CHAPTER 1

Heavy Metal Toxicity In Freshwater Fishes

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Heavy metals contamination caused by anthropogenic and natural processes of freshwater ecosystems (e.g. Rivers, lakes) has become one of the most severe environmental issues as a result of their non-biodegradable properties and extended stability within aquatic ecosystems. Heavy metals that are acknowledged as persistent environmental pollutants (e.g. Cadmium (cd), lead (pb), mercury (hg), chromium (cr), copper (cu), zinc (zn)) have been scientifically accepted worldwide and have an indefinite length of time they remain within aquatic ecosystems. Heavy metals are inorganic and cannot degrade and do therefore end up in aquatic ecosystems as accumulation. As such, these metals in aquatic systems cause irreparable damage to the environment and pose serious risk both ecologically and through toxic exposure (Jaishankar *et al.* 2014). Fish inhabiting freshwater systems are at risk of heavy metals exposure because they live in polluted waters with many possible routes of exposure and absorption from contaminated water (i.e. Including body tissues via filter feeding mechanisms through gills; non-filter feeding; ingestion of contaminated food versus water intake via mouth) (Authman, Zaki, Khallaf, And Abbas, 2015). Gills are the primary site for metal absorption when fish are exposed to heavy metals through water since the gills have an extremely large surface area compared to the rest of the body and are in contact with significantly larger volumes of water than any other organs of the fish; consequently, fish may also become exposed to heavy metals through their own ingestion of fish (via eating other fish) and through the ingestion of contaminated food or sediment, thus facilitating the accumulation of heavy metals in their soft body tissues. Once in the fish's tissues, heavy metals affect vital physiological functions similar to how they would affect people (e.g., Disrupt/Alter Multiple Processes By Binding To Proteins, Inhibiting/Enhancing/Creating Enzyme Activity, Producing Free Radicals Which Can Cause Oxidative Stress, etc). Heavy metals have been shown to cause various toxicity to fish such as decreased growth rates, metabolism, histopathology, reproductive disruption and behavioural changes. Fish gill, liver, kidney and muscle tissues are particularly susceptible to accumulating metals within those tissues due to their role in respiration, detoxification and metabolism (Atli & Canli, 2010). Therefore, the increasing levels of heavy metal toxicity in fish are harmful to fish populations while also threatening the integrity of aquatic food webs and biodiversity. The accumulation of heavy metals in fish tissues may also pose significant health risks to humans. Fish are one of the world's primary dietary protein sources; therefore, contaminated fish may transmit toxic metal to humans and lead to neurological disorders, kidney failure and chronic illness (Burger And Gochfeld, 2005). Therefore, research on the effects of heavy metal toxicity on freshwater fishes is necessary for environmental monitoring purposes, ecological risk assessments and effective pollution control strategies.

Sources Of Heavy Metals In Freshwater Ecosystems

Heavy metals enter freshwater ecosystems from both natural and anthropogenic sources. Heavy metals are persistent pollutants that do not degrade biologically, and thus accumulate in aquatic ecosystems over long timeframes. Once released into rivers, lakes or reservoirs, heavy metals can dissolve in the water or bind to sediments and organic matter so that they ultimately become available for uptake by aquatic organisms. The accumulation of these metals in aquatic systems creates serious ecological risks and jeopardizes the health and survival of freshwater fish and other aquatic biota (Jaishankar *et al.*, 2014). Natural sources of heavy metals include volcanic eruptions, weathering of rocks and erosion of soil. Through natural geological processes, trace amounts of metals such as copper, iron, zinc and manganese are slowly released into water bodies over geological time scales. Though these natural inputs usually are low and occur over extended geological timeframes, they provide a background concentration of metals to freshwater ecosystems (Tchounwou *et al.*, 2012). However, the primary contributor to heavy metal pollution is human activity, including industrial discharges, mining operations, application of pesticides and fertilizers, and urban wastewater. Rapid industrialization and urban development have markedly raised the concentrations of many toxic heavy metals in similar aquatic environments.

Common sources include:

1. Industrial effluents from electroplating, tanning, and textile industries
2. Agricultural runoff containing pesticides and fertilizers
3. Mining and smelting operations
4. Domestic sewage and municipal waste
5. Thermal power plants and battery industries

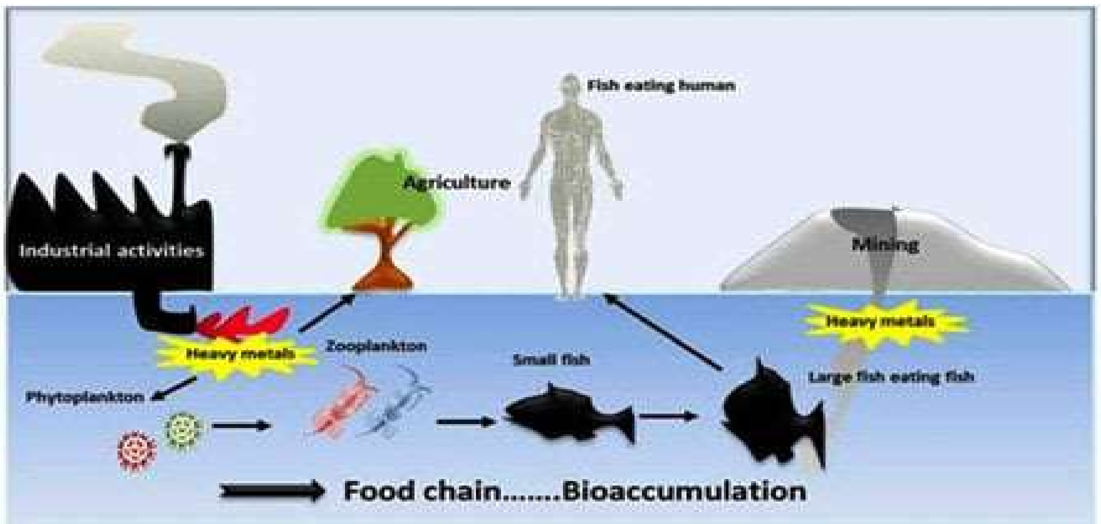
Activities like these introduce heavy metals (such as cadmium, lead, mercury, chromium, and arsenic) to freshwater systems at high volumes. Continual release of these contaminants causes an increase in the total metals in the water beyond legal limits, which creates a toxic environment for animals living in the water. Because freshwater fish biosorp these metals into their tissues, it causes physiological stress to fish, damages organs, and creates an ecological imbalance in aquatic ecosystems (Authman *et al.*, 2015).

Major Heavy Metals Affecting Freshwater Fishes

- **Lead (Pb)**
  Lead is a highly toxic metal commonly released from batteries, paints, and industrial waste. In fishes, lead exposure can damage gills, liver, kidneys, and nervous systems. It interferes with enzyme activity and causes anemia, behavioral changes, and impaired growth.
- **Cadmium (Cd)**
  Cadmium is released through mining, fertilizers, and industrial waste. It accumulates mainly in fish kidneys and liver. Chronic exposure causes kidney dysfunction, oxidative stress, and disruption of calcium metabolism.
- **Mercury (Hg)**
  Mercury is one of the most dangerous heavy metals due to its high toxicity and bioaccumulation potential. In aquatic environments, mercury is converted into methylmercury, which easily accumulates in fish tissues and enters the food chain.
- **Chromium (Cr)**
  Chromium contamination mainly originates from leather tanning industries and electroplating processes. Hexavalent chromium (Cr VI) is highly toxic and can cause DNA damage, oxidative stress, and histopathological alterations in fish organs.
- **Copper (Cu) and Zinc (Zn)**

Copper and zinc are essential trace elements required in small quantities for metabolic functions. However, at higher concentrations, they become toxic and disrupt ion regulation, enzyme activity, and respiratory functions in fish.

Routes Of Heavy Metal Entry Into Fish



Heavy metals enter fish bodies through multiple pathways:

- **Gill Absorption**

Gills are the primary site of metal uptake because of their large surface area and direct contact with water. Dissolved metals diffuse across gill membranes and enter the bloodstream.

- **Digestive Tract**

Fish ingest contaminated food, sediments, or plankton containing heavy metals. These metals are absorbed through the intestinal lining.

- **Skin Absorption**

In some fish species, metals can also penetrate through the skin, especially when the mucus layer is damaged. After entering the body, metals are transported through blood circulation and accumulate in organs such as liver, kidney, gills, brain, and muscles.

Physiological And Biochemical Effects

Freshwater fish suffer from numerous physiological disruptions after being exposed to heavy metals. These metals disrupt normal biological processes and affect vital organs responsible for respiration, metabolic functions, and excretion of waste. When heavy metals accumulate within fish tissues, they disrupt cellular function and alter homeostatic balance. The gills, liver, kidney, and circulatory system are highly susceptible to the effects of toxic metals due to their direct participation in respiration (Gas exchange), detoxification, and metabolic control.

Major effects include:

1. Impaired respiration due to gill damage
2. Alteration in blood parameters
3. Disruption of ion regulation
4. Reduced growth and metabolic activity
5. Increased energy expenditure

Heavy metals like cadmium, lead and mercury can adversely affect gill lamellae, thereby decreasing their oxygenation capacity, which in turn causes respiratory distress. Metal-exposed fish also exhibit alterations in hematological parameters (e.g., Hemoglobin, Red blood cell count and Hematocrit) that indicate impaired oxygen transport and physiological stress due to changes in blood parameters after being exposed to heavy metals. Furthermore, toxic metals disrupt ionic homeostasis by interfering with the regulation and transport of electrolytes (sodium, potassium and calcium) across gill membranes. From a biochemical perspective, heavy metals have the potential to inhibit several metabolic enzymes (e.g., ALT, AST, and ALP) and disrupt metabolism of both proteins and carbohydrates. Such enzymatic changes indicate hepatic dysfunction and metabolic dysregulation; in turn, reduced growth potential, decreased immunity and decreased ability of freshwater fish to survive in contaminated environments are evident.

Ecological And Human Health Implications

The contamination of water with heavy metals can cause harm to both fish and the environment of those fish. Heavy metals, such as lead, cadmium, mercury, and chromium, can build up in the water, sediments, and the body's tissues of aquatic animals. As these metals accumulate, they change the natural balance of the ecosystem and reduce it in terms of biodiversity. Fish that are exposed to toxic metals can exhibit stunted growth and reduced ability to reproduce and survive, resulting in fewer fish and altering the types of fish within the ecosystems where they live. This decrease in fish populations can lead to a decrease in both biodiversity and productivity of fisheries, which will affect food webs and the overall stability of the aquatic ecosystems. Heavy metals can also accumulate in lower trophic level organisms (e.g., plankton, benthic invertebrates) and facilitate the transfer of these toxins up the food chain, resulting in biomagnification at higher trophic levels (Authman, Zaki, Khallaf, & Abbas, 2015). The consumption of fish that have high levels of heavy metal contamination poses a serious risk to human health. These dangers include neurological defects, damage to the kidneys, and developmental defects. The most dangerous forms of metals include methylmercury and lead due to their ability to accumulate in human tissue and interfere with the normal function of the nervous system. These risks are especially critical for developing children and pregnant women. Long-term consumption of heavy metals in the diet can contribute to the development of cardiovascular diseases, dysfunction of the immune system, and deterioration of internal organs over time (Jaishankar *et al.*, 2014). As a result, freshwater ecosystems must always be monitored for heavy metals to protect the environment and maintain food safety. Monitoring will allow us to evaluate the amount of metals present in water, sediment, and fish tissues, which will allow us to track pollution sources and develop appropriate strategies to reduce ecological risk and protect people from harm.

Conclusion

Heavy metal pollution has emerged as a major threat to freshwater ecosystems and fish health. Rapid industrialization, agricultural intensification, and urban development have significantly increased the release of toxic metals into aquatic environments. Metals such as cadmium, lead, mercury, and chromium accumulate in fish tissues and interfere with physiological, biochemical, and molecular processes. These toxic effects lead to oxidative stress, tissue damage, reproductive impairment, behavioral abnormalities, and increased mortality in freshwater fishes. Continuous exposure to such pollutants not only affects individual fish health but also disrupts population dynamics and ecological balance within aquatic ecosystems. Understanding the mechanisms of heavy metal toxicity is crucial for assessing environmental risks and developing effective pollution management strategies. Scientific studies on metal uptake, bioaccumulation, histopathological alterations, and enzymatic responses in fish provide valuable insights into the impact of pollution on aquatic organisms. Sustainable environmental policies, proper waste treatment, and strict regulation of industrial discharge are necessary to reduce heavy metal contamination in aquatic ecosystems. Effective implementation of environmental regulations and pollution control technologies can significantly minimize the release of toxic metals into freshwater bodies. Future research should focus on biomonitoring techniques, molecular biomarkers, and eco-friendly remediation strategies to protect freshwater biodiversity and ensure safe fish consumption. Continuous environmental monitoring and awareness programs are also essential for maintaining healthy aquatic ecosystems and safeguarding human health.

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