollution*, *227*, 139–145. https://doi.org/10.1016/j.envpol.2017.04.034

Miranda, T., Vieira, L. R., & Guilhermino, L. (2019). Neurotoxicity, behavior, and lethal effects of cadmium, microplastics, and their mixtures on Pomatoschistus microps juveniles from two wild populations exposed under laboratory conditions-implications to environmental and human risk assessment. *International Journal of Environmental Research and Public Health, 16*(16), 2857.

Musilova, J., Arvay, J., Vollmannova, A., Toth, T., & Tomas, J. (2016). Environmental contamination by heavy metals in region with previous mining activity. *Bulletin of Environmental Contamination and Toxicology, 97*, 569–575.

Nakashima, E., Isobe, A., Kako, S., Itai, T., & Takahashi, S. (2012). Quantification of Toxic Metals Derived from Macroplastic Litter on Ookushi Beach. *Japan. Environmental Science & Technology, 46*(18), 10099–10105. https://doi.org/10.1021/es301362g

Noventa, S., Boyles, M. S. P., Seifert, A., Belluco, S., Jiménez, A. S., Johnston, H. J., et al. (2021). Paradigms to assess the human health risks of nano-and microplastics. *Microplastics and Nanoplastics, 1*(1), 1–27.

Oliveira, P., Barboza, L. G. A., Branco, V., Figueiredo, N., Carvalho, C., & Guilhermino, L. (2018). Effects of microplastics and mercury in the freshwater bivalve Corbicula fluminea (Müller, 1774): Filtration rate, biochemical biomarkers and mercury bioconcentration. *Ecotoxicology and Environmental Safety, 164*, 155–163.

Pandiyan, P., Balaraman, D., Thirunavukkarasu, R., George, E. G. J., Subaramaniyan, K., Manikkam, S., & Sadayappan, B. (2013). Probiotics in aquaculture. *Drug Invention Today*, *5*(1), 55–59. https://doi.org/10.1016/j.dit.2013.03.003

Purwiyanto, A. I. S., Suteja, Y., Ningrum, P. S., Putri, W. A. E., Agustriani, F., Cordova, M. R., & Koropitan, A. F. (2020). Concentration and adsorption of Pb and Cu in microplastics: Case study in aquatic environment. *Marine Pollution Bulletin, 158*, 111380.

Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: a comprehensive and critical review. *npj Clean Water*, *4*(1), 36. https://doi.org/10.1038/s41545-021-00127-0

Qiao, P., Wang, S., Li, J., Zhao, Q., Wei, Y., Lei, M., et al. (2023). Process, influencing factors, and simulation of the lateral transport of heavy metals in surface runoff in a mining area driven by rainfall: A review. *Science of the Total Environment, 857*, 159119.

Qiu, H., Hu, J., Zhang, R., Gong, W., Yu, Y., & Gao, H. (2019). The photocatalytic degradation of diesel by solar light-driven floating BiOI/EP composites. *Colloids and Surfaces a: Physicochemical and Engineering Aspects, 583*, 123996.

Rahman, A., Sarkar, A., Yadav, O. P., 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.

Rivera-Hernández, J. R., Fernández, B., Santos-Echeandia, J., Garrido, S., Morante, M., Santos, P., & Albentosa, M. (2019). Biodynamics of mercury in mussel tissues as a function of exposure pathway: Natural vs microplastic routes. *Science of the Total Environment, 674*, 412–423.

Roch, S., Friedrich, C., & Brinker, A. (2020). Uptake routes of microplastics in fishes: Practical and theoretical approaches to test existing theories. *Scientific Reports, 10*(1), 3896. https://doi.org/10.1038/s41598-020-60630-1

Roda, J. F. B., Lauer, M. M., Risso, W. E., & dos Reis Martinez, C. B. (2020). Microplastics and copper effects on the neotropical teleost Prochilodus lineatus: Is there any interaction? *Comparative Biochemistry and Physiology Part a: Molecular & Integrative Physiology, 242*, 110659.

Rose, P. K., Yadav, S., Kataria, N., & Khoo, K. S. (2023a). Microplastics and nanoplastics in the terrestrial food chain: Uptake, translocation, trophic transfer, ecotoxicology, and human health risk. *TrAC Trends in Analytical Chemistry*, *167*, 117249. https://doi.org/10.1016/j.trac.2023.117249

Rose, P. K., Jain, M., Kataria, N., Sahoo, P. K., Garg, V. K., & Yadav, A. (2023b). Microplastics in multimedia environment: A systematic review on its fate, transport, quantification, health risk, and remedial measures. *Groundwater for Sustainable Development*, *20*, 100889. https://doi.org/10.1016/j.gsd.2022.100889

Santillo, D., Miller, K., & Johnston, P. (2017). Microplastics as contaminants in commercially important seafood species. *Integrated Environmental Assessment and Management, 13*(3), 516–521.

Santos, D., Felix, L., Luzio, A., Parra, S., Bellas, J., & Monteiro, S. M. (2021). Single and combined acute and subchronic toxic effects of microplastics and copper in zebrafish (Danio rerio) early life stages. *Chemosphere, 277*, 130262.

Santos, D., Luzio, A., Félix, L., Bellas, J., & Monteiro, S. M. (2022). Oxidative stress, apoptosis and serotonergic system changes in zebrafish (Danio rerio) gills after long-term exposure to microplastics and copper. *Comparative Biochemistry and Physiology Part c: Toxicology & Pharmacology, 258*, 109363.

Santos-Echeandia, J., Rivera-Hernández, J. R., Rodrigues, J. P., & Molto, V. (2020). Interaction of mercury with beached plastics with special attention to zonation, degradation status and polymer type. *Marine Chemistry, 222*, 103788.

Sarkar, D. J., Sarkar, S. D., Das, B. K., Sahoo, B. K., Das, A., Nag, S. K., et al. (2021). Occurrence, fate and removal of microplastics as heavy metal vector in natural wastewater treatment wetland system. *Water Research, 192*, 116853.

Setälä, O., Fleming-Lehtinen, V., & Lehtiniemi, M. (2014). Ingestion and transfer of microplastics in the planktonic food web. *Environmental Pollution*, *185*, 77–83. https://doi.org/10.1016/j.envpol.2013.10.013

Shen, M., Song, B., Zeng, G., Zhang, Y., Teng, F., & Zhou, C. (2021). Surfactant changes lead adsorption behaviors and mechanisms on microplastics. *Chemical Engineering Journal, 405*, 126989.

Shi, M., Xie, Q., Li, Z.-L., Pan, Y.-F., Yuan, Z., Lin, L., et al. (2023). Adsorption of heavy metals on biodegradable and conventional microplastics in the Pearl River Estuary. *China. Environmental Pollution, 322*, 121158.

Sıkdokur, E., Belivermiş, M., Sezer, N., Pekmez, M., Bulan, Ö. K., & Kılıç, Ö. (2020). Effects of microplastics and mercury on manila clam Ruditapes philippinarum: Feeding rate, immunomodulation, histopathology and oxidative stress. *Environmental Pollution, 262*, 114247.

Singh, J., & Kalamdhad, A. S. (2011). Effects of heavy metals on soil, plants, human health and aquatic life. *Int J Res Chem Environ, 1*(2), 15–21.

Sobhani, Z., Zhang, X., Gibson, C., Naidu, R., Megharaj, M., & Fang, C. (2020). Identification and visualisation of microplastics/nanoplastics by Raman imaging (i): Down to 100 nm. *Water Research, 174*, 115658.

Sun, N., Shi, H., Li, X., Gao, C., & Liu, R. (2022). Combined toxicity of micro/nanoplastics loaded with environmental pollutants to organisms and cells: Role, effects, and mechanism. *Environment International*, 107711.

Ta, A. T., & Babel, S. (2020). Microplastic contamination on the lower Chao Phraya: Abundance, characteristic and interaction with heavy metals. *Chemosphere, 257*, 127234.

Ta, A. T., & Babel, S. (2023). Occurrence and spatial distribution of microplastic contaminated with heavy metals in a tropical river: Effect of land use and population density. *Marine Pollution Bulletin, 191*, 114919.

Tang, S., Lin, L., Wang, X., Feng, A., & Yu, A. (2020). Pb (II) uptake onto nylon microplastics: Interaction mechanism and adsorption performance. *Journal of Hazardous Materials, 386*, 121960.

Tang, S., Lin, L., Wang, X., Yu, A., & Sun, X. (2021). Interfacial interactions between collected nylon microplastics and three divalent metal ions (Cu (II), Ni (II), Zn (II)) in aqueous solutions. *Journal of Hazardous Materials, 403*, 123548.

Thakuria, R., Nath, N. K., & Saha, B. K. (2019). The Nature and Applications of π–π Interactions: A Perspective. *Crystal Growth & Design, 19*(2), 523–528. https://doi.org/10.1021/acs.cgd.8b01630

Thompson, L. A., & Darwish, W. S. (2019). Environmental chemical contaminants in food: review of a global problem. *Journal of toxicology*, *2019*.

Tunali, M., Uzoefuna, E. N., Tunali, M. M., & 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.

Turner, A., Holmes, L., Thompson, R. C., & Fisher, A. S. (2020). Metals and marine microplastics: Adsorption from the environment versus addition during manufacture, exemplified with lead. *Water Research, 173*, 115577.

Vaisakh, P. S., Adarsh, U. K., Amrutha, K., Warrier, A. K., Kartha, V. B., & Unnikrishnan, V. K. (2023). Integrated LIBS-Raman spectroscopy: A comprehensive approach to monitor microplastics and heavy metal contamination in water resources. *Environmental Research, 231*, 116198.

Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M. B., Mees, J., & Janssen, C. R. (2013). Assessment of marine debris on the Belgian Continental Shelf. *Marine Pollution Bulletin*, *73*(1), 161–169. https://doi.org/10.1016/j.marpolbul.2013.05.026

Vedolin, M. C., Teophilo, C. Y. S., Turra, A., & Figueira, R. C. L. (2018). Spatial variability in the concentrations of metals in beached microplastics. *Marine Pollution Bulletin*, *129*(2), 487–493. https://doi.org/10.1016/j.marpolbul.2017.10.019

Wang, F., Yang, W., Cheng, P., Zhang, S., Zhang, S., Jiao, W., & Sun, Y. (2019). Adsorption characteristics of cadmium onto microplastics from aqueous solutions. *Chemosphere, 235*, 1073–1080.

Wang, Q., Wangjin, X., Zhang, Y., Wang, N., Wang, Y., Meng, G., & Chen, Y. (2020a). The toxicity of virgin and UV-aged PVC microplastics on the growth of freshwater algae Chlamydomonas reinhardtii. *Science of The Total Environment*, *749*, 141603. https://doi.org/10.1016/j.scitotenv.2020.141603

Wang, F., Zhang, X., Zhang, S., Zhang, S., Adams, C. A., & Sun, Y. (2020b). Effects of co-contamination of microplastics and Cd on plant growth and Cd accumulation. *Toxics, 8*(2), 36.

Wang, Q., Zhang, Y., Wangjin, X., Wang, Y., Meng, G., & Chen, Y. (2020c). The adsorption behavior of metals in aqueous solution by microplastics effected by UV radiation. *Journal of Environmental Sciences, 87*, 272–280.

Wang, X., Zhang, R., Li, Z., & Yan, B. (2022). Adsorption properties and influencing factors of Cu (II) on polystyrene and polyethylene terephthalate microplastics in seawater. *Science of the Total Environment, 812*, 152573.

Wang, Z., Dong, H., Wang, Y., Ren, R., Qin, X., & Wang, S. (2020d). Effects of microplastics and their adsorption of cadmium as vectors on the cladoceran Moina monogolica Daday: Implications for plastic-ingesting organisms. *Journal of Hazardous Materials, 400*, 123239.

Wen, B., Jin, S.-R., Chen, Z.-Z., Gao, J.-Z., Liu, Y.-N., Liu, J.-H., & Feng, X.-S. (2018). Single and combined effects of microplastics and cadmium on the cadmium accumulation, antioxidant defence and innate immunity of the discus fish (Symphysodon aequifasciatus). *Environmental Pollution, 243*, 462–471.

Wright, S. L., Ulke, J., Font, A., Chan, K. L. A., & Kelly, F. J. (2020). Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environment International, 136*, 105411.

Xie, Q., Li, H.-X., Lin, L., Li, Z.-L., Huang, J., & Xu, X.-R. (2021). Characteristics of expanded polystyrene microplastics on island beaches in the Pearl River Estuary: abundance, size, surface texture and their metals-carrying capacity. *Ecotoxicology*, 1–12.

Xu, B., Liu, F., Brookes, P. C., & Xu, J. (2018). Microplastics play a minor role in tetracycline sorption in the presence of dissolved organic matter. *Environmental Pollution, 240*, 87–94.

Yan, W., Hamid, N., Deng, S., Jia, P.-P., & Pei, D.-S. (2020). Individual and combined toxicogenetic effects of

microplastics and heavy metals (Cd, Pb, and Zn) perturb gut microbiota homeostasis and gonadal development in marine medaka (Oryzias melastigma). *Journal of Hazardous Materials, 397*, 122795.
Yang, Z., Ma, J., Liu, F., Zhang, H., Ma, X., & He, D. (2022). Mechanistic insight into pH-dependent adsorption and coprecipitation of chelated heavy metals by in-situ formed iron (oxy)hydroxides. *Journal of Colloid and Interface Science*, *608*, 864–872. https://doi.org/10.1016/j.jcis.2021.10.039
Yao, Z., Seong, H. J., & Jang, Y.-S. (2022). Environmental toxicity and decomposition of polyethylene. *Ecotoxicology and Environmental Safety, 242*, 113933.
Yu, F., Li, Y., Huang, G., Yang, C., Chen, C., Zhou, T., et al. (2020). Adsorption behavior of the antibiotic levofloxacin on microplastics in the presence of different heavy metals in an aqueous solution. *Chemosphere, 260*, 127650.
Yuan, J., Ma, J., Sun, Y., Zhou, T., Zhao, Y., & Yu, F. (2020). Microbial degradation and other environmental aspects of microplastics/plastics. *Science of The Total Environment*, *715*, 136968. https://doi.org/10.1016/j.scitotenv.2020.136968
Yuan, F., Chen, H., Ding, Y., Wang, Y., Liao, Q., Wang, T., et al. (2023). Effects of microplastics on the toxicity of co-existing pollutants to fish: A meta-analysis. *Water Research, 240*, 120113.
Zaheer Ud Din, S., Shah, K., Bibi, N., Mahboub, H. H., & Kakakhel, M. A. (2023). Recent insights into the silver nanomaterials: an overview of their transformation in the food webs and toxicity in the aquatic ecosystem. *Water, Air, & Soil Pollution, 234*(2), 114. https://doi.org/10.1007/s11270-023-06134-w
Zhang, R., Wang, M., Chen, X., Yang, C., & Wu, L. (2020). Combined toxicity of microplastics and cadmium on the zebrafish embryos (Danio rerio). *Science of the Total Environment, 743*, 140638.
Zhang, Z., Wu, X., Liu, H., Huang, X., Chen, Q., Guo, X., & Zhang, J. (2023). A systematic review of microplastics in the environment: Sampling, separation, characterization and coexistence mechanisms with pollutants. *Science of the Total Environment, 859*, 160151.
Zheng, J., Li, C., & Zheng, X. (2022). Polystyrene microplastic ingestion induces the damage in digestive gland of Amphioctopus fangsiao at the physiological, inflammatory, metabolome and transcriptomic levels. *Environmental Pollution, 315*, 120480.
Zhou, Y., Liu, X., & Wang, J. (2019). Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. *Science of the Total Environment, 694*, 133798.
Zhou, Y., Liu, X., & Wang, J. (2020). Ecotoxicological effects of microplastics and cadmium on the earthworm Eisenia foetida. *Journal of Hazardous Materials, 392*, 122273.
Zhu, D., Chen, Q.-L., An, X.-L., Yang, X.-R., Christie, P., Ke, X., et al. (2018). Exposure of soil collembolans to microplastics perturbs their gut microbiota and alters their isotopic composition. *Soil Biology and Biochemistry, 116*, 302–310.
Zou, J., Liu, X., Zhang, D., & Yuan, X. (2020). Adsorption of three bivalent metals by four chemical distinct microplastics. *Chemosphere, 248*, 126064.