Heavy Metal Contamination in Freshwater Ecosystems: Bioaccumulation, Physiological Responses, and Human Health Risks Using Major Carps as Bioindicators

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ABSTRACT

The issue of heavy metal pollution is a major environmental and health-related problem of the freshwater system because of the insidious and toxic nature of such metals as cadmium (Cd), lead (Pb), and mercury (Hg). Although much research has been conducted, the lack of knowledge regarding bioaccumulation, physiological reactions in fish and the health risks involved make it difficult to control. It is a literature review on sources, environmental and bioaccumulation of heavy metals of major carps (*Labeo rohita, Catla catla and Cirrhinus mrigala*) as bioindicators. It assesses the tissue-specific patterns of accumulation, those effects on growth, reproduction, and fish quality, but focuses on the results of the River Chenab (Head Trimmu). The review covers a discussion of the ecological and population health impacts of biomagnification and dietary exposure, and biomaker-based early environmental stress detection. It offers guidelines to assist management and mitigation of pollution strategies in respect to freshwater.

Keywords: Heavy metals, bioaccumulation, major carps, human health risk

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Introduction

Industrialization, agricultural expansion, and urbanization are significant risk factors of freshwater ecosystems due to metallic pollution. Such non-biodegradable heavy metals as cadmium (Cd), lead (Pb), mercury (Hg), and chromium (Cr) remain in the waters and accumulate within the sediments and organisms [1]. Such metals lead to chronic toxicity even at low levels, interfering with the functioning of the bodies and undermining aquatic biodiversity [2-3]. They are bioaccumulative and dangerous to the ecological sustainability and human health. Heavy metals are major sinks of rivers which constantly obtain new inputs due to the anthropogenic activities in rivers. Industries, such as textile, tannery, electroplating, mining are releasing effluents with high concentrations of Cd, Cr, Pb, Ni, and Cu to surface waters [4-5]. The runoff of agriculture, fertilizers, pesticides, and stormwater in cities also contribute to the further pollution of water bodies, particularly in urban areas with high growth [6]. The lack of wastewater treatment and a poor enforcement of regulations on environmental issues worsen the pollution [7]. When they are discharged they are cycled in water and sediments, and become part of aquatic food webs. Fishes, especially big carps (*Labeo rohita, Catla catla, Cirrhinus mrigala*), are very prone to bioaccumulation of heavy metals in the gills, digestive tract, and skin. Bioaccumulation in fish impacts growth, reproduction and survival and biomagnification via trophic levels which gives risks to human populations depending on fish as a staple source of proteins [8-9]. The carps are considered an ideal bioindicator because of their feeding patterns and a wide distribution that indicates the primary sign of environmental stress in time [10-11]. One of the major case studies is the River Chenab, especially the Head Trimmu region, where the water, sediments, and carp tissues have a high concentration of Cd, Pb, Cr, Ni, and Zn, and are usually above the safety limit [12]. This review sums up the inferences of heavy metal contamination in freshwater ecosystems, and the application of carps as bioindicators to the environment and to protect human health.

Major Heavy Metals in Freshwater Systems

The heavy metals are also contaminating freshwater ecosystems through natural weathering and anthropogenic sources of heavy metals which include industrial discharge, agricultural runoff, mining processes and wastewater generated in the urban areas. They do not degrade in water and sediments and accumulate in aquatic organisms and biomagnify in the food webs [13].

Cadmium (Cd) is very toxic and bioavailable in water accumulating in fish organs such as the liver and kidney. It interferes with calcium metabolism, brings about oxidative stress, and produces growth retardation, skeletal demineralization and reproductive toxicity [14]. The key sources are phosphate fertilizers, batteries, and electroplating [15].

Lead (Pb), because of its high affinity to the sediments, disturbs enzyme activities, as well as neuro-biological processes in fish and humans and biomagnifies through food chains. The sources also consist of mining, smelting, and urban runoff [16-17].

Chromium (Cr), especially Cr (VI) is very toxic, which damages DNA and imposes oxidative stress. It goes into organisms easily, and is a significant pollutant emitted by the tanneries, electroplating, and textile industries [18]. Cr (III) is immobilized and is deposited in sediments.

Essential in small amounts, nickel (Ni) is toxic in large amounts leading to oxidative stress and immunological harm [19]. These sources are mining and combustion of fossil fuels.

Physiological needs include Copper (Cu) and Zinc (Zn) which are toxic in high levels leading to impaired metabolism and retardation of growth [20]. The contamination of Cu can be attributed to farm fertilizers that contain fungicides, and Zn is a product of city run-offs.

Mercury (Hg) is very stubborn and toxic, biomagnification of food webs and it attacks fish and humans as a result of the build up of methylmercury [21].

Table 1: Major heavy metals and their characteristics in freshwater ecosystems

Metal	Primary Sources	Toxic Effects	Bioaccumulation Sites
Cd	Fertilizers, batteries	Renal damage, carcinogenic	Liver, kidney
Pb	Industrial waste, fuel	Neurotoxicity	Liver, muscle
Cr	Tanneries, electroplating	Genotoxicity	Gills, liver
Hg	Coal combustion	Neurotoxicity	Muscle, liver
Cu	Pesticides, mining	Oxidative stress	Liver
Zn	Urban runoff	Enzyme disruption	Liver

Major Carps as Bioindicators

Big carps occupy freshwater environments and play a prominent role in transporting pollutants amongst water, sediments, and food. Because of their long life cycle and their continuous exposure to the water, they are the mirror of the accumulated environmental pollution consequences. They are also good bioindicators in determining the level of contamination in water and sediments because of their food preferences, which are species-specific [22].

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Three typical species of carps that have been used in ecotoxicology monitoring include Labeo rohita, Catla catla and Cirrhinus mrigala. Catla catla is a surface and mid-water plankton predator, which is sensitive to dissolved metals. Labeo rohita is an omnivorous, bentho-pelagic species and is able to take up dissolved as well as particle-bound pollution whereas Cirrhinus mrigala is a bottom-dwelling species that gathers metals through sediments. This trophic diversity presents a holistic analysis of pollution [23].

The accumulation of metal in carps is usually in the following order: liver, kidney, gills and muscle. The liver is the primary organ in the detoxification process, and therefore, it retains the excessive amount of metals; kidneys indicate chronicity. Gill Tissues are some of the main indicators of short term exposure as they store metals such as Cd, Pb and Cr, which lead to structural damage. Though less affected, muscle tissues are vital in determining human health risks since it is the main edible tissue. The responses render carps useful sentinel species as they are cost-effective and dependable in detecting heavy metal contamination as well as ecological and health hazards.

Physiological and Hematological Responses

The heavy metals result in numerous physiological and hematological alterations of major carps, which are sensitive biomarkers of both acute and chronic toxic stress. A typical hematological effect is anemia caused by the interference with erythropoiesis by such metals as cadmium (Cd), lead (Pb), and mercury (Hg), which causes the reduction of oxygen delivery and metabolism. There are also leukocyte changes, which are indicative of the presence of immunological stress, high white blood cell (wBC) counts (leukocytosis) indicate the activation of the defense, and low counts (leukopenia) indicate immunosuppression.

Metals such as Cd, Pb and chromium (Cr) cause oxidative stress which leads to the destruction of DNA and cells because of the production of reactive oxygen species (ROS). These alterations coupled with histopathological damage of gills, liver, and kidneys, are indications of pollution of the environment. Biomarkers Hematological, biochemical, histopathological Biomarkers in carps are useful tools as they provide valuable early warning of heavy metal contamination and are therefore valuable in monitoring the environment [24].

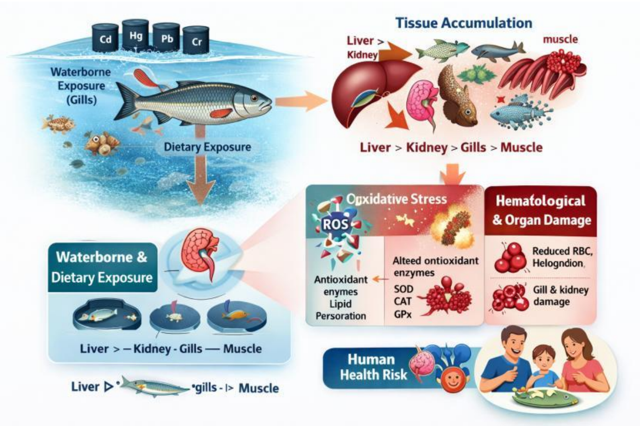

Figure 1: Conceptual illustration of heavy metal uptake, bioaccumulation, and physiological effects in major carps.

Case Study: River Chenab (Head Trimmu)

Chenab River is the major freshwater body in Pakistan sustaining fisheries and irrigation. The industrial, agricultural, and urban sources of pollution such as textile units, tanneries, and pesticide runoff affect the Head Trimmu region, where the Chenab and Jhelum converge. The distribution of heavy metal is influenced by seasonal changes, as high metal concentrations are recorded in dry seasons (Khan et al., 2020). Fish contaminated with high cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) are dangerous to the health of the local population.

Ecological and Public Health Implications

The ecological and health effects of heavy metal pollution in the freshwater ecosystems are devastating. Chronic exposure causes distortion of reproduction causing drop in population and loss of biodiversity. Metals such as Cd, Pb, Hg and Cr are accumulated in the food web where they are biomagnified in fish, birds and humans. When contaminated fish is consumed, it leads to health hazards, including neurological damage and kidney dysfunction and cancer especially to susceptible populations such as children and pregnant women.

Figure 2: Ecological and public health implications of heavy metal contamination in freshwater ecosystems.

Conclusions and Future Perspectives

Pollution of the freshwater ecosystems by heavy metals is ecological and social, because of its persistence, bioaccumulation and biomagnification. Metallic elements such as cadmium (Cd), lead (Pb), mercury (Hg) and chromium (Cr), move up the food web where they agglomerate in predatory fish, birds and the mammalian. The chronic exposure to these metals has negative impacts on fish especially the large carps that have a negative impact on reproduction, physiology and survival. This causes low fecundity, postponed hatching, and increased larval death, which in the end cause the low population sizes, species redistribution, and less genetic diversity, which destabilize aquatic ecosystems.

In human beings, the consumption of polluted fish may result in neuro-related diseases, kidney, heart, and cancer especially because of the presence of Hg, Cd, Pb, and Cr. Children and pregnant women are more at risk as they constitute the vulnerable groups. In addition, heavy metal pollution poses a threat on food security, where fishing communities depend on the wellbeing of the ecosystem to support their activities. Such environmental and health effects demonstrate the necessity to pay close attention to the problem of pollution, constant monitoring, and effective management measures to secure not only the freshwater ecosystem but also human health.

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