Eco-Toxicity Unveiled: Heavy Metals and Their Role in Fish and Aquatic Health

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Abstract

Heavy metal contamination poses a significant environmental hazard, particularly to aquatic ecosystems, due to its non-biodegradable and persistent nature. Increased levels of heavy metals negatively impact aquatic organisms, particularly fish, by generating reactive oxygen species and inducing oxidative stress through the production of oxidising radicals. Exposure to heavy metals induces haematological and biochemical changes, encompassing cellular and nuclear problems in multiple fish species. It alters blood parameters, compromises immune system activities, influences hormonal and enzymatic activity that resulting in systemic toxicity. Principal organs including gills, liver, kidneys, intestines and muscles, demonstrate considerable tissue damage associated with acute and chronic heavy metal exposure. Histopathological analyses demonstrate organ-specific diseases resulting from heavy metal deposition, underscoring the adverse impacts on fish health. The manifestation of genes associated with oxidative stresses and detoxification systems is modified, signifying disturbances in antioxidant defenses and cellular signaling pathways. In this chapter, we will discuss the systemic and molecular disturbances induced by heavy metal pollution in aquatic ecosystems. The results highlight the necessity of protecting aquatic ecosystems from heavy metal contamination and advocating for sustainable management strategies to alleviate their impacts.

Keywords: Heavy metal contamination; Oxidative stress; Organ-specific diseases; Antioxidant defense; Management strategies

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Introduction

The industrial revolution marked a turning point on environment as rapid industrialization introduced unprecedented levels of pollutants into natural ecosystem. Rapid industrial expansion, escalation energy demands and unchecked resources exploitation have accelerated environment pollution over past few decades (Gautam et al., 2016). Aquatic ecosystem which is crucial for supporting the biodiversity, regulating climate and sustaining nutrition cycle has been affected. The aquatic ecosystem is gradually threatened by various forms of pollution such as thermal waste, plastic pollution, organic and inorganic contaminants (Zeitoun & Mehana, 2014). These contaminants elevate fatalities among particular animal and plant species, alter physiological functions, and deteriorate the physicochemical qualities of water to the extent that it becomes unsuitable for human consumption (Alimba & Faggio, 2019).

The diverse organic and inorganic hazardous substances are perpetually emitted from multiple throughout natural and artificial sources throughout land and aquatic ecosystems. Heavy metals are significant cause of the ecological disruption because of their poisonous properties. It also have the tendency to lead bioaccumulation in the food chain (Briffa et al., 2020). The phrase heavy metal describes any metallic chemical element defined by its high density and toxic nature, at even low concentrations (Gheorghe et al., 2017). In biology, heavy metals are typically categorized as essential and non-essential metals. The essential metals (Fe, Cu, Zn) facilitate biological processes and are non-toxic at trace levels within an organism; but they can become hazardous if concentrations surpass a certain threshold (Keller et al., 2018). The non-essential metals like Pb, Cd, Cr etc, lack biological function and are naturally hazardous, even at trace levels. Regardless of a metal's classification as essential or non-essential, being exposed to excessive levels can result in significant detrimental health effects. They cannot be created or extinguished and are closely associated with environmental degradation due to their ability to produce toxicity in living organisms (Sarkar et al., 2022).

The natural origins of heavy metals mostly consist of volcanic eruptions and weathering of rocks, whereas artificial sources encompass waste from agriculture, industrial activity, fossil fuel burning, petrol, waste incineration, and mining (Garai et al., 2021). Each of these sources of contamination impact the physicochemical properties of water, sediments, and living entities, hence affecting the overall health of fish populations (Figure 1). Heavy metals are inherent constituents of the Earth's crust that are indestructible and non-degradable (Singh et al., 2020). Although they naturally occur as trace elements in aquatic environments, their concentrations have increased due to industrial waste, geochemical structures, and farming and mining operations (Sprocati et al., 2006).

The absorption and bioaccumulation of heavy metals are affected by various factors, including the concentration of heavy metals and the period of exposure, interactions with other metals, the age and morphological attributes of fish, detoxifying mechanisms, metabolic impacts, feeding behavior, and the physicochemical aspects of the environment (Delahaut et al., 2020). Fish are among the most extensively spread species in aquatic ecosystems and are vulnerable to metal contamination (Youssef & Tavel, 2004). The homeostatic mechanisms of fish are significantly influenced by their surrounding environment, where even little alterations in water quality can induce a variety of stresses (Singh et al., 2023). Aquatic biota rapidly exposed to dissolved heavy metals in water or soil suffer neurological impairment, inhibiting fish interactions with their environment (Luo et al., 2014).

2. The Dynamics of Bioaccumulation and Sources of heavy Metals in Aquatic Ecosystems

Ecotoxicology is the study of the adverse effects of chemical and physical substances on living organisms, with a particular emphasis on the populations and communities in specific ecosystems (Yu et al., 2020). It comprises the transmission channels of these agents and their relationship with the environment (Gupta et al., 2021). Among them, heavy metals are major cause of disturbance of the ecosystem, not only due to their poisonous characteristics but also because they have the potential for bioaccumulation within the food chain (Briffa et al., 2020). The characteristics of bioaccumulation and biomagnification in cells and tissues of living organisms, together with the incapacity to eradicate them by oxidation or bioremediation, render these components very alarming, similar to organic pollutants (Ngo et al., 2011; Jamil Emon et al., 2023). The unrestricted use and accumulation of these metals provide a considerable health hazard, as most are non-biodegradable into non-toxic forms, hence exerting detrimental effects on human health and aquatic organisms (Lu et al., 2015). These pollutants impact the physicochemical properties of water, sediments and living entities, hence influencing the quality and quantity of fish populations (Singh et al., 2020; Jamil Emon et al., 2023).

The aquatic toxicology has a negative influence on the development and social behaviors of aquatic invertebrates, stimulate oxidative stress, cause DNA damage and potentially lead to teratogenic and carcinogenic effects (Xu et al., 2016). High densities of these contaminants in water ecosystems can also cause danger, as they accumulate in fish and shellfish, leading to toxic exposure in humans through consumption (Sun et al., 2010). They can cause serious health issues, neurological damage and organ dysfunction (Jasim et al., 2016). These toxicants frequently result in two categories of health effects. The first possesses carcinogenic qualities, while the other exhibits non-carcinogenic properties. These impacts can be quantified using target hazard quotients (THQ) and target cancer risk (TR). Therefore, contamination of heavy metals in aquatic creatures remains in food chain, resulting in transmission to human body (Rahman et al., 2012).

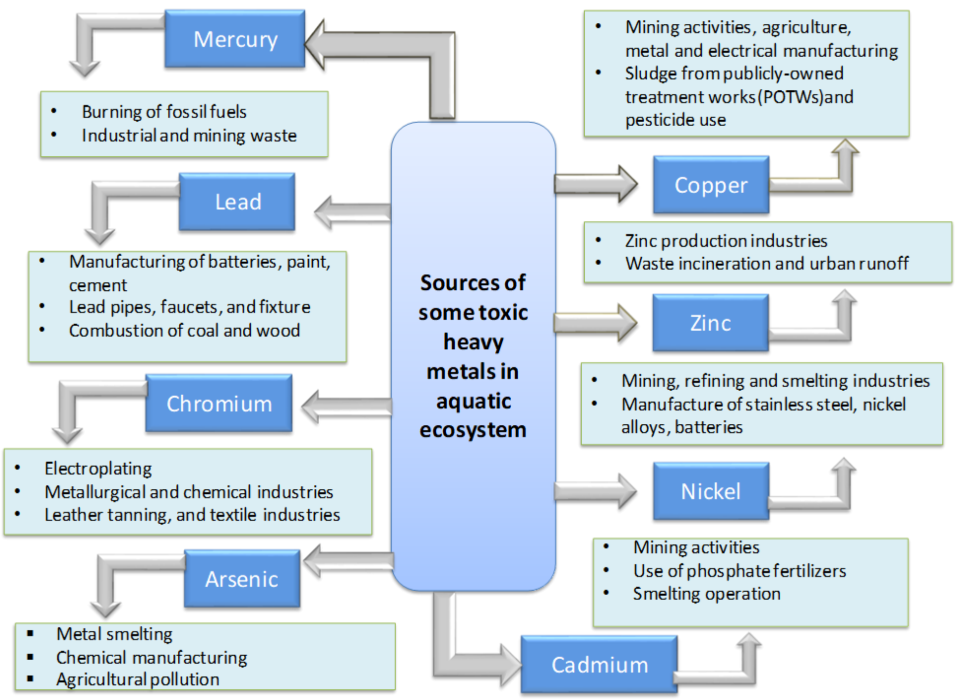

Fig. 1: Toxicity of heavy metals from different sources

3. Lethal Concentration of heavy Metals on fish

Heavy metals toxicity causes significant negative effects on aquatic environment when it is beyond the tolerance level. Toxicity tests are performed to examine the impact of heavy metals on the physiology of fish and other aquatic species. Some trace elements, including Cu, Zn, Fe and Cr are vital for maintaining basic metabolic process of fish but when they cross the threshold concentration, they cause toxicity. However, some non-essential metals including Pb, Hg, Ni and As induce toxicity at minimal concentrations (Wood et al., 2016). Here are some trace elements that cause adverse effect on fish health are discussed below.

3.1 Mercury (Hg)

Mercury is regarded as a severe environmental contaminant and is among the foremost dangerous metals present in our ecosystem.

Mercury is emitted from both natural and synthetic sources. It permeates the water and soil via natural deposits, waste disposal, and the use of mercury-laden fungicides The LC_{50} value were less for Hg in case of *R.sumatrana* than *P. reticulate,* this indicates that *R. sumatrana* exhibited greater susceptibility to heavy metal poisoning compared to *P. reticulate*. Mercury contamination exposed fish gill respiration deficiency, edema, hypertrophy and epithelial cell lesions on *Channa punctata*. Additionally, it is commonly stated that toxicants cause lamellar fusion in the secondary lamellae of carp (Jasim et al., 2016).

3.2 Cadmium (Cd)

Cadmium is a hazardous and nonessential transition metal that poses a significant risk to several organisms in aquatic settings. It is present in the crust of the earth in a standard proportion of 0.1-0.5 ppm and is frequently located along with zinc, copper, and lead ores (Jaiswal et al., 2018). Cadmium is regarded as the most hazardous metal for aquatic ecosystem due to its significant accumulation and delayed excretion rates (Das et al., 2023). Cadmium exhibited greater toxicity in the freshwater prawn *Macrocherax destructor* and juvenile clams *Mercenaria mercenaria*, indicating that biological variables, including genetic composition, account for differences in heavy metal toxicity. Exposure of cadmium impaired gonadal function and sexual maturation in fish (Zhang et al., 2017). It is an endocrine disruptor and a vitellogenesis inhibitor (Haverinen et al., 2021).

3.3 Arsenic (As)

Arsenic is a prevalent element released into aquatic environments from multiple anthropogenic sources, including industrial sites, smelting operations, and power production plants. Arsenic present both in organic and inorganic form but inorganic arsenic is highly toxic and easily absorbed into fish tissues (Kumari et al., 2017). The LC_{50} for *Orechromis mossambicus* exposed to arsenic demonstrates that reduced LC_{50} values are associated with comparable arsenic exposure levels, leading to changes in the tissues of gills and liver cells of the freshwater fishes (Figure 2). The liver histology demonstrated macrophage infiltration, enhanced vascularization, hepatocyte atrophy, sinusoidal dilation, vascular degeneration, nuclear hypertrophy and localized necrosis in *Channa punctatus* (Hwang et al., 2019). A variety of histological changes was observed in the heart of teleosts (Dangleben et al., 2013).

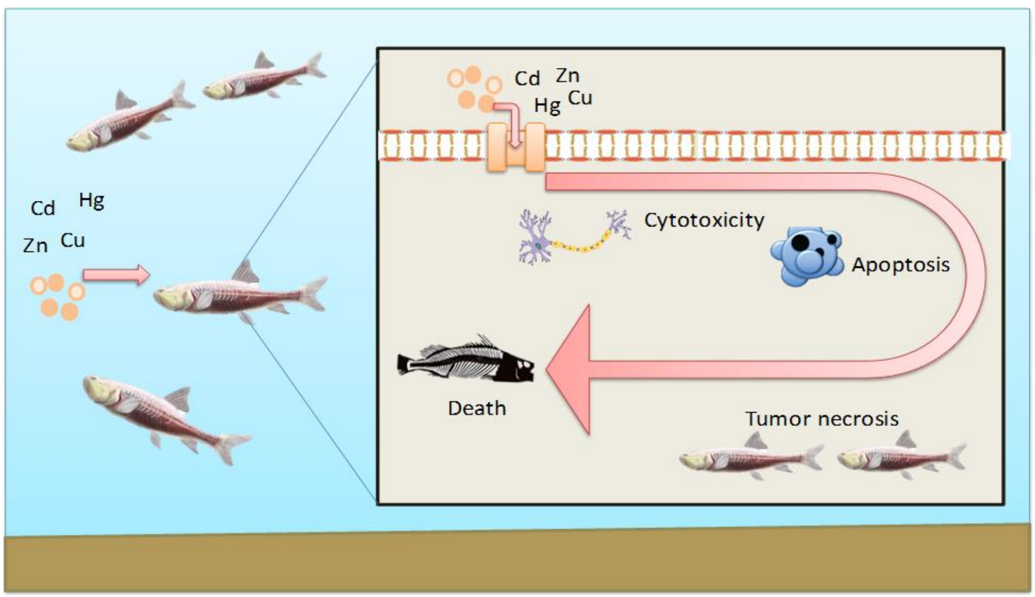

Fig. 2: Toxic pathway of heavy metals in fish cells: Mechanism leading to mortality

3.4 Chromium (Cr)

Chromium is a common metal contaminant in the environment, often entering aquatic systems through effluents from industries such as textiles, tanneries, mining, electroplating, dyeing, printing, photographic printing, and pharmaceuticals (Ahmed et al., 2013). Initial exposure of fish to chromium resulted in several behavioral alterations, including erratic swimming, mucus secretion, color change and decreased hunger etc. Chromium accumulation in the tissue of *Cyprinus carpio* reduce overall protein and fat levels in the muscle, liver and gill. Prolonged exposure to chromium demonstrated cytotoxic effects, reduced lymphocyte activation and impaired phagocyte activities in aquatic fish. It incorporated into fish tissues predominantly in the liver and is found at significantly higher concentrations than in the surrounding environment (Dar et al., 2016).

3.5 Lead (Pb)

Lead is a bluish-gray in color and is occurs naturally in the earth's crust. Lead enters the aquatic ecosystem via precipitation, dry deposition, soil leaching, municipal and industrial waste (Carocci et al., 2016). It is additionally stored in the liver, spleen, kidneys, gastrointestinal tract and gills of fish. A 96-hour lead exposure experiment in Zebrafish indicated that the lethal concentration value was elevated in hard water relative to that in soft water (Kim et al., 2020). Acute lead intoxication results in damage to the gill epithelium and asphyxia Chronic lead toxicity can affect blood chemistry characteristics, resulting in harm to red blood cells, white blood cells and the neurological system (Yildirim et al., 2009).

3.6 Zinc (Zn)

Zinc is an ever-present trace element and a crucial micronutrient for living organisms. Zinc contamination in the environment is escalating due to several anthropogenic sources, including industrial operations, mining, coal combustion and waste disposal (Wuana et al., 2011). Zinc toxicity is particular to species and varies among different developmental stages. Zinc acute toxic concentrations lethally damage fish by damaging gill tissue, whereas chronic toxic levels generate stress that ultimately leads to fish mortality (Skidmore, 1964). Zinc has been demonstrated to promote apoptosis in *Channa punctatus* through oxidative stress, resulting in cytotoxicity due to inflammatory reactions and changes in mitochondrial membranes (Chuang et al., 2014). Zinc sulfate exposure resulted in reduced swimming activity and impaired body balance in *Cyprinus carpio*. LC_{50} values for zinc during 96-hour exposure for adult common carp exhibit a greater tolerance than 2.7g immature fish. Pathways and effects of heavy metal contamination from different sources on aquatic habitat and fish health are described below in Figure 3.

3.7 Copper (Cu)

Copper is a vital trace metal that is crucial for the developmental process and metabolism of living organisms. In fishes and other species, copper is an essential component of various metabolic enzymes as well as glycoproteins. At elevated concentrations, copper induces harmful effects in living creatures. Copper induces toxicity in freshwater fish at concentrations between 10 and 20 ppb (Collins, 2021). For instance, the LC_{50} values for copper after 96 hours of exposure indicate that 60g adult common carp exhibit greater tolerance than 2.6g fish juvenile Exposure to copper sulfate in *Cyprinus carpio* resulted in biochemical and morphological alterations in liver tissue (Tavares-Dais, 2021). Copper toxicity in *Mytilus edulis* results in a reduction of heart rate and cardiac function. The goldfish (*Carassius auratus*) exhibited a significant incidence of physical malformations and death rate upon exposure to copper (Kong et al., 2013). Copper accumulates in the liver at the highest concentration, with lower concentrations seen in the gills and body tissue of fish (Bawuro et al., 2018).

4. Histopathological effects of heavy metals on fish

Fish absorbs and accumulates metals directly from the adjacent water and indirectly via other species, including small fish, crustaceans and aquatic plants (Garai et al., 2021). Fish preferentially store contaminants in their adipose tissues such as the liver (Islam et al., 2020). The liver is regarded as a primary organ responsible for metabolism and detoxification of harmful substances (Al-Attar et al., 2007). When level of toxicants exceeds, reaching a threshold, structural and metabolic changes transpire in the liver, resulting in changes to hepatic enzyme levels. Histopathological changes in the kidney are more significant than those in the gills and liver. Lesions in kidney cells and tissues show ionic imbalance due to heavy metal consumption (Table 1).

5. Effects of heavy metal toxicity on Hemato-biochemical Indices in fish

Fish blood serves as a crucial diagnostic tool for identifying stressed or pathological conditions throughout the body in response to various living and non-living stressors (Ashaf-ud-Doulah et al., 2020). The exposure of fish to toxicants, results in various alterations in hematological and biochemical markers (Islam et al., 2020). Hematological measures, including red blood cells, hemoglobin, leukocytes and lymphocytes dramatically reduced regardless of the toxicity in various fish species were exposed (Suchana et al., 2021). Various heavy metal exposures have been documented to cause distinct cellular and nuclear abnormalities in red blood cells. Other hematological indicators, such as neutrophil counts, have increased; nevertheless, variations in hematocrit and white blood cell differentials (Table 2).

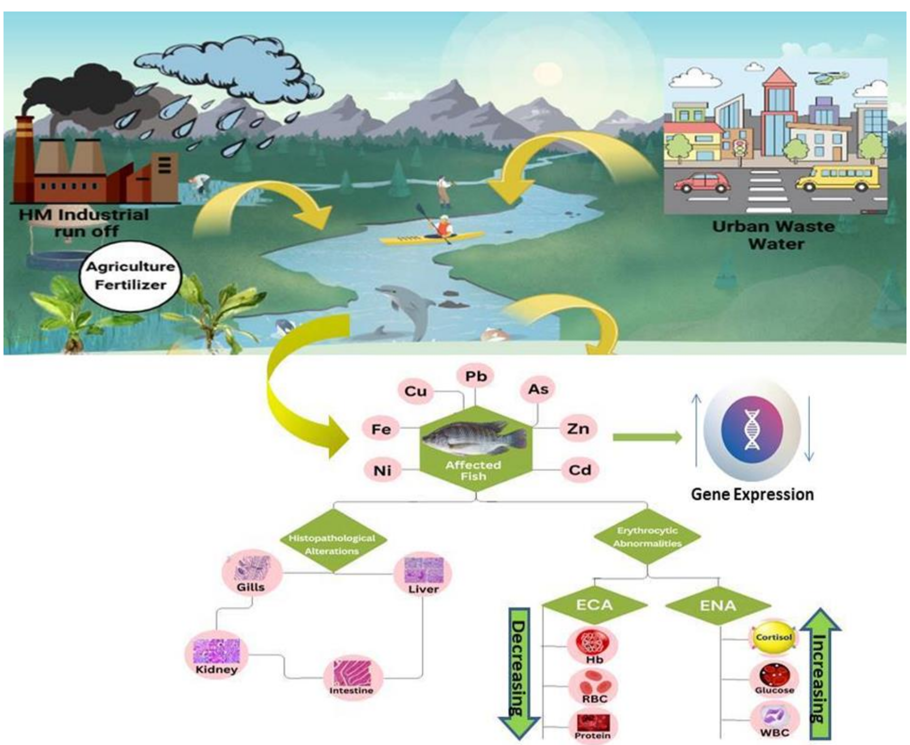

Fig. 3: Pathways and effects of heavy metal contamination from different sources on aquatic habitat and fish health

Table 1: Influence of heavy metal intoxication on the histopathology of numerous fish organs

Species	Doses	Exposure time (days)	Organ	Effects	References
Hg					
Channa gachua	0.106, 0.05mg/L	4	Liver	Nuclear degeneration and cytoplasmic vacuolation	Kawade (2021)
Oreochromis niloticus	550, 70 and 1000mg/kg	60	Gills	Epithelial lifting and enlargement of cells	Al-Ghanim et al. (2019)
			Liver	Necrosis of liver cells, portal veins	
			Muscles	Irregularity in the muscle fascicles	
Cirrhinus mrigala	0.020 and 0.040 ppm	30	Gills	Lamellar degeneration, epithelial cells necrosis	Chavan and Muley (2014)
			Liver	Inflammation of liver cells	
Cd					
Catla catla	4.5mg/L	30	Gills	Lamellar atrophy and telangiectasia	Naz et al. (2021)
			Liver	Hepatic cells degeneration	
			Kidney	Degeneration of renal tubules	
			Intestine	Atrophy of villi	
Cyprinus carpio	0.10mg/L	30	Gills	Spiking of secondary lamellae	Rajeshkumar et al. (2017)
			Liver	Demage of hepatocytes	
Sparus aurata	1mg/L	30	Liver	Displaced the nuclei and vacuolated cytoplasm	Guardiola et al. (2013)
Species	Doses	Exposure time (days)	Organ	Effects	References
Cr					
Labeo rohita	1/10th LC50	60	Liver	Hyperplasia	Velma et al. (2009)
			Gills	Lamellar degradation	
			Kidney	Extensively perforated Bowman's capsule	
			Intestine	Glomerular disorganization	
Channa punctatus	20, 40mg/L	60	Gills	Necrosis of epithelial calls	Mishra & Mohanty (2008)
			Kidney	Hematopoietic tissues necrosis	
			Liver	Vacuolization of cell cytoplasm	
Cyprinus carpio	0.15mg/L	30	Gills	Spiking of secondary lamella	Rajeshkumar et al. (2017)
			Liver	Rupture of hepatic plate	
Cu					
Channa gachua	1.4202mg/L	4	Liver	Degeneration of nuclei	Kawade (2021)
Oreochromis niloticus	0.5, 1.0 and 2.5mg/L	21	Gills	Edema	Figueiredo-Fernandes et al. (2007)
			Liver	Vacuolation and necrosis	
Catla catla	1.25ppm	30	Gills	Lamellar degeneration	Naz et al. 2021
Species	Doses	Exposure time (days)	Organ	Effects	References
Pb					
Myoxocephalus scorpius	4.01µg/L	28	Gills	Epithelial cell hyperplasia	Jantawongsri et al. (2021)
			Liver	Hepatic neoplasm	
Cyprinus carpio	0.25mg/L	30	Gills	Development of club-shaped filaments in interlamellar areas	Rajeshkumar et al. (2017)
			Liver	Intravascular haemolysis in blood vessels	
Cirrhinus mrigala	28.2 and 14.1ppm	30	Gills	Dilation and congestion in blood vessels of gill filaments	Chavan & Muley (2014)
			Liver	Focal necrosis	
Ni					
Hypophthalmichthys molitrix	5.7mg/L	30	Gills	Hypersecretion of mucus	Athikesavan et al. (2006)
			Liver	Degeneration of blood vessels	
			Kidney	Hyperplasia	
Channa gachua	150mg/L	4	Liver	Contraction of the central vein, aggregation of blood cells within the central vein, and rupture of sinusoids	Kawade (2021)
As					
Channa punctatus	3.8 and 7.6mg/L	14	Liver	Disorientation of tissues	Roy & Bhattacharya (2006)
			Kidney	Shrinkage of the glomerulus	
Heteropneustes fossilis	7 and 20ppm	60	Muscle	Atrophy, Intramuscular edema	Begum et al. (2013)
			Intestine	Partial intactness of seros	

Table 2: Impact of heavy metal poisoning on haemato-biochemical parameters in fish

Species	Doses (mg/L)	Exposure time (days)	Effects	References
As				
Clarias batrachus	84	4	Decreased TP levels indicative of protein synthesis impairment.	Pichhode & Gaherwal (2020)
Tilapia mossambica	Sub lethal	21	Significant increase in WBCs accompanied by a decrease in Hb, RBCs.	Soundararajan & Veeraiyan (2014)
Cr				
Cyprinus carpio	25-150	180	Number of WBCs, MCV increased while RBCs, Hb and protein content decreased.	Shaheen & Akhtar (2012)
Labeo rohita	39.40	4	TP and lipid content decreased.	Vutukuru (2005)
Oncorhynchus mykiss	0.367	-	Number of RBCs decreased significantly.	Vosyliene & Jankaite (2006)
Cd				
Channa straiata	0.001	-	Level of glucose dropped.	Phoonaploy et al. (2019)
Labeo rohita	0.826	-	Elevated number of WBCs while RBCs decreased.	Chandamshive et al. (2012)
Oreochromis niloticus	1.0	7 and 14	Cholesterol level dropped.	Firat & Kargin (2010)
Zn				
Channa punctatus	0.54	-	Lipid ad cholesterol level increased accompanied by decrease in level of albumin.	Javed et al. (2017)
Mastacembelus armatus	0.30	-	Glucose level increased	Javed &Usmani (2013) Vvxx
Species	Doses (mg/L)	Exposure time (days)	Effects	References
Tilapia mossambicus	1.0, 2.5, 5.0	14	Decrease in level of WBCs, RBCs and lymphocyte.	Celik et al. (2013)
Pb				
Mugil cephalus	0.0015, 0.0025	4	Glucose and MDA level increased.	Hajirezaee et al. (2021)
Channa straita	0.005	-	Glucose level decreased.	Phoonaploy et al. (2019)
Labeo rohita	0.756	-	Elevated WBCs along with decrease in RBCs.	Chandanshive et al. (2012)
Ni				
Clarias gariepinus	0.302	-	Glucose level evaluated while CK, MCV diminished.	Bandit et al. (2019)
Channa punctatus	0.12	-	Elevated WBCs along with decrease in RBCs.	Javed & Usmani (2014)
Cyprinus carpio	6, 9,12, 15, 18	4	RBC, WBC and Hb decreased.	Al-Ghanim (2011)
Hg				
Oreochromis niloticus	0.025	30	ALT, AST, SOD increased	Mahboub et al. (2019)
Labeo rohita	0.0987		Elevated WBCs.	Chandanshive et al. (2012)
Acanthopagrus lates	0.01, 0.02, 0.04, 0.08	21	Hb and monocytes increased; decreased lymphocytes and eosinophils.	Safahieh et al. (2010)
Cu				
Clarias gariepinus	100	4	Significant increase in albumin and globulin.	Javed &Usmani (2019)
Mastacembelus armatus	0.86	-	Increase in glucose level.	Javed & Usmani (2013)

Conclusion

Heavy metal contamination constitutes a significant and escalating issue for water ecosystems and human health. Industrial activities, farming, and pollution have led to metals like mercury, cadmium, lead, and arsenic building up in rivers, lakes, and oceans. Once in the water, these metals get absorbed by fish through their gills, skin, and food, affecting their health, growth, and even causing death in some species. As fish take in these metals, they accumulate in their bodies. When humans eat fish contaminated with heavy metals, they are exposed to these harmful substances, which can lead to issues like nerve damage, organ problems, and even cancer. Some metals, like zinc and copper, are necessary for health in tiny amounts, but too much can be toxic. This lasting presence of aquatic toxicity highlights the importance of monitoring and controlling pollution to protect fish and human health. It's crucial to limit heavy metal discharges from factories, farms and other sources to keep our water clean, ensure safe food and protect the environment. Enhanced legislation, advanced technologies and consistent monitoring are essential to mitigate heavy metal pollution, whereas remediation initiatives and international collaboration safeguard water quality, ecosystems and public health.

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