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Synergistic Impacts of Microplastics and Heavy Metals in Aquatic Environments and Strategies for Mitigation

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Abstract

One increasing environmental concern is the extensive pollution of aquatic habitats by heavy metals and microplastics. Oceans, estuaries, lakes, and even deep-sea sediments are contaminated by microplastics, which are now found from the polar regions to the equator. They come from both primary sources, like synthetic fabrics, and secondary sources, like the breakdown of bigger plastic waste. Heavy metals, introduced through industrial, agricultural, and urban activities, interact with these microplastics, particularly after the particles undergo physical and chemical weathering in aquatic environments. The surface area, size, and type of polymer of the microplastics, as well as the water's salinity and pH, all affect these interactions. This article examines the complex dynamics between microplastics and heavy metals, shedding light on their combined impact on aquatic ecosystems and the broader implications for environmental health.

Keywords:
Microplastics, Heavy metals, Environmental pollution, Contaminant interaction, Aquatic environments

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Introduction

Microplastics are extensively dispersed in a variety of environmental contexts as a result of the century-long, explosive growth in plastic production (da Costa *et al.*,2017). Microplastics are plastic particles with a diameter <5 millimeters; they are frequently the cause of contamination in aquatic settings (Chubarenko *et al.*, 2016; Elgarahy *et al.*, 2021). These "particles are found in a variety of aquatic habitats, from the equator to the poles (Barnes *et al.* 2009; Browne *et al.* 2011; Hidalgo-Ruz *et al.,* 2012), polluting the open ocean's water surface(Law *et al.,* 2010; Collignon *et al.,* 2012; Goldstein *et al.,* 2012), estuaries (Sadri and Thompson, 2014), and lakes (Eriksen *et al.,* 2013). They can also be found in subtidal sediments that reach the deep sea (Van Cauwenberghe *et al.,* 2013; Woodall *et al.* 2014), as well as on shorelines that are freshwater (Imhof *et al.,* 2013) and marine (Browne *et al.* , 2011). Because" plastic polymers are naturally durable and resistant to natural breakdown processes, the persistence of microplastics in the environment may be attributed in large part to this (Zhang *et al.*, 2021). Consequently, once introduced into the environment, plastic can remain for hundreds to thousands of years, breaking into smaller fragments rather than undergoing complete degradation (Chamas *et al.*,2020; Key,2023). Primary microplastics are released as minute particles into the environment (Wright *et al.*, 2013); secondary microplastics have been created when bigger plastic trash is broken up by mechanical processes and weathering (Andrady, 2011).

Aquatic habitats are contaminated by a variety of pollutants in addition to microplastics, such as "heavy metals(HMs) and persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs) (Liu *et al.*, 2020; Wang *et al.*, 2020). These contaminants can have an effect on ecosystems, human health, and aquatic life. They also provide extra dangers. Recent investigation has demonstrated that microplastics can absorb various contaminants, like heavy metals (Khalid *et al.*, 2021; Li *et al.*, 2022; Liu *et al.*, 2022). HM, like mercury, lead(Pb), and cadmium(Cd), are hazardous because of their high toxicity as well as persistence in the environment (Ali *et al.*, 2019). When these metals" adhere to microplastics, they can be transported across different parts of aquatic systems, increasing their bioavailability and potential harm (Khan *et al.*,2022). The detrimental impacts of HM and microplastics may be compounded by this combination, creating more difficult environmental and health issues. To effectively address the combined presence of HM and microplastics in aquatic habitats, a more dense knowledge of their interactions is required.

1. Sources and Pathways of Heavy Metals and Microplastics in Aquatic Ecosystems

1.1 Microplastics

Primary Microplastics: Primary microplastics are microscopic plastic particles that are purposefully created; they are usually smaller than 5 mm. Products include industrial abrasives (Sommer *et al.*, 2018), paint products (Turner, 2021), and microbeads in personal care goods (Godoy *et al.*, 2019; Sun *et al.*, 2020) contain them. When these products are used, these particles are released into the environment. Furthermore, when microfibers from synthetic textiles are lost after washing, primary microplastics are created. Because of their small size, these fibers can immediately enter aquatic ecosystems and pass through wastewater treatment systems (Napper, and Thompson, 2016).

Secondary Microplastics: When bigger plastic debris breaks down as a result of weathering processes like UV radiation, thermal deterioration, and mechanical abrasion, secondary microplastics are created (Song *et al.*,2017). For instance, over time, discarded plastic bottles, bags, and other big materials decompose into tiny pieces. These fragments are then transported to aquatic systems via runoff, wind dispersion, and drainage systems (Wayman *et al.*, 2021).

1.2 Heavy Metals

Industrial Discharges:

- ***Mining and Metal Processing***: The mining, smelting, and metal refining processes discharge heavy metals into the environment, like Pb, Cd, and Hg (Najaand Volesky,2017). These metals are often discharged directly into water bodies or leach into groundwater, eventually reaching surface waters (Cimboláková *et al.*, 2019).
- ***Wastewater Treatment Plants:*** Industrial effluents containing heavy metals are frequently treated in wastewater plants, but not all metals are effectively removed. Residual heavy metals can be released into aquatic systems through treated wastewater (Vardhan *et al.*, 2019).

Agricultural Runoff:

- ***Fertilizers and Pesticides***: Many fertilizers as well as pesticides contain metals like **arsenic (As)**, **copper (Cu)**, and **zinc (Zn)**. When these materials are incorporated into the soil, surface runoff and leaching during irrigation or rainstorm events can carry them into water bodies (Rashmi *et al.*, 2020).

Atmospheric Deposition:

- ***Airborne Contaminants:*** Heavy metals like **mercury** can be deposited into aquatic systems through atmospheric deposition. Metals emitted from industrial processes and combustion sources become airborne and are subsequently deposited into water bodies via precipitation (acid rain) or as dust particles (Kumar *et al.*, 2023).

Urban Runoff:

- ***Stormwater:*** Urban areas with impervious surfaces generate runoff that can carry heavy metals from roadways, construction sites, and industrial areas into stormwater systems and eventually into aquatic environments (Adedejiand Olayinka, 2013).
- ***Interaction between microplastics and heavy metals in aquatic environments***

  Due to the possible consequences for ecosystem health and public safety, the association among microplastics and HM in aquatic settings is an important subject. Although microplastics and heavy metals independently pose significant environmental risks, their combined presence in aquatic ecosystems leads to complex and potentially hazardous interactions.

  Microplastics, initially characterized by low surface reactivity, undergo significant transformations through physical and chemical weathering processes once they enter aquatic environments (Luo *et al.*, 2022). These processes, including UV radiation exposure, thermal degradation, and mechanical abrasion, alter the surface properties of microplastics, resulting in the development of negatively charged sites that are able to absorb metal ions (Godoy et al ., 2019 b; Li *et al.*, 2022). Numerous factors impact this interaction, all of which contribute to the overall dynamics of adsorption of HMs:

- **Particle Size**: The capacity of microplastic particles to absorb HMs is significantly influenced by their size. Smaller microplastics have a higher adsorption capacity because they have more sites for metal ion attachment because of their bigger specific surface area relative to their volume

(Wang *et al.*, 2019). Removing HMs from the surrounding environment is easier with smaller particles because they have greater surface area and reactive sites to interact with metal ions. (Li *et al.*, 2020)

- **Polymer Type**: Plastic polymer type has a major impact on how well it adsorps heavy metals (Bakir *et al.* 2012). Different polymers have unique chemical compositions and surface characteristics, which influence their interaction with metal ions. For example, plastics with specific functional groups or higher surface areas may demonstrate a greater propensity for metal ion binding (Cássio *et al.*, 2022; Miller and Holcombe,2001). The inherent chemical structure of the polymer determines its interaction potential with various metal ions, leading to varying degrees of adsorption efficiency (Cao *et al.*, 2021).

- **Environmental Conditions**: The sorption efficacy of HMs onto microplastics is significantly influenced by the surrounding environmental factors, particularly the pH and salinity of the water (Cooper and Corcoran, 2010). Variations in pH can alter the charge on microplastic surfaces and the speciation of metal ions, affecting their availability and reactivity (Medyńska and Jadhav, 2022). Additionally, variations in salinity have the potential to affect the aquatic environment's ionic strength, which in turn can affect the electrostatic interactions among metal ions and microplastics (Holmes *et al.*, 2014).

- **Surface Modification**: Microplastics that have undergone weathering or have been modified by the attachment of organic matter exhibit enhanced adsorption properties for heavy metals in contrast to their virgin counterparts (Brennecke *et al.*, 2016; Tang *et al.*, 2019). Weathering processes, such as exposure to sunlight, mechanical wear, and the accumulation of biofilms, increase the surface area of microplastics and introduce functional groups that facilitate metal binding (Seidensticker *et al.*, 2018; Guo and Wang,2020). These modifications make weathered microplastics more reactive and capable of adsorbing higher concentrations of HMs.

- **Metal Characteristics**: The characteristics of HMs themselves, including their ionic charge, atomic size, and surface valence state, also influence their interaction with microplastics (Fu *et al.*, 2021; Wang *et al.*,2021). Metals with specific chemical properties may bind more readily to microplastic surfaces. For instance, metals with higher valence states or specific ionic radii may exhibit stronger interactions with the functional groups present on microplastic surfaces (Tang *et al.*, 2021). These intrinsic properties of metals dictate their adsorption behavior and determine the extent to which they can accumulate on microplastics.

Ashton *et al.* (2010) were among the first to investigate metal interactions with both beached and new plastic production pellets. Their study revealed that metals like iron (Fe), copper (Cu), and zinc (Zn) accumulated on microplastic surfaces collected from the SW England coastline. Because extraneous materials like silt grains have larger surface areas and charged sites than fresh pellets, it is probable that the concentration of these metals on beached plastics is greater than on new pellets. Moreover, suspended plastic pellets in harbor seawater showed discoloration and structural changes after 8 weeks, with significant metal concentrations observed on their surfaces.

The kind of polymer affects metal adsorption because "of changes in specific surface area as well as functional groups Guo *et al.* (2019) ranked microplastics for cadmium (Cd) adsorption as follows: polyethylene (PE) <polypropylene (PP) <polystyrene (PS). This order is consistent with" Turner and Holmes (2015), who found that polyvinyl chloride (PVC) had the highest adsorption capacity, followed by polypropylene (PP), polyamide (PA), and polyethylene (PE).

Turner and Holmes (2015) carried out significant research on the adsorption of trace metals on freshwater microplastics. According to their research, higher pH values in river water improved the adsorption of trace metals like zinc (Zn), cobalt (Co), nickel (Ni), Pb, Cd, and silver (Ag), but had no discernible influence on the adsorption of chromium (Cr) or mercury (Hg) or copper (Cu). Adsorption rates were higher for beached pellets compared to new ones, likely due to organic complexes and surface modifications (Turner and Holmes, 2011).

2. Impacts of Microplastics and Heavy Metals on Aquatic Ecosystems

The ecological systems and human health are both susceptible to significant and complex effects from the existence of HMs and microplastics in aquatic environments. These contaminants seriously impair aquatic habitats' ability to function and maintain their natural equilibrium.

2.1 Ecological Effects

Many negative consequences are imposed on aquatic organisms by microplastics and heavy metals. Many freshwater and marine animals, such as fish, invertebrates, and filter feeders, consume microplastics because of their small size (Scherer, *et al.*,2017). Physical injury from this consumption may include gastrointestinal system abrasions and obstructions, decreased feeding effectiveness, and impaired growth and reproduction (Wright *et al.*, 2013). Additionally, microplastics can carry toxic chemicals, which may leach into organisms, causing further physiological and biochemical disturbances (Teuten *et al.*, 2009).

Conversely, HMis well recognized for having harmful impacts on aquatic life. Pb, Cd, and Hg are instances of metals that can obstruct vital biological functions like protein synthesis, enzyme activity, and cell membrane integrity (Bánfalvi,2011). These disruptions can lead to increased mortality rates, reproductive failures, and alterations in behavior and development in aquatic species. Bioaccumulation, the process by which heavy metals build up in an organism's tissues over time, has been demonstrated to result from long-term exposure to HMs and might have negative effects on health (Ali *et al.*, 2019).

2.2 Bioaccumulation and Biomagnification

The impacts of heavy metals and microplastics in aquatic food webs are amplified by the processes of biomagnification and bioaccumulation. The term "bioaccumulation" refers to the gradual accumulation of substances, like HMs or microplastics, within an organism over time (Gbarukoand Friday, 2007; Qu et al 2018). When the rate of absorption surpasses the rate of excretion, this occurs. For instance, fish that ingest microplastics or contaminated prey can accumulate these pollutants in their tissues, resulting in concentrations that are higher than in their surroundings (Rochman *et al.*, 2015).

2.3 Human Health Risks

Heavy metals and microplastics could be introduced to humans through the consumption of contaminated seafood as well as water. Microplastics and other related dangerous materials might enter the human food chain when fish and shellfish eat them (Unuofin, and Igwaran, 2023). According to studies, microplastics may accumulate in seafood and pose health hazards to individuals, such as gastrointestinal inflammation and possible connections to chronic diseases (Smith *et al.*, 2018). Hms, which are known to be highly toxic, can also pose significant health risks to humans. Heavy metal poisoning, which can result from consuming contaminated seafood, can affect the nervous system, the heart, and the kidneys. Chronic heavy metal exposure has been related to a number of health problems, like cancer and developmental abnormalities (Mohmand *et al.*, 2015).

Effective mitigation measures are necessary because of the established detrimental effects of HMsas well as microplastics on aquatic ecosystems and human health. Addressing these pollutants requires a comprehensive approach to reduce their sources and manage their impacts. The subsequent segments delineate diverse approaches intended to alleviate the existence of these pollutants and augment ecological safeguarding.

3. Mitigation and Management Strategies

A wide range of strategies are needed to effectively mitigate the effects of HMsas well as microplastics on aquatic habitats. In India, several government initiatives are being implemented to address these issues through policy, regulation, and public engagement. These strategies focus on reducing pollution at its source, enhancing waste management practices, and promoting innovative solutions.

3.1 Source Reduction

The Indian government has taken significant steps to curb plastic pollution through regulatory measures. The Plastic Waste Management Rules, 2016, amended in 2018, "enforce Extended Producer Responsibility (EPR), making producers, importers, and brand owners" accountable for managing plastic waste. This includes campaigns to promote the use of sustainable practices and alternatives by gradually phasing out single-use plastics like straws and bags.The use of cleaner production technologies by industries is being encouraged to minimize the emission of pollutants, like microplastics and HM. Policies under the National Clean Energy Fund (NCEF) support innovative projects aimed at reducing environmental pollution, including those targeting heavy metal contamination and plastic waste. Companies are incentivized to invest in technologies that minimize waste and adopt less harmful substitutes (Guptaand Dash,2023).

3.2 Waste Management

The Swachh Bharat Mission (SBM) emphasizes improved waste management and sanitation practices across India, including enhanced recycling of plastic waste (GOGRIand RUPAREL, 2019). Further encouraging efficient waste management and recycling procedures are "the Plastic Waste Management (Amendment) Rules, 2021, which impose stronger regulations and outlaw some single-use plastic" products (Nøklebye *et al.*, 2023).

3.3 Policy and Regulation

The Indian government fosters public-private partnerships to drive innovation and large-scale projects aimed at reducing pollution. Collaborative efforts between government agencies, businesses, and non-governmental organizations (NGOs) support initiatives such as advanced recycling programs and pollution control technologies. Policies such as the National Environment Policy (NEP), 2006, and National Policy on Electronics (NPE), 2019 provide a framework for addressing environmental pollution. These policies include provisions for managing plastic waste and electronic waste, which often contains heavy metals, and promote sustainable practices and technological innovation (Bhatia, 2020; Shimray,2024).

3.4 Research and Monitoring

The success of mitigation techniques and understanding of pollution patterns depend on ongoing study and monitoring. In order to hone and enhance management techniques, government programs promote the gathering of data on pollution levels and the effects of various mitigation strategies.The National Clean Energy Fund (NCEF) plays a significant role in funding research and development projects aimed at reducing environmental pollution. By supporting innovative solutions and technologies, this fund helps advance efforts to manage plastic waste and heavy metal contamination (Baliand Mongia, 2013; Thapar *et al.*,2016)

Conclusion

Microplastics and heavy metals in aquatic habitats require a multifaceted approach that incorporates sociological, technological, and regulatory approaches to successfully address the problem. Regulatory frameworks must be strengthened to limit the production and discharge of microplastics and heavy metals, emphasizing stricter standards for industrial emissions and wastewater treatment. The removal of these contaminants from aquatic systems before they reach sensitive areas can be greatly enhanced by the development and implementation of enhanced monitoring systems and innovative filtration technology. Public engagement and education have a vital part in raising awareness about the sources and impacts of these contaminants, encouraging responsible consumption, recycling, and support for sustainable practices. Furthermore, ongoing research and innovation are vital for developing new materials, cleanup methods, and comprehensive pollution management strategies. By combining stringent regulations, cutting-edge technology, active public participation, and robust scientific research, we can make meaningful progress in mitigating the adverse impacts of microplastics and HMs, thereby protecting aquatic ecosystems and ensuring a healthier environment for future generations.

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