



## Heavy metals in aquatic ecosystems and their consequences on fish health: A comprehensive review

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### Abstract

Aquatic ecosystems across the globe are increasingly threatened by heavy metal contamination due to rapid industrialization, urban expansion, agricultural intensification, and improper waste disposal. Heavy metals such as cadmium, lead, mercury, arsenic, chromium, copper, nickel, and zinc persist in the aquatic environment because of their non-biodegradable nature and long biological half-lives. Fish, as integral components of aquatic food webs and key indicators of environmental health, are particularly vulnerable to heavy metal exposure. Uptake of metals occurs through gills, digestive tract, and skin, leading to bioaccumulation in vital organs such as liver, kidney, gills, and muscle. Heavy metal toxicity in fish manifests through a wide range of adverse effects, including physiological dysfunction, oxidative stress, histopathological damage, hematological alterations, immune suppression, endocrine disruption, reproductive failure, and genotoxicity. Chronic exposure not only affects fish survival and population sustainability but also poses significant risks to human health through consumption of contaminated fish. This review provides a comprehensive synthesis of current knowledge on sources, uptake mechanisms, bioaccumulation patterns, and toxicological effects of heavy metals on fish health. The use of fish as bioindicators and biomarkers for aquatic pollution assessment is also discussed. Emphasis is placed on the need for continuous monitoring, stricter environmental regulations, and sustainable pollution management strategies to protect aquatic biodiversity and ensure food safety.

**Keywords:** Aquatic pollution, bioaccumulation, heavy metals, fish health, immunotoxicity, oxidative stress

### Introduction

Aquatic ecosystems serve as vital reservoirs of biodiversity and provide essential ecosystem services, including food security, nutrient cycling, and livelihood support for millions of people worldwide. However, increasing anthropogenic pressure has led to widespread degradation of freshwater and marine environments. Among the various pollutants affecting aquatic systems, heavy metals are considered one of the most hazardous due to their toxicity, persistence, and ability to bioaccumulate in living organisms (Ali *et al.*, 2019)<sup>[1]</sup>.

Heavy metals are defined as metallic elements with high atomic weight and density that are toxic even at low concentrations. Unlike organic pollutants, heavy metals cannot be degraded and tend to accumulate in sediments and biota, thereby exerting long-term ecological impacts (Jaishankar *et al.*, 2014)<sup>[6]</sup>. Fish are particularly sensitive to metal pollution and occupy a crucial position in aquatic food chains, making them ideal indicators of environmental contamination (Authman *et al.*, 2015)<sup>[2]</sup>.

Exposure to heavy metals has been shown to disrupt multiple biological systems in fish, leading to reduced growth, impaired reproduction, altered behavior, increased disease susceptibility, and mortality. Furthermore, consumption of contaminated fish represents a major route of metal exposure to humans, raising concerns about food safety and public health (Tchounwou *et al.*, 2012)<sup>[13]</sup>. Therefore, understanding the effects of heavy metals on fish health is of paramount importance for environmental risk assessment and ecosystem management.

### Sources of Heavy Metals in Aquatic Ecosystems

#### Natural Sources

Naturally occurring heavy metals enter aquatic systems through geological processes such as rock weathering,

volcanic eruptions, and soil erosion. These sources usually contribute low background concentrations of metals, which are generally within the tolerance limits of aquatic organisms (Förstner & Wittmann, 2012).

#### Anthropogenic Sources

Anthropogenic activities are the dominant contributors to heavy metal pollution in aquatic environments. Major sources include industrial effluents from mining, smelting, electroplating, textile, tannery, and battery manufacturing units; agricultural runoff containing metal-based pesticides and fertilizers; municipal sewage; and combustion of fossil fuels (Nagajyoti *et al.*, 2010)<sup>[10]</sup>. In developing countries, untreated industrial and domestic wastewater discharge into rivers significantly elevates metal concentrations beyond permissible limits.

#### Heavy Metal Uptake and Bioaccumulation in Fish

Fish absorb heavy metals primarily through gills, gastrointestinal tract, and skin. The gills are the main site for uptake of dissolved metals due to their large surface area and direct contact with water (Evans *et al.*, 2005)<sup>[5]</sup>. Dietary intake through contaminated prey and sediments represents another major exposure route, especially for benthic and carnivorous fish species.

Once absorbed, metals are transported via the bloodstream and accumulated in specific tissues. The liver serves as the primary detoxification organ, binding metals to metallothioneins, while kidneys play a key role in excretion. Gills and muscles also accumulate metals, with muscle tissue being of particular concern due to its direct relevance to human consumption (Burger & Gochfeld, 2005)<sup>[4]</sup>.

Bioaccumulation depends on several factors, including metal type, concentration, exposure duration, fish species, age, trophic level, and environmental parameters such as pH and temperature (Wang & Rainbow, 2008).

### Physiological Effects of Heavy Metals on Fish

Heavy metals disrupt normal physiological processes by interfering with enzyme activity, ion regulation, and metabolic pathways. Metals such as cadmium and lead impair osmoregulation by damaging gill epithelium, resulting in altered sodium and chloride balance (Wood *et al.*, 2012). Respiratory distress is another common effect, caused by reduced oxygen uptake due to gill damage and increased mucus secretion. Chronic exposure often results in reduced feeding efficiency, slower growth rates, and decreased swimming performance, ultimately affecting survival and fitness (Jeziarska *et al.*, 2009)<sup>[7]</sup>.

### Histopathological Alterations

Histopathological examination provides direct evidence of metal-induced tissue damage. Gills exposed to heavy metals frequently exhibit epithelial lifting, lamellar fusion, hyperplasia, and necrosis, which impair respiratory and osmoregulatory functions (Mallatt, 1985)<sup>[9]</sup>. The liver shows hepatocellular degeneration, vacuolization, necrosis, and disruption of hepatic cords following metal exposure. Renal damage includes tubular degeneration, glomerular shrinkage, and impaired filtration capacity (Hinton *et al.*, 2001). These structural changes compromise organ function and serve as reliable biomarkers of metal toxicity.

### Oxidative Stress and Biochemical Toxicity

One of the primary mechanisms of heavy metal toxicity is the induction of oxidative stress. Metals generate reactive oxygen species (ROS), overwhelming the antioxidant defense system and leading to lipid peroxidation, protein oxidation, and DNA damage (Lushchak, 2011)<sup>[8]</sup>. Studies have reported altered activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) in metal-exposed fish (Pandey *et al.*, 2003)<sup>[11]</sup>. Persistent oxidative stress contributes to cellular dysfunction and apoptosis.

### Hematological Effects

Hematological parameters are sensitive indicators of physiological stress. Heavy metal exposure often results in decreased hemoglobin concentration, reduced red blood cell count, and altered leukocyte profiles, indicating anemia and immune dysfunction (Witeska, 2005). Such changes impair oxygen transport and immune competence, reducing the ability of fish to cope with environmental stressors.

### Immunotoxic Effects

Heavy metals adversely affect both innate and adaptive immune responses in fish. Suppression of macrophage activity, reduced lysozyme levels, and impaired antibody production have been documented in metal-exposed fish (Kumar *et al.*, 2017). Immunosuppression increases susceptibility to pathogens, leading to higher disease incidence and mortality in polluted environments.

### Reproductive and Endocrine Disruption

Heavy metals interfere with endocrine regulation by disrupting hormone synthesis, secretion, and receptor binding. Metals such as cadmium and mercury impair gonadal development, reduce fecundity, and affect spawning behavior (Sumpter, 2005)<sup>[12]</sup>. Embryotoxic and teratogenic effects, including reduced egg viability and

abnormal larval development, have also been reported, threatening population sustainability.

### Genotoxic and Molecular Effects

Several heavy metals exhibit genotoxic properties, inducing DNA strand breaks, chromosomal aberrations, and micronuclei formation in fish cells (Bolognesi & Hayashi, 2011)<sup>[3]</sup>. Molecular biomarkers such as altered gene expression of stress and detoxification-related genes provide early warning signals of metal exposure.

### Fish as Bioindicators of Heavy Metal Pollution

Fish are widely used as bioindicators due to their ecological relevance, sensitivity to pollutants, and ability to bioaccumulate metals. Biomarkers at biochemical, cellular, tissue, and organismal levels offer valuable tools for monitoring aquatic pollution and assessing ecological risk (van der Oost *et al.*, 2003)<sup>[14]</sup>.

### Implications for Human Health

Consumption of metal-contaminated fish poses significant health risks to humans, including neurological, renal, cardiovascular, and carcinogenic effects. Methylmercury exposure through fish consumption is a major concern, particularly for pregnant women and children (WHO, 2007)<sup>[15]</sup>.

### Conclusion and Future Perspectives

Heavy metal pollution represents a serious threat to fish health and aquatic ecosystem integrity. The wide range of toxic effects—from physiological dysfunction to genetic damage—highlights the need for integrated monitoring and management strategies. Future research should focus on combined metal toxicity, climate change interactions, and the application of molecular tools for early detection. Strengthening environmental regulations and promoting sustainable industrial practices are essential to protect aquatic life and ensure food safety.

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