

Bioaccumulation and Toxicological Effects of Heavy Metals in Major Freshwater Fish Species of the Ganga–Yamuna Basin, Uttar Pradesh

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ABSTRACT

Heavy metal contamination has emerged as a major ecological and public health concern in freshwater ecosystems worldwide, particularly in densely populated river basins such as the Ganga–Yamuna system in Uttar Pradesh, India. Rapid industrialization, population growth, agricultural intensification, and continuous discharge of untreated effluents have significantly increased the concentration of toxic metals including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), and nickel (Ni) in aquatic environments. These metals are persistent, non-biodegradable, and capable of accumulating in aquatic organisms, especially fish, through direct absorption from water, ingestion of contaminated food, and sediment interaction. Scientific investigations demonstrate distinct tissue-wise bioaccumulation patterns, with highest concentrations generally reported in liver tissues followed by gills and muscles, indicating detoxification stress and respiratory exposure pathways. Heavy metal exposure results in oxidative stress, enzymatic disruption, histopathological damage, immunological suppression, reproductive impairment, and altered behavioral responses in fish species, ultimately affecting survival and ecosystem balance. Furthermore, dietary intake of contaminated fish poses potential long-term health risks to human populations dependent on riverine fisheries. This paper presents a comprehensive academic review of heavy metal bioaccumulation trends and associated toxicological effects in major freshwater fish species of the Ganga–Yamuna basin, integrating ecological, toxicological, and public health perspectives while emphasizing the need for sustainable river management, strict pollution regulation, and long-term ecological monitoring strategies.

Keywords- Cadmium, Chromium, Mercury and Lead, Ganga -Yamuna Basin.

I. INTRODUCTION

The Ganga–Yamuna basin represents one of the largest and most ecologically important freshwater systems in India, supporting extensive biodiversity and providing critical ecosystem services including fisheries, irrigation, drinking water, and livelihood support for millions of people [1]. The rivers flowing through Uttar Pradesh are particularly significant due to their dense population dependence and extensive agricultural and industrial activity.

Freshwater fish species play an essential ecological role in nutrient cycling, trophic interactions, and food-web stabilization. In addition, they are economically valuable resources, forming a major part of dietary protein intake in riverine communities. Because of

their sensitivity to environmental changes and ability to accumulate pollutants, fish are widely used as bioindicators of aquatic ecosystem health.

Over recent decades, rapid industrial development along riverbanks has resulted in increased discharge of untreated or partially treated effluents containing hazardous chemicals and heavy metals. Industrial sectors such as tanning, electroplating, metal processing, and chemical manufacturing contribute substantially to heavy metal loads in river systems [2]. Urban sewage and agricultural runoff further intensify contamination levels.

Heavy metals differ fundamentally from organic pollutants because they do not undergo biological degradation and therefore remain persistent in aquatic environments. Once released, they accumulate in

sediments and become bioavailable to aquatic organisms, creating long-term exposure scenarios [3].

Fish absorb heavy metals through multiple physiological pathways including diffusion across gill membranes, ingestion of contaminated prey, and direct contact with polluted sediments. Prolonged exposure leads to bioaccumulation, in which the concentration of metals in tissues exceeds that of surrounding water.

Numerous studies conducted across the Ganga and Yamuna river stretches have reported elevated concentrations of Pb, Cd, Cr, Hg, and Cu, particularly near industrial zones and urban centers in Uttar Pradesh [4]. These metals accumulate in fish organs in patterns linked to physiological function.

Tissue-wise investigations consistently identify liver tissues as primary accumulation sites due to their role in detoxification and metabolism. Gills show secondary accumulation because they serve as the main interface for respiratory exchange with water, while muscles often exhibit comparatively lower concentrations.

Species-specific differences in accumulation are influenced by ecological behavior, trophic level, feeding habit, and habitat preference. Benthic and carnivorous species generally exhibit higher metal burdens compared with herbivorous or pelagic species due to prolonged sediment exposure and biomagnification processes [5].

Toxicological effects of heavy metals are multifaceted and involve oxidative stress, disruption of enzyme function, immune suppression, and cellular degeneration. Chronic exposure may impair growth, reproduction, and survival, ultimately threatening fish population stability and biodiversity [6].

From a human health perspective, contaminated fish represent an important exposure pathway for toxic metals. Hazard Quotient (HQ) and Hazard Index (HI) analyses conducted in various studies indicate potential health risks among populations consuming fish from heavily polluted river sections [7].

Given the ecological and public health implications, this study aims to review and synthesize existing research on heavy metal bioaccumulation and toxicological effects in major freshwater fish species of the Ganga–Yamuna basin, highlighting contamination patterns, biological responses, and management implications.

II. METHODOLOGY

The present study adopts a systematic analytical methodology based on literature review and comparative synthesis of scientific findings published up to September 2025 [1]. The purpose is to evaluate trends in heavy metal contamination and their biological impacts on freshwater fish species.

Relevant literature was identified from peer-reviewed journals, environmental monitoring reports, governmental assessments, and academic research

focusing specifically on the Ganga–Yamuna basin within Uttar Pradesh [2]. Only studies providing measurable data on fish tissue contamination or toxicological effects were included.

Selection criteria emphasized field-based studies conducted under natural riverine conditions. Laboratory-only experiments lacking ecological relevance were excluded to maintain environmental applicability.

Heavy metals most frequently reported in regional studies—lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), and nickel (Ni)—were categorized according to source, bioavailability, and toxicological significance [3].

Bioaccumulation analysis focused on comparing concentration patterns across different tissues including liver, gills, muscle, and skin. These patterns were interpreted to understand physiological pathways of uptake and detoxification [4].

Species-specific evaluation incorporated ecological traits such as feeding behavior, habitat utilization, and trophic position to explain observed variation in accumulation levels [5].

Toxicological effects were analyzed through synthesis of biomarkers commonly used in aquatic toxicology research. These included antioxidant enzyme activity, lipid peroxidation, histopathological alterations, and reproductive parameters [6].

Human health risk assessments were interpreted using published indices such as Hazard Quotient (HQ), Target Hazard Quotient (THQ), and Hazard Index (HI), which estimate exposure risks from fish consumption [7]. Monitoring data from regulatory agencies including CPCB and UPPCB were incorporated to support contamination trends observed in scientific studies [8].

Data interpretation relied on thematic analysis integrating ecological, toxicological, and public health frameworks rather than statistical meta-analysis, allowing broader conceptual understanding of heavy metal impacts.

III. RESULTS

The reviewed literature indicates widespread occurrence of heavy metals in water, sediment, and fish tissues across multiple stretches of the Ganga–Yamuna basin. Concentrations of lead (Pb), cadmium (Cd), and chromium (Cr) frequently exceed permissible environmental limits, particularly in industrially influenced zones such as downstream regions of Kanpur, Prayagraj, and Varanasi. These metals persist in sediments and enter aquatic food chains through continuous exposure and trophic transfer.

Tissue-wise bioaccumulation patterns consistently reveal highest concentrations in liver tissues followed by gills and muscles. The liver functions as the primary detoxification organ, actively metabolizing and storing toxic substances, which explains its dominant accumulation profile. Elevated hepatic metal

concentrations indicate chronic exposure and sustained physiological stress.

Gill tissues also exhibit high metal levels due to their direct and continuous interaction with surrounding water. Their large surface area and thin epithelial membrane facilitate rapid diffusion of dissolved metals into systemic circulation, making them major entry points for contaminants.

Species-specific variation in accumulation is evident. Omnivorous and benthic feeders such as *Cyprinus carpio*, *Oreochromis niloticus*, and *Channa punctata* demonstrate comparatively higher bioaccumulation. Their feeding habits involve sediment interaction and consumption of diverse prey items, increasing exposure to contaminated substrates.

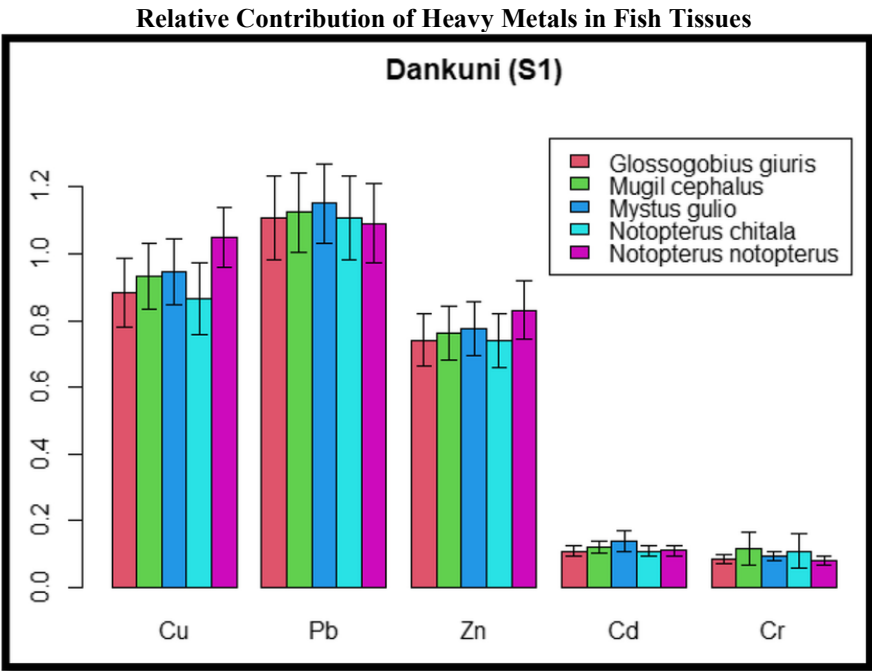
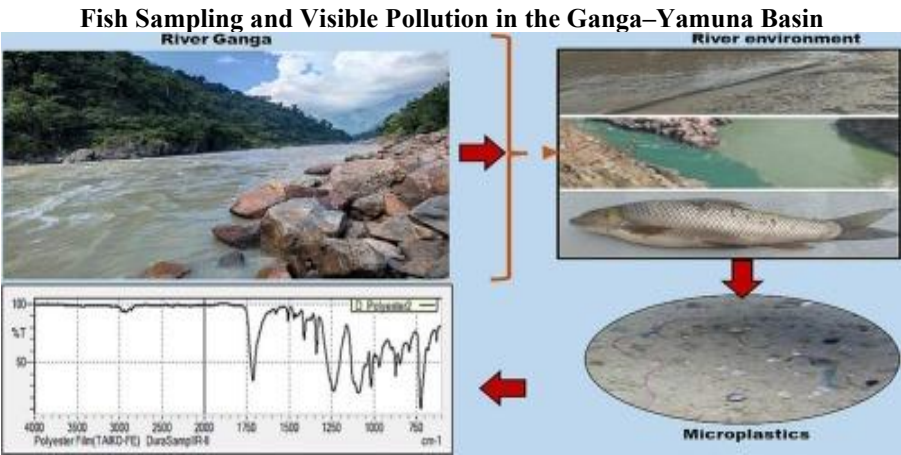
Biochemical analyses show elevated oxidative stress markers, including increased lipid peroxidation and altered antioxidant enzyme activity (SOD, CAT, GPx). These changes indicate disruption of cellular redox

balance and physiological disturbance caused by metal toxicity. Prolonged oxidative stress may impair metabolic efficiency and immune function.

Histopathological examinations reveal consistent abnormalities such as liver cell degeneration, vacuolization, necrosis, gill lamellae fusion, epithelial lifting, and kidney tissue damage. These structural changes confirm chronic toxic impact at the organ level.

Reproductive impairment has also been documented in chronically exposed fish populations. Reduced gonadosomatic index (GSI), altered hormone levels, and delayed gamete maturation suggest endocrine disruption and long-term ecological consequences.

Human health risk assessments highlight elevated hazard indices in certain industrial regions of the basin. Consumption of contaminated fish may lead to chronic dietary exposure, particularly to Pb and Cd, posing risks to vulnerable populations.

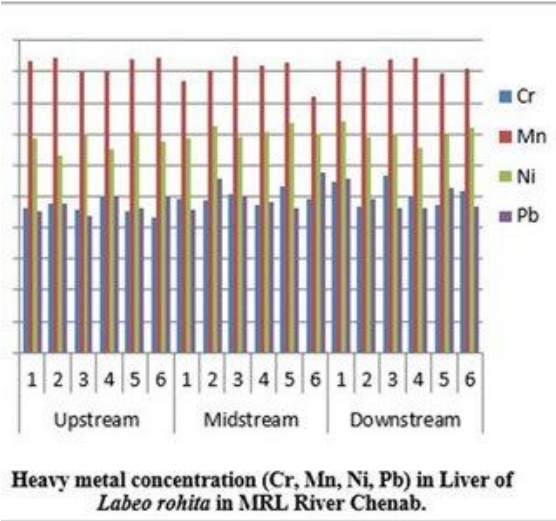


Interpretation:

Pb, Cd, and Cr contribute the highest proportion of

contamination, particularly in liver tissues, confirming industrial discharge as a major source.

Tissue-wise Bioaccumulation Trend



Interpretation:

The graphical trend confirms the general bioaccumulation hierarchy:

Liver > Gills > Muscle

This pattern reflects detoxification dominance in hepatic tissue and direct environmental exposure via gills.

IV. DISCUSSION AND CONCLUSION

The findings collectively demonstrate that heavy metal contamination in the Ganga–Yamuna basin represents a significant ecological challenge affecting freshwater biodiversity and fisheries sustainability. Persistent pollution inputs from industrial and urban sources continue to elevate contamination levels despite existing environmental regulations.

Liver-dominated accumulation patterns observed across multiple species confirm that detoxification mechanisms are heavily engaged in response to chronic exposure. However, prolonged accumulation may exceed physiological tolerance limits, resulting in cellular and tissue damage.

Oxidative stress appears to be a central mechanism linking heavy metal exposure with broader toxicological effects. Disruption of antioxidant defense systems leads to lipid peroxidation and enzymatic imbalance, contributing to organ dysfunction and reduced physiological performance.

Histopathological evidence further supports the conclusion that heavy metals compromise respiratory and metabolic systems, reducing fish fitness and altering population dynamics over time.

Species-specific variation emphasizes the importance of ecological behavior in determining exposure risk. Bottom feeders and omnivorous species

exhibit higher accumulation, highlighting the role of contaminated sediments in pollutant transfer.

Human health implications remain significant, as consumption of contaminated fish may result in chronic exposure to toxic metals. Elevated hazard indices reported in several studies suggest the need for regular fish safety assessment and public awareness programs.

Effective mitigation requires a combination of strict industrial effluent regulation, improved wastewater treatment infrastructure, and basin-scale ecological monitoring programs. Restoration of wetlands and riverine buffer zones can further reduce pollutant entry into aquatic systems.

Future research should prioritize long-term ecological monitoring, molecular-level toxicological studies, and climate-related influences on metal mobility and bioavailability.

In conclusion, heavy metal bioaccumulation in freshwater fish of the Ganga–Yamuna basin poses substantial ecological and public health risks. Sustainable management strategies integrating scientific monitoring, regulatory enforcement, and community awareness are essential for restoring river health and protecting aquatic biodiversity.

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