Received: 21 April 2025 | Revised: 29 April 2025 | Accepted: 2 June 2025 | Available online: 3 June 2025
DOI: https://doi.org/10.31102/eam.2025.2.1.15-33

REVIEW ARTICLE

Environmental & Agriculture Management

Interaction of microplastics and heavy metals on aquatic organisms : A review

Adinda Kurnia Putri[1,*], Yenni Arista Cipta Ekalaturrahmah[2], Ahmad Ahmad[2], Moh Shoheh[2]

[1]Department of Aquatic Resources, Jendral Soedirman University, Banyumas Central Java, 53122, Indonesia
[2]Centre for Environmental and Agriculture Management, Universitas Islam Madura
Correspondence
Adinda Kurnia Putri, Department of Aquatic Resources, Jendral Soedirman University, Banyumas Central Java, 53122, Indonesia.
Email: adinda.kurnia@unsoed.ac.id

Abstract
Microplastics, which originate from a variety of sources and are widespread in aquatic ecosystems, have a significant capacity to adsorb heavy metals through a variety of physicochemical mechanisms, including electrostatic interactions, complex formation, ion exchange, and surface precipitation. A systematic review was used in this study of 50 published articles on the interactions of microplastics and heavy metals on aquatic organisms. The characteristics of microplastics (size, shape, type of polymer) and environmental conditions (pH, salinity, dissolved organic matter) greatly influence the adsorption efficiency and behavior of microplastics in the aquatic environment. Once inside the organism through direct consumption, gills, cuticle penetration, or cellular translocation, microplastics can release adsorbed heavy metals, creating effects that increase the bioavailability and toxicity of the metal. Biological responses that occur include oxidative stress, DNA damage, disruption of the antioxidant defense system, histopathological changes in tissues and organs, growth and reproductive disorders, and behavioral changes. At the population and ecosystem level, microplastic-heavy metal interactions can lead to shifts in community composition, disruption of food webs, changes in biogeochemical cycles, and degradation of ecosystem services.

KEYWORDS
adsorption; desorption; ecotoxicology; heavy metals; microplastics

1. INTRODUCTION

Pollution of microplastics and other pollutants, particularly heavy metals, has been a major threat to global aquatic ecosystems in recent decades (Haque, 2022; Xiang et al., 2022). Microplastics, defined as plastic particles less than 5 mm in size, are found in almost all aquatic environments ranging from deep ocean to freshwater, and even drinking water (Hale et al., 2020; Horton et al., 2017). The combination of microplastics and heavy metals creates a potentially synergistic pollution complex, where microplastics can act as vectors that transport heavy metals and increase their bioavailability and toxicity to aquatic organisms (Adeleye et al., 2024; Cao et al., 2021; Kajal & Thakur, 2024). Microplastic pollution varies significantly across different aquatic environments. In open oceans, levels range between 0.002 and 62.50 item/m³ (Mutuku et al., 2024), while coastal regions exhibit concentrations from 0.001 to 140 particles/m³ (Albaseer et al., 2024),

 © 2025 EAM All right reserved

Freshwater lakes show even greater variability, with microplastic accumulation reaching up to 540 MP/kg (Pierdomenico et al., 2024), Similarly, in water samples, microplastic abundance has been recorded at 0.5 to 0.9 particles per liter (Garfansa et al., 2024). Heavy metal contamination is also prevalent, with chromium (Cr) levels in sediment and water measuring up to 55 mg/kg and 86.93 mg/L, respectively (Rakib et al., 2022), Additionally, cadmium (Cd) concentrations have been reported between 0.019 and 0.025 mg/L (Elhussien & Adwok, 2018) and 0.46 to 4.40 µg/L (Sabbir et al., 2018). This phenomenon raises serious concerns for the integrity of aquatic ecosystems, biodiversity, and may ultimately impact human health through the food chain, making understanding of these complex interactions a priority in contemporary environmental research.

Previous research has resulted in significant advances in understanding the dynamics of interactions between microplastics and heavy metals and their impact on aquatic organisms. Various studies have characterized the adsorption capacity of microplastics against different types of heavy metals such as cadmium, lead, mercury, and copper, taking into account factors such as particle size, polymer type, and environmental conditions (Cao et al., 2021; Kinigopoulou et al., 2022; Kutralam-Muniasamy et al., 2021; Naqash et al., 2020; Tang et al., 2022; Zhou et al., 2019). The interaction between microplastics and heavy metals poses significant environmental risks, especially since they can lead to increased bioaccumulation in organisms. Research by Han et al. (2021) shows that polyethylene (PE) has a higher heavy metal adsorption capacity than polypropylene (PP) due to its more porous surface structure. The adsorption process for both types of microplastics follows a quasi-secondary kinetic model, but PE consistently exhibits a higher rate of adsorption (S. Wang et al., 2023). Toxicology research has demonstrated the effects of microplastics and heavy metals at various levels of biological organization, from cellular and molecular responses to behavioral and reproductive changes in diverse aquatic organisms (Das, 2023; Vimalkumar et al., 2022; Vo & Pham, 2021; Wu et al., 2024). In addition, bioaccumulation and biomagnification studies have identified microplastic and heavy metal transfer pathways through the aquatic food chain, suggesting a greater potential risk to high-level predators, including humans (Bețianu et al., 2024; Dang et al., 2021; Marcharla et al., 2024; Sawangproh & Paejaroen, 2025). Most studies were short-term (hours to days), whereas environmental exposure was chronic. lack of data on the characteristics of microplastics in the environment, interactions of microplastics and heavy metals, Adsorption-Desorption mechanisms, entry pathways, biological responses, and Long-Term Ecological Implications.

Despite significant research progress, a number of constraints and knowledge gaps still hinder a comprehensive understanding of the interactions of microplastics and heavy metals on aquatic organisms. The transfer mechanisms and bioavailability of heavy metals adsorbed to microplastics in biological systems are still not fully understood, especially how the physiological conditions of organisms can affect desorption and absorption (Kumar et al., 2022; Menéndez-Pedriza & Jaumot, 2020). The limitations of standard methodologies for the characterization and quantification of microplastics in complex biological samples make it difficult to compare between studies and establish accurate dose-response relationships (de Ruijter et al., 2020). In addition, the majority of research focused on short-term exposure and used unrealistic concentrations of pollutants in an environmental context, while the effects of chronic exposure on relevant environmental concentrations as well as transgenerational impacts are still very limited (Hamilton et al., 2016). The lack of understanding of the synergistic, antagonistic or additive effects of mixtures of different types of microplastics and heavy metals is also a challenge in accurately predicting ecological risks. Although a lot of research has been done, the gap in understanding remains for three main reasons: (1) The mechanism of heavy metal-microplastic transfer is highly dependent on unstable environmental conditions, making it difficult to generalize the results of laboratory studies; (2) The bioavailability of heavy metals adsorbed by microplastics has not been fully quantified in the food chain, especially in high-level organisms; and (3) Standard methods for measuring these interactions are still evolving, causing inconsistencies in data between studies.

This review article aims to integrate and synthesize the current knowledge on the interactions of microplastics and heavy metals and their impact on aquatic organisms, with a particular focus on the adsorption-desorption mechanisms, pathways into organisms, biological responses at various levels of organization, and long-term ecological implications. The significance of this review lies in its ability to identify critical knowledge gaps and provide a comprehensive conceptual framework for understanding the ecological risks of these mixed contaminants. Furthermore, this synthesis of knowledge will serve as a solid scientific basis for the development of effective environmental management and policy strategies in addressing the increasingly complex problem of mixed pollution, as well as contributing to sustainable conservation and preservation efforts of aquatic ecosystems.

2. METHODS

The literature review was carried out by searching for related scientific publications using the Scopus database (2020-2025). The search was conducted using key terms such as "microplastics", "interactions", "aquatics", "metal", and "organisms", to gather the necessary information. Five keywords used in the livelihood process, resulting in 2748 articles. The specific criteria for this review article is that it must be published in a Scopus indexed journal. Furthermore, articles are selected based on the relevance of the title, abstract and articles with research categories. Relevant data are systematically extracted and analyzed to identify key findings related to the topic of this review. Finally the 50 most relevant articles were selected and used in this study.

3. CHARACTERISTICS OF MICROPLASTICS IN THE AQUATIC ENVIRONMENT

Microplastics are defined as plastic particles less than 5 mm in size in all dimensions, although the lower limit of size varies in the scientific literature (Shamskhany et al., 2021). Based on their origin, microplastics are classified into two main categories: primary and secondary microplastics (Song et al., 2024). The spatial distribution of primary and secondary microplastics shows different patterns in aquatic environments, with primary microplastics (microbeads, nurdles, and textile fibers) tending to be dominant in open waters (60-75% of total microplastics) due to the ability to transport over long distances via ocean currents and wind-driven transport (Alfaro-Núñez et al., 2021; Sterl et al., 2020). In contrast, secondary microplastics resulting from larger plastic fragmentation are more common in coastal and nearshore areas (70-85% within a 1 km radius of shore) due to higher fragmentation intensity due to UV exposure, mechanical abrasion from wave action, and proximity to terrestrial sources of plastic debris (Kumar et al., 2025; Pal et al., 2025). Primary microplastics are particles that are deliberately produced in micro sizes for specific applications, such as microbeads in personal care products, plastic resin pellets (nurdles) as industrial raw materials, and synthetic microfibers from textiles (Hafeez et al., 2023). Secondary microplastics are formed through the fragmentation of larger plastic products due to physical, chemical, and biological degradation processes in the environment, such as mechanical abrasion, photodegradation, and biodegradation (Andrady & Koongolla, 2022; Mishra et al., 2025).

Based on their morphology, microplastics are classified into several main forms: fragments (irregular pieces), fibers/filaments (elongated structures), films (thin sheets), foam (porous structures), pellets (cylindrical or disc-shaped granules), and beads (spherical particles) (Hafeez et al., 2023). The composition of microplastic polymers is very diverse, with the most common polymers found in aquatic environments being polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), reflecting global patterns of plastic production and use (Fan et al., 2021; Fernández-González et al., 2022).

The source of microplastics to the aquatic environment is very diverse and widespread (Wang et al., 2021). Land-based sources include poorly managed plastic waste, urban runoff containing particles from the degradation of plastic and fiber products from synthetic textile washing, wastewater treatment plant effluent containing microbeads from personal care products and microfibers from laundry, and agricultural activities that use plastic mulch films and fertilizers containing microplastics (Onyeabor, 2024). Marine-based sources include lost or discarded fishing equipment, peeling ship paint, and waste from ship operations and offshore installations (Onyeabor, 2024; Watson et al., 2023). Atmospheric transport has also been identified as an important pathway for the long-distance movement of microplastics, with microplastic particles detected in atmospheric dust and dust deposits.

4. FACTORS AFFECTING THE FATE AND BEHAVIOR OF MICROPLASTICS IN THE ENVIRONMENT

Density is the main factor that influences the floating or submerged behavior of microplastics in the water column (Almeida et al., 2023; Feng et al., 2023). Polymers with a lower density than water (PE: 0.91-0.97 g/cm³, PP: 0.90-0.91 g/cm³) tend to float on the surface, while polymers with higher densities (PVC: 1.38-1.41 g/cm³, PET: 1.38-1.39 g/cm³, PS: 1.04-1.09 g/cm³) tend to sink (S. Liu et al., 2022; Meneses Quelal et al., 2022). However, this behavior can change significantly over time due to biofilm colonization (biofouling), in which microorganisms and organic matter accumulate on the surface of the plastic, increases the overall density and causes previously floating particles to sink (Gaylarde et al., 2023; Miao et al., 2021).

The degradation of microplastics in the aquatic environment occurs through a combination of physical, chemical, and biological processes (Corcoran, 2022; Debroy et al., 2022). Photodegradation through UV radiation becomes the dominant degradation mechanism in the upper pelagic zone, resulting in the formation of oxygen functional groups on plastic surfaces and increased material brittleness (Pinto et al., 2024; L. Wang et al., 2023). Chemical hydrolysis plays a greater role in sediments, although the rate is much slower (Dimassi et al., 2022). Mechanical degradation through abrasion by wave action, friction with sediments, and biological activities such as grinding in the digestive tract of biota contribute to further fragmentation (Issac & Kandasubramanian, 2021; Kumar et al., 2024). Biodegradation is very limited to most conventional synthetic polymers, although some specialized microorganisms have been identified to degrade certain polymers (Mukherjee et al., 2023).

Photodegradation through UV radiation becomes the dominant degradation mechanism in the upper pelagic zone, resulting in the formation of oxygen functional groups on plastic surfaces and increased material brittleness

Microplastic transport is affected by hydrodynamics such as current circulation, wave action, and turbulence (Kumar et al., 2021). In rivers, microplastic concentrations show variation based on water discharge, with increases during flood events when sediment is resuspended (Xiaorong Lu et al., 2023). In the marine environment, thermohaline circulation and surface currents affect global distribution, causing accumulation in marine gyres (Lima et al., 2021). Wind forcing and internal waves can affect the vertical distribution in the water column (Fourniotis, 2024). In the deep sea, turbidity currents and solid water cascades facilitate the transport of microplastics to deep-sea sediments (Pierdomenico et al., 2023).

Microplastic transport is affected by hydrodynamics such as current circulation, wave action, and turbulence

The interaction between microplastics and biotic factors also affects fate and behavior. Absorption by organisms can alter spatial distribution, while joint excretion of fecal material can accelerate vertical export to sediment through a "rain" of rapidly sinking fecal particles (Qian et al., 2021). Excavation and bioturbation activity by benthic organisms can remobilize microplastics in sediments or bury them deeper, affecting their long-term persistence and bioavailability (Venâncio et al., 2024).

Absorption by organisms can alter spatial distribution, while joint excretion of fecal material can accelerate vertical export to sediment through a "rain" of rapidly sinking fecal particles

5. ADSORPTION-DESORPTION MECHANISM

5.1 Mechanism of Adsorption of Heavy Metals in Microplastics

Figure.1 Show the process of adsorption of heavy metals in microplastics involves several complex physicochemical mechanisms (Cao et al., 2021). First, electrostatic interactions occur when the surface charge of microplastics (usually negative due to the degradation process that results in carboxyl groups) attracts positively charged metal ions such as Cd^{2+}, Pb^{2+}, and Cu^{2+} (Patra, 2023). Second, the formation of complexes (chelation) occurs between metal ions and oxygen functional groups on the surface of oxidized microplastics, such as carbonyl, hydroxyl, and carboxyl groups (He et al., 2023). Third, ion exchange can occur where metal cations replace hydrogen ions from functional groups on the surface of microplastics. Fourth, surface precipitation occurs when the concentration of metal ions is high, causing the deposition of metal compounds on the surface of microplastics (Xiao Lu et al., 2023).

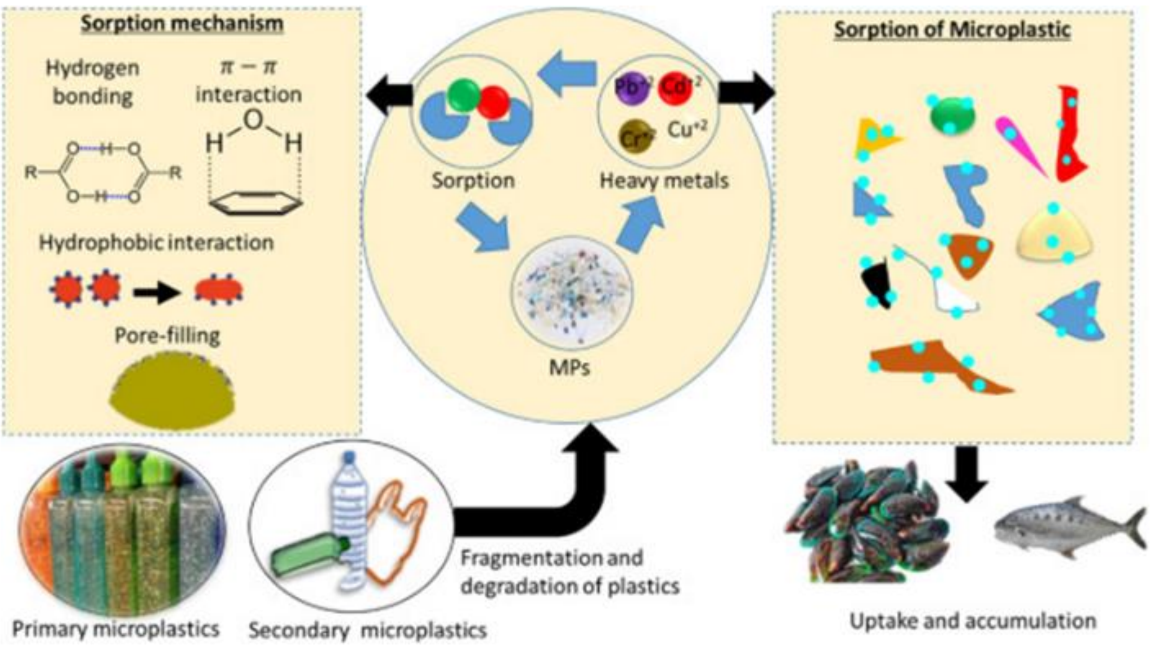

Figure 1. Heavy metal and microplastic adsorption mechanism. Source : (Prabhu et al., 2024)

The adsorption efficiency is greatly influenced by the environmental conditions of the waters (Miranda et al., 2022). pH plays an important role as it affects the surface charge of microplastics and metal speciation; generally adsorption increases at higher pH for most cationic metals due to the deprotonation of functional groups (Tang et al., 2021). Salinity affects adsorption through the effect of ion competition, where cations such as Na^+, K^+, Ca^{2+}, and Mg^{2+} in seawater compete with heavy metal ions for binding sites on microplastics. Dissolved organic matter (DOM) can form a layer on the surface of microplastics, creating additional binding sites for metals or competing with microplastics for metal bonding (Zhu et al., 2024).

5.2 Mechanism of Desorption and Transfer to Organisms

The desorption of heavy metals from microplastics in aquatic organisms is affected by specific physiological conditions (H. Pan et al., 2023). In the digestive tract of organisms, significant changes in pH (usually more acidic than the external environment) can increase the solubility of metal-microplastic complexes (Zink et al., 2024). Digestive enzymes and bile acids can degrade biofilms on microplastic surfaces and release bound metals (I. Pan et al., 2023). The gut microbiota environment can also change the redox shape of metals, affecting their mobility (Bist & Choudhary, 2022). The variation in species response to heavy metal desorption from microplastics is significant. In fish, acidic stomach conditions (pH 1.5–3.5) and short retention times accelerate the release of metals such as Cd and Pb, while in filter-feeder invertebrates (e.g., shellfish), a neutral digestive environment (pH 6.5–8.5) and prolonged particle retention increase chronic metal accumulation (Jeyasanta et al., 2024; Wu et al., 2025). These differences suggest that the bioavailability of metals depends not only on the characteristics of the microplastics, but also on the physiological adaptations of the target organism. Once the metal is desorpated, several absorption pathways can occur: (1) direct absorption through the intestinal epithelium, where the metal enters the bloodstream and is distributed to various organs, (2) absorption by gill epithelial cells when very small microplastics reach the gills, and (3) penetration through the skin or external membranes for smaller organisms (Hu et al., 2023). Very small microplastics (nanoplastics) can cross the cellular barrier through endocytosis, potentially carrying metals directly into cells.

In the digestive tract of organisms, significant changes in pH (usually more acidic than the external environment) can increase the solubility of metal-microplastic complexes

6. ENTRY PATH

Direct consumption is the most dominant entry route for microplastics that adsorb heavy metals into aquatic organisms (Fig 2). Filter feeder organisms such as shellfish, oysters, and zooplankton actively filter water and ingest microplastic particles that look like food (Fabra et al., 2021). Visual predators such as fish and waterfowl often mistakenly identify microplastics as prey due to their similarities in size, color, and shape to natural organisms (Benson et al., 2022). Indirect consumption occurs when organisms feed on prey that has accumulated microplastics, creating trophic transfer pathways (Provencher et al., 2022). Research shows that aquatic organisms of various sizes and trophic levels, from zooplankton to predatory fish, consume microplastics to varying rates based on the type of food and feeding strategy (Uy & Johnson, 2022).

Visual predators such as fish and waterfowl often mistakenly identify microplastics as prey due to their similarities in size, color, and shape to natural organisms

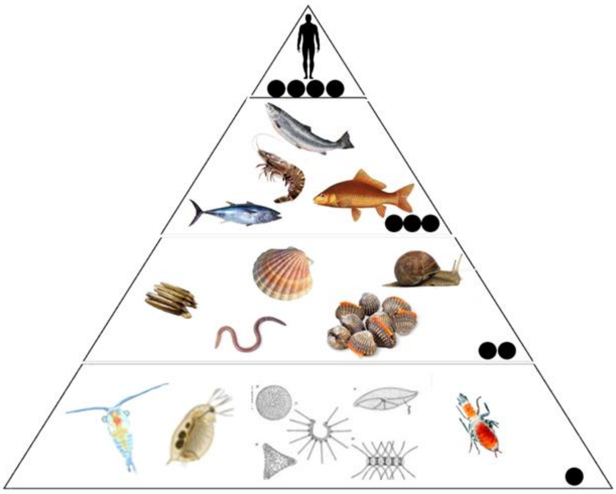

Figure 2. The transfer of microplastics (MP) between trophic levels in animals suggests that organisms at higher trophic levels experience greater MP accumulation as a result of consuming contaminated prey. The black dot describes the location of MP accumulation in the organism's body.

Gills are the second important entry route, especially for very small microplastics and nanoplastics (1-1000 nm) (Guerrera et al., 2021). These small particles can be trapped in the gill filaments during the process of respiration and filtration (Alsafy et al., 2025). Microplastic absorption by gills occurs through a filtration mechanism and direct contact with gill filaments and secondary lamellae, where microplastic particles measuring 1-100 μm can be trapped in the mucus layer and then integrate with the respiratory epithelium through the process of endocytosis or physical penetration (Liu et al., 2024; Zheng & Wang, 2024). The accumulation of microplastics in the gill structure causes morphological disorders in the form of epithelial hyperplasia, fusion of secondary lamellae, and increased mucus production in a defensive response, which significantly reduces the effective surface area for gas exchange and can reduce oxygen uptake efficiency by 15-30% (Hamed et al., 2021; Kama et al., 2024).

Further physiological impacts include chronic inflammation characterized by infiltration of inflammatory cells, increased activity of antioxidant enzymes such as catalase and superoxide dismutase in response to oxidative stress, as well as histopathological changes in the form of desquamation and necrosis of the gill epithelium that can progress to respiratory distress and decreased aerobic capacity of the organism (Sayed et al., 2023). In addition, microplastics accumulated in gills can act as vectors for the transfer of adsorbed heavy metals into the circulatory system through rich vascularization of gill tissue, thereby increasing the bioavailability of contaminants and magnifying the risk of systemic toxicity (Ghosh et al., 2025; Liu et al., 2021). This condition causes prolonged contact between metal-containing microplastics and highly vascularized tissues, facilitating metal desorption and direct absorption into the bloodstream (Cameron et al., 2022). Absorption through gills is particularly relevant for fish, crustaceans, and shellfish. Various studies have shown that heavy metals desorpted from microplastics in the gill area can enter the tissues without passing through the digestive tract, causing significant accumulation in these respiratory organs

7. BIOLOGICAL RESPONSE

Simultaneous exposure to microplastics and heavy metals triggers complex oxidative stress responses in the cells of aquatic organisms (Chen et al., 2025). The increased production of reactive oxygen species (ROS) occurs through a dual mechanism: microplastics can physically disrupt cellular membranes and organelles such as mitochondria, while heavy metals such as Cu, Cd, and Hg participate in the Fenton reaction that produces highly reactive hydroxyl radicals (Waqas et al., 2024). Studies on zebrafish showed that exposure to a combination of polyethylene (PE) and cadmium (Cd) microplastics resulted in up to 2.5-fold increase in malondialdehyde (MDA) levels and decreased superoxide dismutase (SOD) activity compared to exposure to each pollutant separately, demonstrating a synergistic effect on cellular redox status (Wazne et al., 2023).

Disruption of the antioxidant defense system often occurs when cells are exposed to a combination of microplastics and heavy metals (Chen et al., 2025). The activity of detoxifying enzymes such as catalase, glutathione peroxidase, and glutathione-S-transferase is significantly modulated, generally showing decreased capacity at chronic exposure (Abdelfattah et al., 2021). Changes in antioxidant gene expression and detoxification occur through pathways such as nuclear factor erythroid 2-related factor 2 (Nrf2) and aryl hydrocarbon receptor (AhR) pathways (Zhao et al., 2021). Metallothionine, a cysteine-rich metal-binding protein, often undergoes up-regulation in response to metal exposure, but the presence of microplastics can interfere with this protective function through interaction with metal-binding proteins or interfere with cellular signals that regulate their expression (Menone & Pérez, 2023; Rai et al., 2023).

DNA damage increases significantly in organisms exposed to a combination of microplastics and heavy metals (Turna Demir et al., 2022). The mechanism of damage includes the oxidation of DNA bases by ROS, the formation of DNA adduct by reactive metabolites, and disruption of DNA repair mechanisms (Juan et al., 2021). Studies on the sea mussels Mytilus galloprovincialis showed that simultaneous exposure to polystyrene (PS) and lead (Pb) microplastics increased the frequency of micronuclei in hemocytes by up to 3 times compared to controls, indicating severe genotoxic damage (Pappa et al., 2021). Epigenetic disorders are also observed, including changes in DNA methylation, histone modification, and microRNA expression, which can have transgenerational implications in aquatic organism populations (Z. Liu et al., 2022).

DNA damage increases significantly in organisms exposed to a combination of microplastics and heavy metals

8. LONG-TERM ECOLOGICAL IMPLICATIONS

Long-term exposure to a combination of microplastics and heavy metals can fundamentally alter the structure and population dynamics of aquatic organisms (Turna Demir et al., 2022). The selective pressures posed by these combined toxicities tend to favor individuals with higher pollutant tolerances, potentially reducing the genetic diversity of the population (Cao et al., 2021). Research on the crab Carcinus maenas showed that populations chronically exposed to a combination of polyethylene and cadmium microplastics experienced a 35% decrease in genetic variability after four generations (Chen et al., 2024). This reduction in genetic diversity weakens the adaptive capacity of populations, making them more vulnerable to additional environmental pressures such as climate change, pathogens, or the introduction of invasive species.

The differential sensitivity of different species to this combination of pollutants can lead to significant shifts in the composition of aquatic communities (Adeleye et al., 2024). More sensitive species such as amphipods and larvae of certain aquatic insects experience faster population declines, while tolerant organisms such as oligochaeta and some gastropods are becoming more dominant (Feng et al., 2023). Experimental lake ecosystem studies showed that simultaneous exposure to polystyrene and copper microplastics altered predator-predator zooplankton ratios, with a 45% decrease in the abundance of sensitive large daphnia and a proportional increase in the proportion of more tolerant rotifers(Tang et al., 2022). This shift has a cascading effect on the entire food web, altering predator-prey dynamics and energy transfer between trophic levels.

Changes in community composition due to exposure to microplastics and heavy metals can disrupt ecosystem function through the loss of key species and fundamental shifts in trophic structures. Species that are sensitive to microplastic contamination, such as filter feeders and primary consumers, experience significant population declines, while more tolerant or opportunistic species tend to experience proliferation (Jeong et al., 2024; Marykate & Kate, 2024). This shift leads to community homogenization and a decrease in functional diversity, where species with different functional traits are replaced by species with similar characteristics, resulting in reduced functional redundancy and decreased ecosystem stability (Cavalcante et al., 2023). The loss of key species such as ecosystem engineers or keystone predators can result in cascading effects that spread throughout the food web, altering habitat structure and disrupting established predator-prey interactions (Sanders & Frago, 2024).

Disruptions to community composition further have an impact on fundamental ecosystem processes such as primary productivity, nutrient cycling, and energy flow. A decrease in phytoplankton diversity and changes in species dominance can reduce the efficiency of photosynthesis and primary production by 20-40%, impacting the entire trophic level above it (Krumhardt et al., 2022). Changes in the composition of decomposers and decomposing microorganisms disrupt the cycle of nutrients such as nitrogen and phosphorus, leading to the accumulation of organic matter and altered nutrient stoichiometry that can trigger eutrophication or local oligotrophication (Duhamel, 2025). In addition, changes in the community structure of zooplankton and benthos alter bioturbation and sediment mixing patterns, which impacts oxygen penetration in sediments and biogeochemical processes at the sediment-water interface (Chakraborty et al., 2022). These systemic disturbances ultimately reduce the resilience of ecosystems to other environmental stressors and the ability to recover after disturbances, creating negative feedback loops that can result in regime shift or ecosystem collapse.

9. CONCLUSION

The sources of microplastics to the aquatic environment are diverse, including plastic waste, urban runoff, wastewater treatment effluents, agricultural activities, fishing equipment, ship paints, and atmospheric transportation. The main factors affecting the fate of microplastics in the environment are density, degradation (photodegradation, hydrolysis, mechanical degradation, biodegradation), hydrodynamic transport, and interactions with biotic factors such as biofilm colonization. The adsorption of heavy metals in microplastics involves several physicochemical mechanisms: electrostatic interactions, complex formation (chelation), ion exchange, and surface precipitation. Adsorption efficiency is affected by environmental conditions such as pH, salinity, and dissolved organic matter. The desorption of heavy metals from microplastics in aquatic organisms is affected by specific physiological conditions such as changes in pH in the digestive tract, digestive enzymes, bile acids, and the gut microbiota environment. Once desorpated, the metal can be absorbed through the intestinal epithelium, gill cells, or penetration through the cuticle. There are several major entry routes of microplastics and heavy metals into aquatic organisms, Direct consumption, gills, cuticle and integument penetration, and cellular translocation. Simultaneous exposure to microplastics and heavy metals triggers a variety of biological responses, oxidative stress (increased ROS), disruption of the antioxidant defense system, DNA damage, and epigenetic disorders. Histopathological damage to the gills, digestive tract, and detoxifying organs such as the hepatopancreas and liver. Impaired growth and development, reproduction, and behavioral changes. Changes in population demographic structure, shifts in community composition, food chain disruptions, and changes in biogeochemical cycles. Long-term exposure to a combination of microplastics and heavy metals can lead to 1) Changes in population structure and dynamics, with selective pressures that benefit individuals with higher pollutant tolerances and potentially reduce genetic diversity. 2) Shifts in the composition of aquatic communities, with sensitive species experiencing faster population declines, while tolerant organisms become more dominant. 3) Disruption of energy transfer between trophic levels and heavy metal bioaccumulation in the food chain. 4) Degradation of ecosystem services, including fishery products, carbon sequestration, water purification, and recreational value.

Recommendations to address the complex impacts of microplastics and heavy metals in waters, policies include: (1) strengthening regulations to restrict primary microplastics (e.g., in cosmetic and textile products) and heavy metal industrial wastes, (2) circular economy-based waste management with advanced filtration technologies (such as nanomembranes or biochar) in wastewater treatment plants. On the research side, priorities include: (a) molecular toxicology studies to understand the synergistic mechanisms of microplastic-heavy metals at the cellular and epigenetic levels, (b) development of pollutant-absorbing materials (such as hydrogels or engineered microbes) that are effective in various environmental conditions, (c) ecosystem modeling to predict long-term impacts on community structure and ecosystem services, and (d) nature-based remediation tests (phytoremediation, constructed wetlands) that are integrated with the water restoration policy.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Adinda Kurnia Putri: Writing – original draft, Conceptualization, Writing – review & editing. Yenni Arista Cipta Ekalaturrahmah: Conceptualization, Methodology, Supervision, Writing – review & editing. Ahmad Ahmad: Data curation, Conceptualization, Writing – review & editing. Moh Shoheh: Conceptualization, Methodology, Supervision.

ACKNOWLEDGMENT

The author would like to express his appreciation to the Universitas Jenderal Soedirman and Universitas Islam Madura, for their support and facilitation during this research.

ETHICS APPROVAL

No ethical approval was needed for this study.

FUNDING

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Abdelfattah, E. A., Augustyniak, M., & Yousef, H. A. (2021). Stage-, sex-and tissue-related changes in H 2 O 2, glutathione concentration, and glutathione-dependent enzymes activity in Aiolopus thalassinus (Orthoptera: Acrididae) from heavy metal polluted areas. *Ecotoxicology*, 30, 478-491.

Adeleye, A. T., Bahar, M. M., Megharaj, M., Fang, C., & Rahman, M. M. (2024). The unseen threat of the synergistic effects of microplastics and heavy metals in aquatic environments: a critical review. *Current Pollution Reports*, 10(3), 478-497.

Albaseer, S. S., Al-Hazmi, H. E., Kurniawan, T. A., Xu, X., Abdulrahman, S. A. M., Ezzati, P., Habibzadeh, S., Hollert, H., Rabiee, N., Lima, E. C., Badawi, M., & Saeb, M. R. (2024). Microplastics in water resources: Global pollution circle, possible technological solutions, legislations, and future horizon. *Science of the Total Environment*, 946, 173963. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.173963

Alfaro-Núñez, A., Astorga, D., Cáceres-Farías, L., Bastidas, L., Soto Villegas, C., Macay, K., & Christensen, J. H. (2021). Microplastic pollution in seawater and marine organisms across the Tropical Eastern Pacific and Galápagos. *Scientific Reports, 11*(1), 6424.

Almeida, M. P. d., Gaylarde, C., Pompermayer, F. C., Lima, L. d. S., Delgado, J. d. F., Scott, D., Neves, C. V., Vieira, K. S., Baptista Neto, J. A., & Fonseca, E. M. (2023). The complex dynamics of microplastic migration through different aquatic environments: Subsidies for a better understanding of its environmental dispersion. *Microplastics*, 2(1), 62-77.

Alsafy, M. A., Abd-Elhafeez, H. H., Rashwan, A. M., Erasha, A., Ali, S., & El-Gendy, S. A. (2025). Anatomy, histology, and morphology of fish gills in relation to feeding habits: a comparative review of marine and freshwater species. *BMC zoology, 10*(1), 3.

Andrady, A. L., & Koongolla, B. (2022). Degradation and fragmentation of microplastics. *Plastics and the ocean: origin, characterization, fate, and impacts*, 227-268.

Benson, N. U., Agboola, O. D., Fred-Ahmadu, O. H., De-la-Torre, G. E., Oluwalana, A., & Williams, A. B. (2022). Micro (nano) plastics prevalence, food web interactions, and toxicity assessment in aquatic organisms: a review. *Frontiers in Marine Science*, 9, 851281.

Bețianu, C., Cozma, P., & Gavrilescu, M. (2024). Human Health Hazards and Risks Generated by the Bioaccumulation of Lead from the Environment in the Food Chain. *In Lead Toxicity Mitigation: Sustainable Nexus Approaches* (pp. 73-123). Springer.

Bist, P., & Choudhary, S. (2022). Impact of heavy metal toxicity on the gut microbiota and its relationship with metabolites and future probiotics strategy: a review. *Biological Trace Element Research, 200*(12), 5328-5350.

Cameron, S. J., Sheng, J., Hosseinian, F., & Willmore, W. G. (2022). Nanoparticle effects on stress response pathways and nanoparticle–protein interactions. *International journal of molecular sciences, 23*(14), 7962.

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.

Cavalcante, L. L., Daga, V. S., Braga, R. R., & Padial, A. A. (2023). Functional homogenization in aquatic ecosystems: a review and framework proposal. *Hydrobiologia, 850*(6), 1283-1302. https://doi.org/10.1007/s10750-022-04919-4

Chakraborty, A., Saha, G. K., & Aditya, G. (2022). Macroinvertebrates as engineers for bioturbation in freshwater ecosystem. *Environmental Science and Pollution Research, 29*(43), 64447-64468.

Chen, C., Wang, X., Jin, Y., Yao, Y., Li, S., Liao, Z., Zhang, X., & Yan, X. (2025). Simultaneous exposure to microplastics and heavy metal lead induces oxidative stress, histopathological damage, and immune dysfunction in marine mussel Mytilus coruscus. *Ecotoxicology and Environmental Safety*, 289, 117493.

Chen, H., Huang, D., Zhou, W., Deng, R., Yin, L., Xiao, R., Li, S., Li, F., & Lei, Y. (2024). Hotspots lurking underwater: Insights into the contamination characteristics, environmental fates and impacts on biogeochemical cycling of microplastics in freshwater sediments. *Journal of Hazardous Materials*, 476, 135132. https://doi.org/https://doi.org/10.1016/j.jhazmat.2024.135132

Corcoran, P. L. (2022). Degradation of microplastics in the environment. *In Handbook of Microplastics in the Environment* (pp. 531-542). Springer.

Dang, F., Huang, Y., Wang, Y., Zhou, D., & Xing, B. (2021). Transfer and toxicity of silver nanoparticles in the food chain. *Environmental Science: Nano, 8*(6), 1519-1535.

Das, A. (2023). The emerging role of microplastics in systemic toxicity: Involvement of reactive oxygen species (ROS). *Science of the Total Environment*, *895*, 165076.

de Ruijter, V. N., Redondo-Hasselerharm, P. E., Gouin, T., & Koelmans, A. A. (2020). Quality criteria for microplastic effect studies in the context of risk assessment: a critical review. *Environmental Science & Technology, 54*(19), 11692-11705.

Debroy, A., George, N., & Mukherjee, G. (2022). Role of biofilms in the degradation of microplastics in aquatic environments. J*ournal of Chemical Technology & Biotechnology, 97*(12), 3271-3282.

Dimassi, S. N., Hahladakis, J. N., Yahia, M. N. D., Ahmad, M. I., Sayadi, S., & Al-Ghouti, M. A. (2022). Degradation-fragmentation of marine plastic waste and their environmental implications: A critical review. Arabian *Journal of Chemistry, 15*(11), 104262. https://doi.org/https://doi.org/10.1016/j.arabjc.2022.104262

Duhamel, S. (2025). The microbial phosphorus cycle in aquatic ecosystems. *Nature Reviews Microbiology, 23*(4), 239-255.

Elhussien, M. E., & Adwok, B. A. (2018). Determination of heavy metals in fish and water of White Nile during watery diarrhea outbreak from June to July, 2017, Gezira Aba–Sudan. *Science Journal of Analytical Chemistry, 6*(1), 1-6.

Fabra, M., Williams, L., Watts, J. E., Hale, M. S., Couceiro, F., & Preston, J. (2021). The plastic Trojan horse: Biofilms increase microplastic uptake in marine filter feeders impacting microbial transfer and organism health. *Science of the Total Environment, 797*, 149217.

Fan, C., Huang, Y.-Z., Lin, J.-N., & Li, J. (2021). Microplastic constituent identification from admixtures by Fourier-transform infrared (FTIR) spectroscopy: The use of polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) and nylon (NY) as the model constituents. *Environmental Technology & Innovation, 23*, 101798.

Feng, Q., Chen, Z., An, C., Yang, X., & Wang, Z. (2023). Tide-induced infiltration and resuspension of microplastics in shorelines: Insights from tidal tank experiments. *Water Research, 236*, 119970.

Fernández-González, V., Andrade-Garda, J. M., López-Mahía, P., & Muniategui-Lorenzo, S. (2022). Misidentification of PVC microplastics in marine environmental samples. *TrAC Trends in Analytical Chemistry, 153*, 116649.

Fourniotis, N. T. (2024). Effect of Internal Waves on the Hydrodynamics of a Mediterranean Sea Strait. *Journal of Marine Science and Engineering, 12*(4), 532.

Garfansa, M. P., Zalizar, L., Husen, S., Triwanto, J., Iswahyudi, I., & Ekalaturrahmah, Y. A. C. (2024). Fate and distribution of microplastics in water and sediment collected from Samiran ditch irrigation. *Environmental Quality Management, 34*(1), e22204. https://doi.org/https://doi.org/10.1002/tqem.22204

Gaylarde, C. C., de Almeida, M. P., Neves, C. V., Neto, J. A. B., & da Fonseca, E. M. (2023). The importance of biofilms on microplastic particles in their sinking behavior and the transfer of invasive organisms between ecosystems. Micro,

Ghosh, S., Dey, S., Mandal, A. H., Sadhu, A., Saha, N. C., Barceló, D., Pastorino, P., & Saha, S. (2025). Exploring the ecotoxicological impacts of microplastics on freshwater fish: A critical review. *Journal of Contaminant Hydrology, 269*, 104514. https://doi.org/https://doi.org/10.1016/j.jconhyd.2025.104514

Guerrera, M. C., Aragona, M., Porcino, C., Fazio, F., Laurà, R., Levanti, M., Montalbano, G., Germanà, G., Abbate, F., & Germanà, A. (2021). Micro and nano plastics distribution in fish as model organisms: histopathology, blood response and bioaccumulation in different organs. *Applied Sciences, 11*(13), 5768.

Hafeez, A., Saleem, A., & Shaker, K. (2023). Generation, Assessment, and Mitigation of Microplastics. In *Circularity in Textiles* (pp. 247-266). Springer.

Hale, R. C., Seeley, M. E., La Guardia, M. J., Mai, L., & Zeng, E. Y. (2020). A global perspective on microplastics. *Journal of Geophysical Research: Oceans, 125*(1), e2018JC014719.

Hamed, M., Soliman, H. A. M., Badrey, A. E. A., & Osman, A. G. M. (2021). Microplastics induced histopathological lesions in some tissues of tilapia (Oreochromis niloticus) *early juveniles. Tissue and Cell, 71*, 101512. https://doi.org/https://doi.org/10.1016/j.tice.2021.101512

Hamilton, P. B., Cowx, I. G., Oleksiak, M. F., Griffiths, A. M., Grahn, M., Stevens, J. R., Carvalho, G. R., Nicol, E., & Tyler, C. R. (2016). Population-level consequences for wild fish exposed to sublethal concentrations of chemicals–a critical review. *Fish and Fisheries, 17*(3), 545-566.

Han, X., Wang, S., Yu, X., Vogt, R. D., Feng, J., Zhai, L., Ma, W., Zhu, L., & Lu, X. (2021). Kinetics and Size Effects on Adsorption of Cu(II), Cr(III), and Pb(II) Onto Polyethylene, Polypropylene, and Polyethylene Terephthalate Microplastic Particles [Brief Research Report]. *Frontiers in Marine Science, Volume 8* - 2021. https://doi.org/10.3389/fmars.2021.785146

Haque, S. E. (2022). Urban water pollution by heavy metals, microplastics, and organic contaminants. In *Current directions in water scarcity research* (Vol. 6, pp. 21-43). Elsevier.

He, H., Liu, K., Guo, Z., Li, F., Liao, Z., Yang, X., Ren, X., Huang, H., Huang, B., & Pan, X. (2023). Photoaging mechanisms of microplastics mediated by dissolved organic matter in an iron-rich aquatic environment. *Science of the Total Environment, 860*, 160488.

Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment, 586*, 127-141.

Hu, W., Wang, C., Gao, D., & Liang, Q. (2023). Toxicity of transition metal nanoparticles: A review of different experimental models in the gastrointestinal tract. *Journal of Applied Toxicology, 43*(1), 32-46.

Issac, M. N., & Kandasubramanian, B. (2021). Effect of microplastics in water and aquatic systems. *Environmental Science and Pollution Research*, 28, 19544-19562.

Jeong, E., Lee, J.-Y., & Redwan, M. (2024). Animal exposure to microplastics and health effects: A review. *Emerging Contaminants, 10*(4), 100369. https://doi.org/https://doi.org/10.1016/j.emcon.2024.100369

Juan, C. A., Pérez de la Lastra, J. M., Plou, F. J., & Pérez-Lebeña, E. (2021). The chemistry of reactive oxygen species (ROS) revisited: outlining their role in biological macromolecules (DNA, lipids and proteins) and induced pathologies. *International journal of molecular sciences, 22*(9), 4642.

Kajal, S., & Thakur, S. (2024). Coexistence of microplastics and heavy metals in soil: Occurrence, transport, key interactions and effect on plants. *Environmental Research*, 119960.

Kama, N. A., Djawad, M. I., & Yaqin, K. (2024). Effects of Microplastics on the Oxygen Consumption and Histological Changes of the Cultured Nile Tilapia Oreochromis niloticus. *Egyptian Journal of Aquatic Biology & Fisheries, 28*(5).

Kinigopoulou, V., Pashalidis, I., Kalderis, D., & Anastopoulos, I. (2022). Microplastics as carriers of inorganic and organic contaminants in the environment: A review of recent progress. *Journal of Molecular Liquids, 350*, 118580.

Krumhardt, K. M., Long, M. C., Sylvester, Z. T., & Petrik, C. M. (2022). Climate drivers of Southern Ocean phytoplankton community composition and potential impacts on higher trophic levels. *Frontiers in Marine Science, 9*, 916140.

Kumar, D., Biswas, J. K., Mulla, S. I., Singh, R., Shukla, R., Ahanger, M. A., Shekhawat, G. S., Verma, K. K., Siddiqui, M. W., & Seth, C. S. (2024). Micro and nanoplastics pollution: Sources, distribution, uptake in plants, toxicological effects, and innovative remediation strategies for environmental sustainability. *Plant Physiology and Biochemistry*, 108795.

Kumar, M., Chaudhary, V., Kumar, R., Chaudhary, V., & Srivastav, A. L. (2025). Microplastics, their effects on ecosystems, and general strategies for mitigation of microplastics: A review of recent developments, challenges, and future prospects. *Environmental Pollution and Management, 2,* 87-105. https://doi.org/https://doi.org/10.1016/j.epm.2025.03.001

Kumar, R., Ivy, N., Bhattacharya, S., Dey, A., & Sharma, P. (2022). Coupled effects of microplastics and heavy metals on plants: Uptake, bioaccumulation, and environmental health perspectives. *Science of the Total Environment, 836*, 155619.

Kumar, R., Sharma, P., Verma, A., Jha, P. K., Singh, P., Gupta, P. K., Chandra, R., & Prasad, P. V. (2021). Effect of physical characteristics and hydrodynamic conditions on transport and deposition of microplastics in riverine ecosystem. *Water, 13*(19), 2710.

Kutralam-Muniasamy, G., Pérez-Guevara, F., Martínez, I. E., & Shruti, V. (2021). Overview of microplastics pollution with heavy metals: analytical methods, occurrence, transfer risks and call for standardization. *Journal of Hazardous Materials, 415*, 125755.

Lima, A. R., Ferreira, G. V., Barrows, A. P., Christiansen, K. S., Treinish, G., & Toshack, M. C. (2021). Global patterns for the spatial distribution of floating microfibers: Arctic Ocean as a potential accumulation zone. *Journal of Hazardous Materials, 403*, 123796.

Liu, G., Dave, P. H., Kwong, R. W. M., Wu, M., & Zhong, H. (2021). Influence of Microplastics on the Mobility, Bioavailability, and Toxicity of Heavy Metals: A Review. *Bulletin of Environmental Contamination and Toxicology, 107*(4), 710-721. https://doi.org/10.1007/s00128-021-03339-9

Liu, S., Huang, Y., Luo, D., Wang, X., Wang, Z., Ji, X., Chen, Z., Dahlgren, R. A., Zhang, M., & Shang, X. (2022). Integrated effects of polymer type, size and shape on the sinking dynamics of biofouled microplastics. *Water Research, 220*, 118656.

Liu, W., Liao, H., Wei, M., Junaid, M., Chen, G., & Wang, J. (2024). Biological uptake, distribution and toxicity of micro(nano)plastics in the aquatic biota: A special emphasis on size-dependent impacts. *TrAC Trends in Analytical Chemistry, 170,* 117477. https://doi.org/https://doi.org/10.1016/j.trac.2023.117477

Liu, Z., Zhou, T., & Gao, D. (2022). Genetic and epigenetic regulation of growth, reproduction, disease resistance and stress responses in aquaculture [Review]. *Frontiers in Genetics, Volume 13* - 2022. https://doi.org/10.3389/fgene.2022.994471

Lu, X., Hu, H., Li, J., Li, J., Wang, L., Liu, L., & Tang, Y. (2023). Microplastics existence affected heavy metal affinity to ferrihydrite as a representative sediment mineral. *Science of the Total Environment, 859*, 160227.

Lu, X., Wang, X., Liu, X., & Singh, V. P. (2023). Dispersal and transport of microplastic particles under different flow conditions in riverine ecosystem. *Journal of Hazardous Materials, 442*, 130033.

Marcharla, E., Vinayagam, S., Gnanasekaran, L., Soto-Moscoso, M., Chen, W.-H., Thanigaivel, S., & Ganesan, S. (2024). Microplastics in marine ecosystems: A comprehensive review of biological and ecological implications and its mitigation approach using nanotechnology for the sustainable environment. *Environmental Research*, 119181.

Marykate, E. M., & Kate, L. S. (2024). Bioaccumulation, transfer, and impacts of microplastics in aquatic food chains. *Journal of Environmental Exposure Assessment, 3*(3), 15. https://doi.org/https://doi.org/10.20517/jeea.2023.49

Menéndez-Pedriza, A., & Jaumot, J. (2020). Interaction of environmental pollutants with microplastics: a critical review of sorption factors, bioaccumulation and ecotoxicological effects. *Toxics, 8*(2), 40.

Meneses Quelal, W. O., Velázquez-Martí, B., & Ferrer Gisbert, A. (2022). Separation of virgin plastic polymers and post-consumer mixed plastic waste by sinking-flotation technique. *Environmental Science and Pollution Research, 29,* 1364-1374.

Menone, M. L., & Pérez, D. J. (2023). Biomarkers in aquatic macrophytes: traditional and novel approaches for monitoring responses to exposure to pollutants. *In The Ecotoxicology of Aquatic Macrophytes* (pp. 11-52). Springer.

Miao, L., Gao, Y., Adyel, T. M., Huo, Z., Liu, Z., Wu, J., & Hou, J. (2021). Effects of biofilm colonization on the sinking of microplastics in three freshwater environments. *Journal of Hazardous Materials, 413,* 125370.

Miranda, L. S., Ayoko, G. A., Egodawatta, P., & Goonetilleke, A. (2022). Adsorption-desorption behavior of heavy metals in aquatic environments: Influence of sediment, water and metal ionic properties. *Journal of Hazardous Materials, 421*, 126743.

Mishra, S. K., Chowdhury, S. D., Bhunia, P., Sarkar, A., Surampalli, R. Y., & Zhang, T. C. (2025). Degradation of Plastics and Formation of Primary and Secondary Microplastics. *Microplastics in the Environment: Fate, Impacts, Removal, and Management*, 43-68.

Mukherjee, C., Varghese, D., Krishna, J., Boominathan, T., Rakeshkumar, R., Dineshkumar, S., Rao, C. B., & Sivaramakrishna, A. (2023). Recent advances in biodegradable polymers–properties, applications and future prospects. *European Polymer Journal*, 192, 112068.

Mutuku, J., Yanotti, M., Tocock, M., & Hatton MacDonald, D. (2024). The abundance of microplastics in the world's oceans: a systematic review. Oceans,

Naqash, N., Prakash, S., Kapoor, D., & Singh, R. (2020). Interaction of freshwater microplastics with biota and heavy metals: a review. *Environmental Chemistry Letters, 18*(6), 1813-1824.

Onyeabor, E. (2024). The Marine Environment. In *Environmental Law: International and Regional African Perspectives on Law and Management* (pp. 761-813). Springer.

Pal, D., Prabhakar, R., Barua, V. B., Zekker, I., Burlakovs, J., Krauklis, A., Hogland, W., & Vincevica-Gaile, Z. (2025). Microplastics in aquatic systems: A comprehensive review of its distribution, environmental interactions, and health risks. *Environmental Science and Pollution Research, 32*(1), 56-88. https://doi.org/10.1007/s11356-024-35741-1

Pan, H., Zhao, X., Zhou, X., Yan, H., Han, X., Wu, M., & Chen, F. (2023). Research progress on the role of biofilm in heavy metals adsorption-desorption characteristics of microplastics: A review. *Environmental Pollution,* 336, 122448.

Pan, I., Umapathy, S., Issac, P. K., Rahman, M. M., Guru, A., & Arockiaraj, J. (2023). The bioaccessibility of adsorped heavy metals on biofilm-coated microplastics and their implication for the progression of neurodegenerative diseases. *Environmental Monitoring and Assessment, 195*(11), 1264.

Pappa, A., Papadimitriou-Tsantarliotou, A., Kaloyianni, M., Kastrinaki, G., Dailianis, S., Lambropoulou, D. A., Christodoulou, E., Kyzas, G. Z., & Bikiaris, D. N. (2021). Insights into the toxicity of biomaterials microparticles with a combination of cellular and oxidative biomarkers. *Journal of Hazardous Materials, 413*, 125335.

Patra, A. K. (2023). Clay-Microbe Interaction: Implications on Soil Health and Environment. *Journal of the Indian Society of Soil Science, 71*, S13-S27.

Pierdomenico, M., Bernhardt, A., Eggenhuisen, J. T., Clare, M. A., Lo Iacono, C., Casalbore, D., Davies, J. S., Kane, I., Huvenne, V. A., & Harris, P. T. (2023). Transport and accumulation of litter in submarine canyons: a geoscience perspective. *Frontiers in Marine Science, 10*, 1224859.

Pierdomenico, M., Morgana, S., & Chiocci, F. L. (2024). First report of microplastics in water and sediments of the alkaline Bagno dell'Acqua Lake (Pantelleria Island, southern Italy). *Environmental Pollution, 362,* 124962. https://doi.org/https://doi.org/10.1016/j.envpol.2024.124962

Pinto, E. P., Scott, J., Hess, K., Paredes, E., Bellas, J., Gonzalez-Estrella, J., & Minghetti, M. (2024). Role of UV radiation and oxidation on polyethylene micro-and nanoplastics: impacts on cadmium sorption, bioaccumulation, and toxicity in fish intestinal cells. *Environmental Science and Pollution Research, 31*(35), 47974-47990.

Prabhu, K., Charles, P. E., Jabeen, K., Rajaram, R., Paramasivam, S., & Selvam, S. (2024). Chapter 14 - Adsorption of heavy metals on microplastics in marine environments. In S. Sekar, V. Senapathi, C. Sabarathinam, & P. M. Viswanathan (Eds.), *Meso and Microplastic Risk Assessment in Marine Environments* (pp. 275-292). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-323-90980-8.00016-9

Provencher, J. F., Au, S. Y., Horn, D., Mallory, M. L., Walker, T. R., Kurek, J., Erdle, L. M., Weis, J. S., & Lusher, A. (2022). Animals and microplastics: ingestion, transport, breakdown, and trophic transfer. *In Polluting textiles* (pp. 33-62). Routledge.

Qian, J., Tang, S., Wang, P., Lu, B., Li, K., Jin, W., & He, X. (2021). From source to sink: Review and prospects of microplastics in wetland ecosystems. *Science of the Total Environment*, 758, 143633.

Rai, P. K., Sonne, C., & Kim, K.-H. (2023). Heavy metals and arsenic stress in food crops: Elucidating antioxidative defense mechanisms in hyperaccumulators for food security, agricultural sustainability, and human health. *Science of the Total Environment,* 874, 162327.

Rakib, M. R. J., Rahman, M. A., Onyena, A. P., Kumar, R., Sarker, A., Hossain, M. B., Islam, A. R. M. T., Islam, M. S., Rahman, M. M., Jolly, Y. N., Idris, A. M., Ali, M. M., Bilal, M., & Sun, X. (2022). A comprehensive review of heavy metal pollution in the coastal areas of Bangladesh: abundance, bioaccumulation, health implications, and challenges. *Environmental Science and Pollution Research, 29*(45), 67532-67558. https://doi.org/10.1007/s11356-022-22122-9

Sabbir, W., Rahman, M., Hasan, M., Khan, M., & Ray, S. (2018). Assessment of heavy metals in river water, sediment and fish mussel in rupsha river under Khulna district, Bangladesh. *Int. J. Expt. Agric, 8*(1), 1-5.

Sanders, D., & Frago, E. (2024). Ecosystem engineers shape ecological network structure and stability: A framework and literature review. *Functional Ecology, 38*(8), 1683-1696.

Sawangproh, W., & Paejaroen, P. (2025). Thailand's animals in peril: a systematic review of microplastic contamination and its ecological consequences. *Environmental Sciences Europe, 37*(1), 14.

Sayed, A. E.-D. H., Soliman, H. A. M., Idriss, S. K., Abdel-Ghaffar, S. K., & Hussein, A. A. A. (2023). Oxidative Stress and Immunopathological Alterations of Clarias gariepinus Exposed to Monocyclic Aromatic Hydrocarbons (BTX). *Water, Air, & Soil Pollution, 234*(6), 354. https://doi.org/10.1007/s11270-023-06343-3

Shamskhany, A., Li, Z., Patel, P., & Karimpour, S. (2021). Evidence of microplastic size impact on mobility and transport in the marine environment: a review and synthesis of recent research. *Frontiers in Marine Science, 8*, 760649.

Song, J., Wang, C., & Li, G. (2024). Defining primary and secondary microplastics: a connotation analysis. *ACS ES&T Water, 4*(6), 2330-2332.

Sterl, M. F., Delandmeter, P., & van Sebille, E. (2020). Influence of Barotropic Tidal Currents on Transport and Accumulation of Floating Microplastics in the Global Open Ocean. *J Geophys Res Oceans, 125*(2), e2019JC015583. https://doi.org/10.1029/2019jc015583

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.

Tang, S., Yang, X., Zhang, T., Qin, Y., Cao, C., Shi, H., & Zhao, Y. (2022). Adsorption mechanisms of metal ions (Pb, Cd, Cu) onto polyamide 6 microplastics: New insight into environmental risks in comparison with natural media in different water matrices. *Gondwana Research, 110*, 214-225.

Turna Demir, F., Akkoyunlu, G., & Demir, E. (2022). Interactions of ingested polystyrene microplastics with heavy metals (cadmium or silver) as environmental pollutants: a comprehensive in vivo study using Drosophila melanogaster. *Biology, 11*(10), 1470.

Uy, C. A., & Johnson, D. W. (2022). Effects of microplastics on the feeding rates of larvae of a coastal fish: direct consumption, trophic transfer, and effects on growth and survival. *Marine Biology, 169*(2), 27.

Venâncio, C., Degara, L., & Pires, A. (2024). Assessing the Impact of Arsenic on Benthic Estuarine Fauna Behavior: Implications for Ecosystem Sustainability. *Sustainability, 16*(22), 9728.

Vimalkumar, K., Sangeetha, S., Felix, L., Kay, P., & Pugazhendhi, A. (2022). A systematic review on toxicity assessment of persistent emerging pollutants (EPs) and associated microplastics (MPs) in the environment using the Hydra animal model. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 256, 109320.

Vo, H. C., & Pham, M. H. (2021). Ecotoxicological effects of microplastics on aquatic organisms: a review. *Environmental Science and Pollution Research, 28,* 44716-44725.

Wang, C., Zhao, J., & Xing, B. (2021). Environmental source, fate, and toxicity of microplastics. *Journal of Hazardous Materials, 407*, 124357.

Wang, L., Wang, H., Huang, Q., Yang, C., Wang, L., Lou, Z., Zhou, Q., Wang, T., & Ning, C. (2023). Microplastics in landfill leachate: a comprehensive review on characteristics, detection, and their fates during advanced oxidation processes. *Water, 15*(2), 252.

Wang, S., Wang, X., Wang, X., Qin, Z., Hu, J., Ding, S., & Feng, K. (2023). Study on the Adsorption Behavior of Cadmium by the MPs and Its Environmental Factors. *Polish Journal of Environmental Studies, 32*(5).

Waqas, W., Yuan, Y., Ali, S., Zhang, M., Shafiq, M., Ali, W., Chen, Y., Xiang, Z., Chen, R., & Ikhwanuddin, M. (2024). Toxic effects of heavy metals on crustaceans and associated health risks in humans: a review. Environmental Chemistry Letters, 22(3), 1391-1411.

Watson, S. M., McLean, D. L., Balcom, B. J., Birchenough, S. N., Brand, A. M., Camprasse, E. C., Claisse, J. T., Coolen, J. W., Cresswell, T., & Fokkema, B. (2023). Offshore decommissioning horizon scan: Research priorities to support decision-making activities for oil and gas infrastructure. *Science of the Total Environment, 878*, 163015.

Wazne, M., Mermillod-Blondin, F., Vallier, M., Hervant, F., Dumet, A., Nel, H. A., Kukkola, A., Krause, S., & Simon, L. (2023). Microplastics in freshwater sediments impact the role of a main bioturbator in ecosystem functioning. *Environmental Science & Technology, 57*(8), 3042-3052.

Wu, B., Yu, H., Yi, J., Lei, P., He, J., Ruan, J., Xu, P., Tao, R., Jin, L., & Wu, W. (2024). Behavioral studies of zebrafish reveal a new perspective on the reproductive toxicity of micro-and nanoplastics. *Toxics*, 12(3), 178.

Xiang, Y., Jiang, L., Zhou, Y., Luo, Z., Zhi, D., Yang, J., & Lam, S. S. (2022). Microplastics and environmental pollutants: key interaction and toxicology in aquatic and soil environments. *Journal of Hazardous Materials, 422*, 126843.

Zhao, Y., Bao, R.-K., Zhu, S.-Y., Talukder, M., Cui, J.-G., Zhang, H., Li, X.-N., & Li, J.-L. (2021). Lycopene prevents DEHP-induced hepatic oxidative stress damage by crosstalk between AHR–Nrf2 pathway. *Environmental Pollution*, 285, 117080.

Zheng, S., & Wang, W.-X. (2024). Contrasting the distribution kinetics of microplastics and nanoplastics in medaka following exposure and depuration. *Journal of Hazardous Materials, 478*, 135620. https://doi.org/https://doi.org/10.1016/j.jhazmat.2024.135620

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.

Zhu, Z., Cao, X., Wang, K., Guan, Y., Ma, Y., Li, Z., & Guan, J. (2024). The environmental effects of microplastics and microplastic derived dissolved organic matter in aquatic environments: a review. *Science of the Total Environment*, 173163.

Zink, L., Mertens, E., Zhou, X., Johnston, S. E., Bogard, M., Wiseman, S., & Pyle, G. G. (2024). Reframing microplastics as a ligand for metals reveals that water quality characteristics govern the association of cadmium to polyethylene. *Science of the Total Environment, 948*, 174659.