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Environmental Contamination by Heavy Metals: A Review of the Effects of Chromium, Mercury, Arsenic, Lead, and Cadmium on Fish Physiology and Survival

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ABSTRACT:

The contamination of aquatic ecosystems by heavy metals such as chromium, mercury, arsenic, lead, and cadmium represents a significant environmental challenge, with far-reaching consequences for fish health and ecosystem stability. These metals persist in the environment and accumulate in aquatic organisms, posing serious risks to aquatic life. Fish, in particular, are highly vulnerable to these pollutants, which they bio accumulate through water, sediment, and their diet. The exposure to heavy metals results in a range of toxic effects on fish, disrupting essential physiological processes such as respiration, growth, reproduction, and immune function. The toxicological mechanisms of these metals include oxidative stress, enzyme inhibition, and DNA damage, which impair cellular function and damage vital organs. Physiologically, this can manifest in reduced growth, reproductive failure, behavioral abnormalities, and even mortality. These disruptions not only affect individual fish but also have broader ecological impacts, including the decline in fish populations and the alteration of aquatic food webs. While regulatory measures have been implemented to control metal pollution, persistent contamination underscores the need for improved monitoring and remediation efforts. Furthermore, understanding the cumulative effects of multi-metal exposures remains an important area of research. This review consolidates the current literature on the effects of chromium, mercury, arsenic, lead, and cadmium on fish health, highlighting the need for enhanced mitigation strategies to protect aquatic biodiversity, safeguard public health, and promote sustainable management of aquatic resources.

Introduction

Heavy metals (HMs) are defined as elements with an atomic number greater than 20 and an atomic density exceeding 5 g cm^{-3}, which also exhibit the characteristic properties of metals. These metals can be categorized into two groups: essential and non-essential. Essential heavy metals, such as zinc and copper, are required by living organisms to perform vital functions, including organ formation, growth, and metabolic processes. In contrast, non-essential heavy metals, including cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), and aluminum (Al), are not necessary for any metabolic functions in animals and are often toxic at elevated concentrations.

In recent decades, rapid industrialization, urban expansion, and increased chemical use across various industries have contributed to a significant rise in the release of heavy metal ions into the environment. This widespread contamination, particularly in water bodies, has raised global concerns due to the hazardous nature of these pollutants (Hama Aziz et al., 2023). The contamination of ecosystems by heavy metals is primarily driven by activities such as mining, industrial waste disposal, deforestation, and fossil fuel combustion.

In India, numerous fish species inhabit reservoirs, which serve as valuable indicators of aquatic health, reflecting the biodiversity of local fish populations. Fish are not only an essential protein source for humans but also provide crucial nutrients like vitamins and minerals (K & D, 2015). However, the aquatic environments that accumulate pollutants from these anthropogenic activities are becoming sinks for remobilized heavy metals (Javed & Usmani, 2019).

The toxicity of heavy metals in aquatic species is influenced by various environmental factors, including alkalinity, water hardness, pH, dissolved oxygen levels, temperature, and turbidity (Sonone et al., 2021). Fish, especially juveniles, are particularly susceptible to the toxic effects of heavy metal contamination. Exposure to elevated concentrations of these pollutants can severely impact fish populations, often leading to a drastic reduction in numbers or even complete loss of species in polluted water bodies.

Research indicates that heavy metals can significantly hinder the survival and development of fish larvae, resulting in diminished fish populations in contaminated environments (Vajargah, 2021). The harmful impacts of heavy metals on fish are extensive, affecting various physiological and biochemical processes. These pollutants can disrupt cellular functions, alter organ systems, and cause various physiological impairments (Javed & Usmani, 2019). These effects not only threaten the health of individual fish but also pose broader risks to aquatic ecosystems and the species that depend on them.

1. Sources of Heavy Metals

The primary sources of heavy metal contamination in the environment are closely linked to human activities such as population growth, industrial expansion, and agricultural practices. Although heavy metals can naturally enter aquatic ecosystems through various geological processes, the most significant contribution to environmental contamination comes from anthropogenic sources. Industrial activities like smelting, metal extraction, and nuclear fuel production are major contributors to the release of heavy metals into the environment.

1.1.Smelting:

Smelting, a crucial process in extractive metallurgy, is primarily used to convert ore into metals, including copper and other base metals, as well as iron for steel production. This process involves high temperatures and the release of heavy metals into the surrounding environment as by-products, making it a key source of environmental contamination.

1.2.Mining:

Mining activities contribute to heavy metal contamination as water runoff from mining areas can introduce metals into aquatic environments. The Earth's crust contains various heavy metals, which are often mobilized into water bodies by natural weathering processes. Moreover, acid mine drainage occurs when exposed mining regions interact with air and water, releasing harmful metals into nearby water sources (Fu et al., 2017).

1.3.ElectronicWaste(E-Waste):

E-waste is another significant source of heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and nickel (Ni), as well as harmful organic chemicals such as phthalates, brominated flame retardants (BFRs), and polychlorinated biphenyls (PCBs) (Azuka, 2009). Improper disposal and inadequate recycling of e-waste pose severe environmental and health risks, as these toxic substances can leach into soil and water, threatening ecosystems and human health. Proper management of e-waste is essential to reduce the exposure to carcinogens and prevent various health issues, including cancers, respiratory problems, and neurological disorders.

1.4.PowerPlants:

Thermoelectric power plants, including those fueled by fossil fuels and nuclear reactors, are significant sources of thermal and heavy metal pollution in aquatic systems. These plants release large quantities of contaminants, including cadmium, lead, mercury, arsenic, selenium, and boron, into water bodies. Thermal pollution, resulting from the discharge of heated water, deteriorates water quality and disrupts aquatic ecosystems. According to the Environmental Protection Agency (EPA), thermoelectric power stations contribute to over 50% of all pollutants released into surface waters in the United States under the Clean Water Act (Osann & Hayat, 2014).

1.5.AgriculturalActivities:

The overuse and mismanagement of agrochemicals in agriculture have led to increased pollution of aquatic ecosystems. The runoff from agricultural fields often contains pesticides, fungicides, herbicides, and fertilizers, which can contaminate nearby rivers, lakes, and groundwater. This pollution can have severe consequences for aquatic life, including bioaccumulation of toxic substances in fish, leading to various health risks. Improperly managed agricultural runoff is a source of carcinogens and other harmful compounds that can damage both aquatic organisms and human populations (Schreinemachers & Tipraqsa, 2012).

1.6.BiomedicalWaste:

Biomedical waste, including used needles, syringes, contaminated bandages, and bodily fluids, is a growing concern for environmental pollution. Improper disposal of biomedical waste can lead to the contamination of groundwater and surface water with heavy metals and other toxic substances, such as polycyclic aromatic hydrocarbons (PAHs). These pollutants pose a significant risk to aquatic ecosystems, as well as to human health, by potentially entering the water supply and disrupting local ecosystems (Sonone et al., 2021).

2. Bioaccumulation of Heavy Metals in Fish

Bioaccumulation refers to the process by which pollutants, including heavy metals, accumulate in living organisms over time. Aquatic species, including fish, are particularly vulnerable to bioaccumulation, as they absorb pollutants from the surrounding water faster than they can eliminate them. In fish, heavy metal accumulation occurs through both dietary (via the digestive system) and non-dietary routes (through the skin and gills) (Van der Oost et al., 2003). The bioaccumulation of heavy metals can have serious consequences for fish health, impacting their growth, reproduction, and survival. Over time, the concentration of these metals can increase in the food web, posing further risks to predators, including humans who consume contaminated fish.

The type of pollutant, the species, their trophic level in the food chain, their eating habits, and physical and chemical factors all affect how much metal accumulates(Weber et al., 2013). Compared to species at a lower trophic level, top predator fish (upper food web position) are more likely to acquire metals because they are exposed to relatively higher levels of pollution because to magnification through the trophic chain. Heavy metals typically build up in all of the fish's critical organs. The liver, kidney, gills, and even the stomach of fish contain the highest quantities of heavy metals. However, little is known about the uptake of heavy metals through the integument.

3. Effect of heavy metal on Fish health

The lack of affordable protein sources for the vastly growing population in third-world countries has led to the rise in popularity of fish farming as a substitute. But in a number of these nations, they employ recycled water from sewage, industrial drainage, or agricultural drainage. The fish raised in these recycled water sources, the ecology, or the humans who eat the fish all face health risks. Metal uptake by aquatic organisms occurs in two stages: fast adsorption or binding to the surface, followed by delayed transit into the cell interior. In epithelial tissues, the last stage is the rate-limiting factor for metal trans epithelial transport (Foulkes, 1988). Metals can be transported into the intracellular compartment via diffusion across the cell membrane or active transport by a carrier protein (Baby et al., 2011).

3.1 Effect of chromium on fish:

Chromium toxicity in fish can cause blood disorders such as anemia, lymphocytosis, and eosinophilia, as well as renal and bronchial diseases. Chromium poisoning is most prevalent in fish that swim near wastewater disposal sites.(*Scholar*, n.d.) Fish that are first exposed to chromium exhibit a number of behavioral changes, including rapid operculum, irregular swimming, and suspended feeding behavior. It weakens the body's immune system and may cause structural alterations in the gill epithelium, such as hypertrophy and paraplegia.(Arunkumar et al., 2000). In their investigation of behavioral changes in gold fish (*Carassius auratus),* Ali et al. observed that all of the fingerlings gravitate toward the aquarium's corner and that there was a decrease in hunger brought on by chemical impacts.(Fawad et al., 2017). Exposure of fish in aquaculture to Cr wastes shows cumulative negative effects. Immune cells generated from carp (*Cyprinus carpio*) were studied by Steinhagen et al. and exposed to Cr The findings showed a notable alteration in neutrophil morphology and phagocyte function, as well as a reduction in mitogen-induced lymphocyte activation. When fish were exposed to prolonged chromium challenges, their ability to resist particular infections diminished, as seen by the altered activities of their lymphocytes and neutrophils.

3.2 Effect of Mercury on Fish :

There is strong evidence that long-term exposure to elevated mercury levels can impair vital physiological systems in fish, resulting in immune system weakness, development retardation, and reproductive issues.(Omach et al., 2023)Mercury is an important heavy metal for neurotoxicity. While various factors contribute to neurotoxicity, mercury has a substantial impact on both fish and humans. Monomethyl Hg can cause brain damage, miscarriage, congenital deformities, and developmental anomalies in small fry. Mercury contamination of Japan's waterways. Hg toxicity (via methyl Hg) and Minamata sickness demonstrated severe neurotoxicity.(Govind & Madhuri, 2014). There are significant differences in the bio-accumulation rate of mercury in freshwater and marine fish, and variations in metabolic and environmental characteristics among species affect the amount of mercury. Fish exposed to even low levels of mercury may have metabolic, genetic, psychological, and neurological changes(Hong et al., 2012).

3.3. Effect of Cadmium on Fish health :

It has been observed that cadmium has harmful effects that are nephrotoxic, cytotoxic, genotoxic, immunotoxic, and carcinogenic.(Risso-De Faverney et al., 2001). As a heavy metal, cadmium is very hazardous at extremely low exposure levels and affects aquatic animals' health and the environment both acutely and over time. Aquatic animals can experience a wide range of acute and long-term consequences from prolonged exposure to cadmium.(Kumar & Singh, 2010). Several studies have indicated that exposure to cadmium may have immunosuppressive effects in fish and mammals(Sudarta, 2022) . According to recent research, cadmium poisoning significantly impairs host resistance to experimental infections, phagocytosis, natural killer cell activity, and cell-mediated immunity (Kumar et al., 2008). High levels of cadmium cause changes in the structure and function of several essential organs, such as fish liver, kidney, gills, and intestines. Cadmium damages the kidneys and causes chronic poisoning symptoms, such as malignancies, hepatic dysfunction, reduced renal function, and low reproduction rates, which can eventually cause their generation to go extinct (Mansour & Sidky, 2002). Extended exposure causes the liver's cadmium concentration to rise above its detoxifying threshold, which causes varying degrees of irreparable liver damage(Fatmi et al., 2023). Inhibiting antioxidant enzymes that defend tissues, cadmium either binds to sulfhydryl groups necessary for the enzymes, substitutes bivalent metals like copper and manganese (Mn) that the enzymes need, or reduces the bioavailability of selenium (Se) that the enzymes need(Obaiah et al., 2020)

3.4 Effect of Arsenic on Fish Health :

The most frequent cause of acute heavy metal poisoning in humans is arsenic, which ranks first on the ATSDR's "Top 20 List." Numerous physiological systems, including growth, reproduction, ion control, smoltification, gene expression, immunological function, and enzyme activity, are impacted by high levels of As concentration, or more than the allowable limit, in aquatic environments (Pedlar et al., 2002). Abnormal behaviors such erratic movement, fast opercula movement, jumping out of the test fluid, lateral swimming, and loss of equilibrium were all brought on by sodium arsenate exposure (Islam, 2008). Numerous researchers have noted that fish treated with arsenate exhibit anemic conditions during acute and sub-lethal therapy, leading to low hemoglobin levels (Hb). Another potential cause could be As poisoning, which inhibits erythropoiesis by acting on the membrane (Cockell & Hilton, 1988). Allin and Wilson (2000) and Chowdhury et al. (2004) observed that fish exposed to toxicants have less red blood cells (RBCs). Additionally, there have been reports of As inhibiting mitochondrial respiration, preventing cellular metabolism, and influencing the production of adenosine triphosphate (ATP)(Abernathy et al., 2000).

3.5 Effecct of Lead on Fish Health :

In aquatic settings, lead (Pb) is a very hazardous metal. Generally, four types of As compounds are present in water. These are arsenite, arsenate, monomethyl arsonic acid, and dimethyl arsinic acid. The primary cause of Pb-induced toxicity in fish exposed to toxicants is bioaccumulation in particular tissues, and the processes of accumulation differ depending on the aquatic habitat (freshwater or saltwater) and channel (dietary or waterborne exposure). Because Pb builds up in fish tissues, too many reactive oxygen species are produced, which leads to oxidative stress. Fish exposed to oxidative stress from lead exposure experience neurotoxicity, which results in synaptic damage and neurotransmitter dysfunction(Lee et al., 2019). Chronic Pb exposure is toxic to fish's central nervous system (CNS), resulting in behavioral and cognitive dysfunctions. Oxidative damage caused by Pb exposure is intimately linked to neurotoxicity in fish (Hsu & Guo, 2002).

Discussion

The environmental contamination of water bodies by heavy metals such as chromium (Cr), mercury (Hg), arsenic (As), lead (Pb), and cadmium (Cd) is a pressing concern worldwide. These metals, which are non-biodegradable and accumulate in aquatic ecosystems, pose a significant threat to aquatic organisms, particularly fish. The accumulation of heavy metals in aquatic ecosystems can occur through direct discharge from industrial processes, agricultural runoff, and atmospheric deposition (Javed & Usmani, 2019). These pollutants enter aquatic organisms either via the water, sediment, or through their food, where they accumulate in tissues over time, leading to toxicity at different levels.

Physiological and Biochemical Effects on Fish

The toxicity of heavy metals is largely determined by the metal's chemical form, bioavailability, and concentration in the aquatic environment. Fish are particularly susceptible to heavy metal toxicity due to their high exposure through the gills, digestive tract, and skin. One of the most well-documented effects of heavy metals on fish is oxidative stress, which results from the excessive production of reactive oxygen species (ROS). These ROS can cause cellular damage, including lipid peroxidation, protein denaturation, and DNA strand breaks (Bermudez et al., 2016). Chromium, for instance, primarily affects the gills and kidneys of fish, causing tissue damage and impacting osmoregulation (Patnaik et al., 2017). Mercury has been shown to disrupt the nervous system of fish, impairing motor functions and behavior (Suresh et al., 2015). Arsenic and lead can also interfere with neurological functions, reduce growth rates, and impair reproductive success (Bhattacharya et al., 2018). In contrast, cadmium exposure often leads to bioaccumulation in the liver and kidneys, causing severe oxidative damage and enzyme inhibition (Suresh et al., 2018).

Reproductive and Behavioral Impacts

Heavy metal exposure not only affects the general health of fish but also has severe implications for their reproductive success. Metals like mercury and lead can alter hormone levels, reduce gonadal development, and impair spawning behavior (Javed & Usmani, 2019). For instance, mercury exposure in fish has been linked to reduced fertility and altered sex ratios in several species, potentially leading to population declines (Suresh et al., 2015). Behavioral changes, such as reduced predator avoidance and altered foraging behavior, have been observed in fish exposed to high concentrations of cadmium and arsenic (Bermudez et al., 2016). These disruptions are not only detrimental to individual fish but can also have cascading effects on the entire ecosystem, disrupting the food chain and causing population imbalances.

Ecological Consequences and Bioaccumulation

The bioaccumulation of heavy metals in fish tissues is a major concern, as it poses risks not only to the fish but also to higher trophic levels, including humans, who rely on fish as a primary food source. Bioaccumulation occurs when the rate of metal uptake exceeds the rate of its excretion, resulting in increased metal concentrations in the tissues over time (Van der Oost et al., 2003). This phenomenon is particularly problematic because it leads to biomagnification, where metal concentrations increase as they move up the food chain, potentially affecting predatory species, including birds and mammals (Javed & Usmani, 2019). The persistence of heavy metals in the environment further exacerbates this issue, as metals such as mercury and cadmium can remain in the ecosystem for decades, continuously impacting the health of aquatic organisms (Patnaik et al., 2017).

Regulatory Measures and Mitigation Strategies

Despite global awareness and regulatory efforts, heavy metal pollution remains a significant problem in many aquatic ecosystems. The effectiveness of existing regulations in limiting metal contamination is often hampered by inadequate monitoring, non-compliance with environmental standards, and the complexity of multi-metal contamination (Kang et al., 2019). While measures such as wastewater treatment and the restriction of industrial discharge have been successful in reducing point-source pollution, non-point source pollution from agricultural runoff remains a challenge. Furthermore, the development of novel remediation techniques, including phytoremediation, bioremediation, and advanced filtration systems, offers hope for mitigating the effects of heavy metal contamination (Javed & Usmani, 2019). These methods focus on reducing the bioavailability of heavy metals in water, thereby minimizing their uptake by aquatic organisms.

Conclusion

Heavy metals such as chromium, mercury, arsenic, lead, and cadmium pose a significant threat to the health and survival of fish, with far-reaching ecological consequences. These metals disrupt key physiological processes in fish, including osmoregulation, metabolism, and reproduction. The bioaccumulation of heavy metals in fish tissues not only threatens aquatic biodiversity but also has implications for human health through the consumption of contaminated fish. Despite existing regulatory efforts to control heavy metal pollution, challenges remain in addressing the widespread and persistent nature of contamination. Continued research into the long-term effects of heavy metal exposure, as well as the development of more effective monitoring and remediation strategies, is critical for safeguarding aquatic ecosystems and protecting biodiversity. Ultimately, addressing heavy metal pollution will require a coordinated effort across global, national, and local levels to implement more stringent regulations, enhance public awareness, and develop sustainable practices for mitigating environmental contamination.

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