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Heavy metals in aquatic food webs: Ecological and health consequences

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Abstract
Heavy metal contamination has emerged as a major environmental challenge threatening aquatic ecosystems and human health worldwide. Rapid industrialization, urbanization, mining activities, agricultural intensification, and improper waste disposal have significantly increased the release of toxic metals into aquatic environments. Heavy metals such as mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) enter water bodies through natural and anthropogenic pathways and subsequently accumulate in water, sediments, and aquatic organisms. Due to their persistence and non-biodegradable nature, these contaminants undergo bioaccumulation within organisms and biomagnification across trophic levels, resulting in elevated concentrations in predatory fish and other higher consumers. Exposure to heavy metals adversely affects aquatic organisms by impairing growth, reproduction, metabolism, immune function, and behavior, while also causing histopathological alterations, oxidative stress, genotoxicity, endocrine disruption, and cellular damage. At the ecosystem level, heavy-metal contamination contributes to biodiversity loss, altered community structure, disrupted food-web interactions, and reduced ecosystem productivity. Human exposure occurs primarily through the consumption of contaminated fish and seafood, posing risks of neurotoxicity, renal dysfunction, developmental abnormalities, carcinogenicity, and other chronic health disorders. Future research should focus on the interactions of heavy metals with emerging pollutants, climate change influences, omics-based biomarkers, and sustainable remediation technologies. Effective monitoring, pollution control, and integrated management strategies are essential for safeguarding aquatic biodiversity, ecosystem health, and food security.

Keywords: Heavy metals, aquatic ecosystem, bioaccumulation, fish toxicity, oxidative stress, environmental pollution

Introduction

Heavy metals are among the most hazardous environmental pollutants because of their persistence, non-biodegradability, and ability to accumulate within living organisms. Industrial development, population growth, agricultural expansion, and increased use of fertilizers and pesticides have accelerated the discharge of heavy metals into aquatic ecosystems. Once introduced into water bodies, these contaminants accumulate in aquatic tissues and eventually enter food chains, posing risks to aquatic organisms and humans alike.

Fish represent one of the most important protein sources worldwide (Karayakar et al., 2022) [6]. However, fish can accumulate substantial concentrations of heavy metals from contaminated water and food sources and subsequently transfer these contaminants through aquatic food webs to humans (Mansour and Sidky, 2002) [7]. Heavy metal contamination has been associated with reduced reproductive capacity, respiratory disorders, neurological dysfunction, and impaired growth in aquatic organisms. Long-term exposure may also contribute to carcinogenic, mutagenic, and teratogenic effects (Pandey and Madhuri, 2014; Shah, 2017) [9, 11].

Recent studies continue to identify heavy metals as major drivers of biodiversity loss and ecosystem degradation in freshwater and marine systems (Wang *et al*., 2026) [17].

Environmental Pathways

Heavy metals enter aquatic environments through both natural and anthropogenic pathways.

Natural sources include volcanic eruptions, weathering of rocks, soil erosion, atmospheric dust deposition, river transport, groundwater discharge, and geological processes. These mechanisms contribute baseline concentrations of metals in aquatic ecosystems.

Anthropogenic activities represent the dominant source of contamination. Industrial sources include mining, smelting, petroleum refining, electroplating, battery manufacturing, textile industries, paint production, fuel combustion, and wastewater discharge (Vaseem and Banerjee, 2016; Verma et al., 2018) [15, 16]. Agricultural practices further contribute through fertilizers, pesticides, sewage sludge application, and irrigation with contaminated wastewater. Mining activities are considered among the most important contributors because they release large quantities of toxic metals into surrounding waters.

Once released into aquatic systems, heavy metals partition among water, sediments, and biota. Sediments often act as long-term reservoirs, gradually releasing contaminants back into the water column where they become available for uptake by aquatic organisms.

Trophic Transfer

Bioaccumulation and biomagnification are two key processes that govern the movement and concentration of heavy metals within aquatic ecosystems. Bioaccumulation refers to the gradual uptake and retention of heavy metals by aquatic organisms from their surrounding environment and food sources when the rate of absorption exceeds the rate of elimination. Aquatic organisms absorb metals directly from contaminated water through gills, skin, and epithelial tissues, as well as indirectly through the consumption of contaminated sediments, plankton, aquatic plants, and prey organisms. Because heavy metals are non-biodegradable and can persist in tissues for long periods, their concentrations tend to increase over time, particularly in metabolically active organs such as the liver, kidneys, gills, and muscles (Mansour and Sidky, 2002; Osman *et al*., 2007) [7, 8].

Biomagnification occurs when the concentration of heavy metals progressively increases at successive trophic levels of the food web. Primary producers and microorganisms absorb metals from water and sediments, which are subsequently transferred to zooplankton, benthic invertebrates, and small fish. As predators consume contaminated prey, metal concentrations become increasingly elevated in higher trophic levels. Consequently, large predatory fish such as tuna, swordfish, sharks, and marlin often contain substantially higher concentrations of toxic metals than organisms at lower trophic levels. Among heavy metals, methylmercury exhibits the greatest biomagnification potential because of its high bioavailability, persistence, and affinity for biological tissues.

The extent of bioaccumulation and biomagnification is influenced by several factors, including metal speciation, environmental conditions, organism age and size, feeding behavior, trophic position, metabolic rate, and water chemistry. Changes in pH, temperature, salinity, and dissolved organic matter can alter metal bioavailability and uptake rates. As a result, heavy-metal contamination can be efficiently transferred through aquatic food webs, posing ecological risks to aquatic organisms and increasing the likelihood of human exposure through the consumption of contaminated fish and seafood (Goodwin et al., 2003; Verma *et al*., 2018; Wang *et al*., 2026) [4, 16, 17].

Biological and Ecological Impacts

Heavy metals can adversely affect aquatic organisms at individual, population, and ecosystem levels. Exposure to toxic metals such as mercury, cadmium, lead, arsenic, chromium, and nickel disrupts normal physiological processes, leading to reduced growth, impaired metabolism, behavioral abnormalities, and increased mortality. The gills, liver, kidneys, gonads, and nervous system are among the most vulnerable organs because they are directly involved in respiration, detoxification, excretion, reproduction, and neurological regulation. Heavy-metal accumulation in these tissues often results in histopathological alterations, reduced oxygen uptake, impaired osmoregulation, reproductive dysfunction, developmental abnormalities, and weakened immune responses (Afshan *et al*., 2014; Pandey & Madhuri, 2014) [2, 9].

In fish and other aquatic organisms, chronic exposure may reduce feeding efficiency, alter swimming behavior, decrease reproductive success, and increase susceptibility to diseases and environmental stressors. For example, mercury and lead are known to induce neurotoxicity and behavioral disturbances, whereas cadmium and arsenic can impair growth and reproductive performance. Additionally, heavy metals can interfere with hematological parameters, enzyme activities, and endocrine functions, ultimately reducing organismal fitness and survival (Shah, 2017; Vajargah, 2021) [11, 14].

Beyond individual organisms, heavy-metal contamination can have profound ecological consequences. Persistent metal accumulation may alter species composition, reduce biodiversity, and disrupt trophic interactions within aquatic food webs. Sensitive species often decline or disappear from contaminated habitats, while more tolerant species become dominant, leading to changes in community structure and ecosystem functioning. Heavy metals can also affect primary producers, zooplankton, benthic organisms, and fish populations, thereby influencing nutrient cycling, energy flow, and overall ecosystem productivity. Through bioaccumulation and biomagnification, these contaminants are transferred across trophic levels, posing long-term risks to aquatic biodiversity and ecosystem stability. Recent studies further suggest that interactions between heavy metals, climate change, and emerging pollutants such as microplastics may intensify ecological impacts and increase the vulnerability of aquatic ecosystems to environmental degradation (Wang *et al*., 2026; Adeleye *et al*., 2024) [1, 17].

Table 1: Toxic Effects of Major Heavy Metals on Aquatic Organisms

Metal	Main Target Organs	Major Effects
Mercury (Hg)	Brain, liver, muscle	Neurotoxicity, oxidative stress
Cadmium (Cd)	Kidney, liver, gonads	Reproductive impairment, tissue damage
Lead (Pb)	Brain, bone, liver	Developmental and neurological disorders
Arsenic (As)	Liver, kidney	Carcinogenicity, cellular damage
Chromium (Cr)	Gills, liver	DNA damage, oxidative stress
Nickel (Ni)	Gills	Respiratory dysfunction
Copper (Cu)	Liver, gills	Enzyme inhibition
Zinc (Zn)	Gills, kidney	Growth impairment at high concentrations

Toxicity Mechanisms

Heavy metals exert toxicity through multiple interconnected molecular and cellular pathways that collectively impair the health and survival of aquatic organisms. One of the primary mechanisms is the generation of reactive oxygen species (ROS), which disrupt the balance between oxidants and antioxidants, leading to oxidative stress. Excessive ROS production damages cellular lipids, proteins, and nucleic acids, resulting in membrane dysfunction, mitochondrial impairment, and tissue injury (Jaishankar *et al*., 2014) [5]. Although antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase are activated in response to metal exposure, prolonged contamination can overwhelm these defense systems and cause irreversible cellular damage.

Heavy metals also induce genotoxic effects by causing DNA strand breaks, chromosomal aberrations, mutations, and disruptions in DNA repair mechanisms. Metals such as chromium, cadmium, arsenic, nickel, and lead are particularly associated with genetic damage, which may impair growth, reproduction, and development while increasing susceptibility to carcinogenesis (Rossman, 2003; Jaishankar et al., 2014) [5, 10]. In addition, heavy-metal exposure can trigger apoptosis and other forms of programmed cell death through mitochondrial dysfunction, calcium imbalance, and activation of caspase-mediated pathways. These processes contribute to tissue degeneration and histopathological alterations frequently observed in the gills, liver, kidneys, and reproductive organs of aquatic organisms.

Furthermore, heavy metals interfere with endocrine and immune functions by disrupting hormonal regulation, reproductive signaling, and immune-cell activity. Such disturbances can reduce reproductive success, suppress disease resistance, and increase vulnerability to environmental stressors. Heavy metals also inhibit key metabolic enzymes, alter ion transport systems, and impair cellular energy production by disrupting mitochondrial respiration and ATP synthesis. Emerging evidence suggests that heavy-metal exposure may induce epigenetic modifications, including changes in DNA methylation and gene expression, which could have long-term and even transgenerational consequences for aquatic populations. Collectively, these molecular and cellular disturbances underpin the physiological, behavioral, and ecological effects associated with heavy-metal contamination in aquatic ecosystems. (Shah, 2017; Sharma *et al*., 2025) [11, 12].

Health risks

Heavy metals present in aquatic environments can ultimately reach humans through the consumption of contaminated fish, shellfish, and other aquatic organisms. Because many aquatic species occupy different trophic levels and are capable of accumulating heavy metals over time, aquatic food chains serve as an important pathway for the transfer of these contaminants from the environment to humans. Bioaccumulation within individual organisms and biomagnification across trophic levels often result in the highest concentrations being found in large predatory fish, thereby increasing the risk of human exposure through seafood consumption (Mansour & Sidky, 2002; Afshan *et al*., 2014) [2, 7].

The health risks associated with heavy-metal exposure depend on the type of metal, concentration, duration of exposure, and susceptibility of the exposed population. Mercury, particularly in the form of methylmercury, is a potent neurotoxin that can impair cognitive function, memory, motor coordination, and fetal neurological development. Lead exposure has been linked to developmental disorders, reduced intellectual capacity, kidney dysfunction, and cardiovascular diseases, especially in children. Cadmium primarily accumulates in the kidneys and may cause renal damage, skeletal disorders, and impaired calcium metabolism, while chronic arsenic exposure is associated with skin lesions, neurological disorders, cardiovascular complications, and various forms of cancer (Rossman, 2003; Jaishankar *et al*., 2014) [5, 10].

In addition to direct toxic effects, heavy metals may interfere with essential biological processes by disrupting enzyme activity, hormonal regulation, immune function, and nutrient metabolism. Long-term dietary exposure through contaminated aquatic products can therefore contribute to chronic health problems, including reproductive disorders, endocrine disruption, immunosuppression, and increased susceptibility to non-communicable diseases. Vulnerable groups such as pregnant women, infants, children, and populations with high seafood consumption are particularly at risk because heavy metals can cross the placental barrier and affect fetal growth and development. Consequently, continuous monitoring of heavy-metal concentrations in aquatic organisms, adherence to food safety standards, and effective management of aquatic pollution are essential for protecting public health and ensuring the safe consumption of fish and seafood products (Arora *et al*., 2008; Shah, 2017; Wang *et al*., 2026) [3, 11, 17].

Further Research Needs

Despite significant advances in understanding heavy-metal contamination in aquatic ecosystems, several knowledge gaps remain. Future research should focus on the combined effects of heavy metals with other emerging pollutants, such as microplastics, pharmaceuticals, pesticides, and nanomaterials, as these interactions may alter metal bioavailability, toxicity, and ecological impacts. Additionally, climate change-related factors, including rising temperatures, ocean acidification, altered precipitation patterns, and changes in salinity, are expected to influence the mobility, speciation, and toxicity of heavy metals, necessitating long-term studies under realistic environmental conditions (Adeleye *et al*., 2024) [1].

Recent developments in molecular biology and environmental toxicology offer new opportunities for understanding the mechanisms of heavy-metal toxicity. Advanced approaches such as genomics, transcriptomics, proteomics, metabolomics, and epigenetics can provide deeper insights into cellular responses, early biomarkers of exposure, and transgenerational effects. Integrating these tools with conventional ecotoxicological assessments may improve the accuracy of environmental risk evaluations and facilitate the development of effective monitoring programs (Tang *et al*., 2023) [13].

There is also a growing need for innovative, sustainable, and cost-effective remediation technologies capable of removing heavy metals from aquatic environments without causing secondary pollution. Nature-based solutions, including phytoremediation, microbial bioremediation, constructed wetlands, and biochar-based adsorbents, have shown considerable promise and warrant further investigation. Furthermore, the application of artificial intelligence, machine learning, remote sensing, and environmental modeling could enhance pollution surveillance, predict contamination hotspots, and support evidence-based management strategies. Strengthening international collaboration, regulatory frameworks, and integrated watershed management approaches will be essential for mitigating heavy-metal pollution, protecting aquatic biodiversity, and ensuring the long-term sustainability of aquatic resources and food security (Wang *et al*., 2026) [17].

Conclusion

Heavy metals remain among the most significant contaminants affecting aquatic ecosystems. Their persistence, bioaccumulation, and biomagnification enable transfer through aquatic food webs, resulting in physiological, ecological, and human-health consequences. Exposure causes reproductive impairment, respiratory dysfunction, oxidative stress, genotoxicity, immune suppression, and biodiversity loss. As industrialization and environmental pressures continue to increase, comprehensive monitoring, effective pollution control policies, and innovative remediation strategies are essential for protecting aquatic biodiversity and safeguarding public health.

References

1. Adeleye AT, Bahar MM, Megharaj M, Fang C, Wang L. The Unseen Threat of the Synergistic Effects of Microplastics and Heavy Metals in Aquatic Environments: A Critical Review. Current Pollution Reports, 2024.
2. Afshan S, Ali S, Chaudhry AU, Ahmad R, Farid M, Shakoor MB, et al. Effect of Different Heavy Metal Pollution on Fish. Research Journal of Chemical and Environmental Sciences,2014:2(1):74–79.
3. Arora M, Kiran B, Rani S, Rani A, Kaur B, Mittal N. Heavy Metal Accumulation in Vegetables Irrigated with Water from Different Sources. Food Chemistry,2008:111(4):811–815.
4. Goodwin TH, Young AR, Holmes MGR, Old GH, Hewitt N, Leeks GJL, et al. The Temporal and Spatial Variability of Sediment Transport and Metal Contamination in Rivers. Science of the Total Environment, 2003, 667–679.
5. Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. Toxicity, Mechanism and Health Effects of Some Heavy Metals. Interdisciplinary Toxicology,2014:7(2):60–72.
6. Karayakar F, et al. Nutritional Importance of Fish and Seafood Consumption: A Review. Aquaculture and Fisheries,2022:7(4):315–324.
7. Mansour SA, Sidky MM. Ecotoxicological Studies of Heavy Metals Contaminating Water and Fish from Fayoum Governorate, Egypt. Food Chemistry,2002:78(1):15–22.
8. Osman AGM, Abuel-Fadl KY, Kloas W. In Situ Evaluation of the Genotoxic Potential of the River Nile. Mutation Research,2007:631(1):14–21.
9. Pandey G, Madhuri S. Heavy Metals Causing Toxicity in Animals and Fishes. Research Journal of Animal, Veterinary and Fishery Sciences,2014:2(2):17–23.
10. Rossman TG. Mechanism of Arsenic Carcinogenesis: An Integrated Approach. Mutation Research,2003:533(1–2):37–65.
11. Shah AI. Heavy Metal Impact on Aquatic Life and Human Health – An Over View. IAIA17 Conference Proceedings, International Association for Impact Assessment, Montréal, Canada, 2017.
12. Sharma M, Kant R, Sharma AK, Sharma AK. Exploring the Impact of Heavy Metals Toxicity in the Aquatic Ecosystem. International Journal of Energy and Water Resources,2025:9(1):267–280.
13. Tang Z, Liu X, Niu X, Yin H, Liu M, Zhang D, et al. Ecological Risk Assessment of Aquatic Organisms Induced by Heavy Metals in the Estuarine Waters of the Pearl River. Scientific Reports,2023:13(1):9145.
14. Vajargah MF. A Review on the Effects of Heavy Metals on Aquatic Animals. Journal of Biomedical Research and Environmental Sciences,2021:2(9):865–869.
15. Vaseem H, Banerjee TK. Heavy Metal Pollution and Its Impact on Aquatic Ecosystems: A Review. International Journal of Fisheries and Aquatic Studies,2016:4(1):211–218.
16. Verma N, et al. Sources and Environmental Impacts of Heavy Metals in Aquatic Ecosystems. Environmental Pollution Reviews,2018:26(3):105–120.
17. Wang J, Deng Q, Ma Y, Feng J, Shui B, Hu C. Trophic Transfer and Potential Human Health Risk Assessment of Heavy Metals in Food Web from Waters Adjacent to Yanpu Bay, China. Marine Pollution Bulletin,2026:222:118646.