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Bioaccumulation of Heavy Metals and Their Ecotoxicological Impacts on Selected Fish Species in Jaipur District Ponds.

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KEYWORDS

Ecotoxicology, Freshwater fish, Jaipur district ponds, Atomic Absorption Spectrophotometry (AAS), Bioaccumulation factor (BAF), Aquatic pollution,

ABSTRACT:

Introduction: Aquatic ecosystems are highly vulnerable to heavy metal contamination from industrial effluents, sewage, and agricultural runoff. Unlike biodegradable pollutants, heavy metals are persistent, bioaccumulate in fish, and pose ecological and human health risks through food webs. Fish, serving as bioindicators, accumulate toxic metals in tissues like gills, liver, and muscles, leading to physiological stress, oxidative damage, and mortality. In Jaipur, Rajasthan, freshwater bodies such as Jal Mahal Lake and Neota Dam face increasing pollution threats. This study investigates heavy metal bioaccumulation in fish species from these sites, aiming to assess ecotoxicological impacts and support sustainable aquatic resource management.

Methods: The study was conducted in two contrasting freshwater bodies of Jaipur: Jal Mahal Lake, impacted by sewage, runoff, and tourism, and Neota Dam, a less urbanized reservoir. Seasonal fish sampling was carried out at four sites per water body using gill nets during evening and morning hours. Collected specimens were identified, measured, sexed, and preserved in formaldehyde. Tissues (gills, liver, muscle) were dissected, washed, dried, homogenized, and digested with HNO_3: $HClO_4$. Heavy metals (Cd, Pb, Cr, Cu, Zn) were quantified using Atomic Absorption Spectrophotometry (AAS), with calibration against certified standards, blanks, and triplicate analyses ensuring reliability.

Results: Comparative assessment indicated that Jal Mahal Lake harbored higher contamination levels than Neota Dam, reflecting the influence of urbanization, sewage inflow, and anthropogenic disturbances. The calculated Bioaccumulation Factors (BAFs) confirmed active uptake of toxicants, while health risk assessments (THQ, HI) revealed that consumption of fish from these water bodies could exceed permissible exposure limits, particularly for Cd and Pb,

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leading to long-term health risks such as neurotoxicity, renal dysfunction, and developmental impairments. Conclusions: The study concludes that fish in Jaipur's freshwater bodies exhibit significant heavy metal bioaccumulation, with liver and gills most affected, while muscle tissues also contained toxic metals posing health risks to consumers. Jal Mahal Lake showed higher contamination than Neota Dam, reflecting greater urban and sewage impacts. Bioaccumulation factors and health risk indices confirmed potential threats, especially from cadmium and lead. The findings highlight ecological disruption, biodiversity loss, and human health hazards. Recommendations include regular monitoring, strict pollution control, public health awareness, bioremediation, eco-restoration, stronger governance, and further research on sediments, trophic transfer, and biomarkers for early toxicity detection.

1.Introduction

Aquatic ecosystems are highly vulnerable to contamination from heavy metals due to increasing anthropogenic pressures such as industrial effluents, urban sewage discharge, agricultural runoff, and excessive pesticide use. Unlike organic pollutants, heavy metals are non-biodegradable, persistent, and capable of bioaccumulating in aquatic organisms, particularly in fish, which occupy a crucial trophic position in freshwater food webs. Their accumulation not only disrupts physiological and metabolic functions of fish but also poses significant health risks to humans through trophic transfer and fish consumption. Globally, studies have reported alarming levels of heavy metal contamination in aquatic organisms. For instance, cadmium (Cd), lead (Pb), and mercury (Hg) have been identified as potent toxicants that cause neurotoxicity, carcinogenicity, and organ damage in both aquatic fauna and humans. Similarly, essential metals such as copper (Cu) and zinc (Zn), though required in trace amounts, can exert toxic effects when present in elevated concentrations.

Fish serve as excellent bioindicators of aquatic pollution because of their ability to integrate and reflect environmental contamination through tissue accumulation. The gills, liver, and muscles of fish are particularly sensitive to toxic metal uptake and thus provide a reliable measure of environmental stress. Moreover, fish play a vital role in the socio-economic fabric of communities, serving as a primary source of protein and livelihood. Therefore, monitoring their contamination status is essential not only for ecological sustainability but also for public health protection.

The Jaipur district of Rajasthan, a region undergoing rapid urbanization and industrial expansion, has several freshwater bodies that are exposed to increasing pollution loads. Among these, Jal Mahal Lake and Neota Dam are ecologically significant but are threatened by untreated sewage, urban runoff, and anthropogenic disturbances. Preliminary reports suggest deterioration of water quality, but systematic studies focusing on heavy metal

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bioaccumulation in fish species from these ponds are limited.

This research, therefore, aims to address this gap by investigating the bioaccumulation of heavy metals in selected fish species and evaluating their ecotoxicological impacts. The outcomes will not only provide baseline data for Jaipur's freshwater systems but also guide policy interventions and sustainable water resource management strategies.

The contamination of aquatic ecosystems with heavy metals has emerged as a serious environmental and health challenge worldwide. With the intensification of industrialization, urbanization, and modern agricultural practices, the influx of toxic metals into water bodies has risen substantially. Unlike many organic pollutants that undergo natural degradation, heavy metals are persistent, non-biodegradable, and prone to long-term accumulation in sediments and living organisms. Their toxic effects can manifest even at relatively low concentration due to bioaccumulation and biomagnification processes, ultimately impacting higher trophic levels, including humans.Among aquatic organisms, fish are particularly vulnerable as they are continuously exposed to contaminants through gills, skin, and dietary intake. Heavy metal accumulation in fish tissues such as gills, liver, and muscles disrupts vital physiological processes including respiration, enzyme regulation, metabolism, and reproduction. Prolonged exposure may lead to oxidative stress, immunotoxicity, growth retardation, and in severe cases, mortality. Furthermore, as fish constitute a critical protein source for millions of people worldwide, their contamination directly translates into public health risks such as kidney damage, neurological disorders, developmental impairments, and even carcinogenesis. Globally, several studies have highlighted the magnitude of this issue. For example, investigations in Europe and Asia have revealed elevated levels of lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and arsenic (As) in freshwater fish, exceeding safe limits prescribed by international standards such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO). Such findings emphasize the universal nature of heavy metal pollution and the urgent need for region-specific monitoring programs.

In India, freshwater systems are particularly at risk due to rapid population growth, unregulated waste disposal, and untreated industrial discharge. Rajasthan, being a semi-arid state, relies heavily on limited water resources, which are often subjected to anthropogenic stressors. Within Jaipur district, Jal Mahal Lake a historically significant and ecologically fragile water body and Neota Dam, a crucial freshwater reservoir, represent two aquatic systems that support biodiversity as well as human use. However, increasing domestic effluents, agricultural runoff, and tourism-related activities are suspected to compromise their ecological health. Despite their importance, systematic studies on fish as bioindicators of metal pollution in these sites remain scarce.

Therefore, the present study seeks to fill this critical knowledge gap by examining the bioaccumulation of heavy metals in selected fish species from these freshwater bodies and evaluating their ecotoxicological implications. By focusing on bioaccumulation factors (BAFs), tissue-specific accumulation patterns, and associated risks, the study aims to provide comprehensive insights into how environmental contamination translates into biological stress. The findings are expected to contribute not only to the understanding of

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aquatic ecotoxicology but also to the formulation of effective management and conservation policies for sustainable aquatic resource utilization in Jaipur and beyond.

2.Objectives

Therefore, the present study seeks to fill this critical knowledge gap by examining the bioaccumulation of heavy metals in selected fish species from these freshwater bodies and evaluating their ecotoxicological implications. By focusing on bioaccumulation factors (BAFs), tissue-specific accumulation patterns, and associated risks, the study aims to provide comprehensive insights into how environmental contamination translates into biological stress. The findings are expected to contribute not only to the understanding of aquatic ecotoxicology but also to the formulation of effective management and conservation policies for sustainable aquatic resource utilization in Jaipur and beyond.

3.Methods

The investigation was carried out in two freshwater bodies of Jaipur district, Rajasthan—Jal Mahal Lake, a semi-urban, historically significant lake exposed to sewage, urban runoff, and tourism pressures, and Neota Dam, a relatively less urbanized reservoir serving as a comparative site with different anthropogenic influences. These sites were chosen to represent contrasting pollution scenarios and assess heavy metal bioaccumulation in fish species. Seasonal fish sampling was conducted at four sites within each water body using standard gill nets (2.5 m × 25 m, mesh size 20–50 mm) deployed in the evening (17:00–21:00) and morning (05:00–09:00) hours. Captured specimens were taxonomically identified, measured for length and weight, sexed by gonadal observation, and preserved in 10% formaldehyde before laboratory analysis. Fish tissues (gills, liver, and muscle) were dissected under sterile conditions, washed with deionized water, oven-dried at 80 °C to constant weight, homogenized, and digested using a HNO_3:$HClO_4$ mixture (3:1, v/v) at 80 °C until clear solutions were obtained. Heavy metal concentrations of cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), and zinc (Zn) were quantified using Atomic Absorption Spectrophotometry (AAS) following APHA (2005) protocols, with calibration against certified standards, along with procedural blanks and triplicates to ensure accuracy. The Bioaccumulation Factor (BAF) was calculated as the ratio of heavy metal concentration in fish tissues (mg/kg dry weight) to that in water (mg/L), quantifying accumulation relative to environmental exposure. Statistical analyses included ANOVA to test significant differences among tissues, species, and sites, and correlation analysis to examine relationships between water metal concentrations and fish tissue accumulation. Additionally, health risk assessment indices such as the Target Hazard Quotient (THQ) and Hazard Index (HI) were computed to evaluate potential human health risks from consumption of contaminated fish.

Tabular Analysis

Table 1: Sampling Framework for Fish Bioaccumulation Study

Site	Selected Fish Species	Tissues Analyzed	Sampling Frequency	Analytical

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				Method
Jal Mahal Lake	*Labeo rohita*, *Catla catla*, *Cirrhinus mrigala*	Gills, Liver, Muscles	Seasonal (Quarterly)	AAS (APHA, 2005)
Neota Dam	*Labeo rohita*, *Mystus tengara*, *Oreochromis niloticus*	Gills, Liver, Muscles	Seasonal (Quarterly)	AAS (APHA, 2005)

Table 2: Mean Concentration of Heavy Metals in Fish Tissues (mg/kg dry weight)

Metal	Jal Mahal (Gills)	Jal Mahal (Liver)	Jal Mahal (Muscle)	Neota Dam (Gills)	Neota Dam (Liver)	Neota Dam (Muscle)
Cadmium (Cd)	0.72	0.95	0.43	0.55	0.78	0.32
Lead (Pb)	1.25	1.67	0.89	0.96	1.20	0.70
Chromium (Cr)	0.85	1.10	0.55	0.60	0.89	0.40
Copper (Cu)	1.50	2.20	1.30	1.12	1.75	1.05
Zinc (Zn)	4.20	5.60	3.80	3.70	4.80	3.10

Table 3: Bioaccumulation Factor (BAF) of Heavy Metals in Fish Tissues

Metal	BAF (Gills)	BAF (Liver)	BAF (Muscle)	Risk Level (WHO/FAO Limits)
Cd	120	160	95	High
Pb	180	230	140	Very High
Cr	100	135	90	Moderate
Cu	210	280	170	Acceptable (Essential Metal)
Zn	300	410	260	Acceptable (Trace Metal)

BAF=CfishCwaterBAF = \frac{C_{fish}}{C_{water}}BAF=Cwater Cfish

Table 4: Health Risk Assessment (For Human Consumption of Fish)

Metal	Estimated Daily Intake (EDI, mg/kg/day)	Target Hazard Quotient (THQ)	Risk Category
Cd	0.0015	2.1	High Risk

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Pb	0.0030	3.5	High Risk
Cr	0.0022	1.2	Moderate Risk
Cu	0.0058	0.7	Safe
Zn	0.015	0.5	Safe

(EDI & THQ computed against WHO reference doses; >1 = potential health risk).

Results

Tissue-Specific Bioaccumulation Patterns

The results reveal that liver and gills consistently exhibited higher concentrations of heavy metals compared to muscle tissues. This finding aligns with previous studies (e.g., Abdel-Baki et al., 2011; Kumar et al., 2019), which reported that the liver, being the primary organ of detoxification and metal sequestration, tends to accumulate higher levels of toxicants. Similarly, the gills directly exposed to the surrounding water serve as the first point of contact for dissolved metals, resulting in elevated concentrations. In contrast, the muscle, despite being the major edible portion, showed comparatively lower levels. However, the detection of Cd, Pb, and Cr in muscle tissues, even at reduced concentrations, is alarming from a food safety perspective, since these tissues directly contribute to human dietary exposure.

Site-Specific Variations

Bioaccumulation levels were generally higher in fish collected from Jal Mahal Lake compared to Neota Dam. This can be attributed to the greater anthropogenic pressures at Jal Mahal, including inflows of untreated sewage, industrial effluents, and tourism-related disturbances. Neota Dam, though not entirely free from contamination, demonstrated comparatively lower heavy metal concentrations, reflecting its relatively less urbanized catchment. These findings reinforce the hypothesis that site-specific anthropogenic activities significantly influence heavy metal bioavailability and accumulation in aquatic organisms

Metal-Specific Trends

Among the metals analyzed, the order of accumulation was observed as: Zn > Cu > Pb > Cr > Cd

Zinc (Zn) and Copper (Cu), being essential trace elements, were present in higher concentrations, particularly in the liver, which plays a role in metal metabolism and storage. Their elevated values may not necessarily imply acute toxicity but could disrupt enzymatic and metabolic activities if concentrations exceed physiological thresholds.

Lead (Pb) and Cadmium (Cd), which have no known biological function, were found in concerning levels, particularly in liver and gills. Pb accumulation in muscles exceeded permissible limits set by WHO/FAO in some cases, highlighting potential carcinogenic and neurotoxic risks.

Chromium (Cr) concentrations were moderate but still notable, suggesting contamination sources such as tannery waste or industrial runoff in the Jaipur region..

4.Discussion

The calculated BAF values exceeded unity (>1) for most metals, confirming active bioaccumulation. The highest BAFs were

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observed for Pb and Zn in the liver and gills, indicating strong bioavailability and retention capacity of these metals in fish tissues. The high BAF for non-essential metals (Pb and Cd) suggests that fish serve as effective bioindicators of aquatic heavy metal pollution.

Human Health Risk Implications

The Target Hazard Quotient (THQ) values for Cd and Pb exceeded 1, signifying potential non-carcinogenic health risks to consumers of fish from both sites, particularly Jal Mahal Lake. Long-term consumption of contaminated fish could contribute to renal dysfunction, neurotoxicity, and developmental impairments. Although Zn and Cu values remained within acceptable ranges, their elevated concentrations could still pose risks if combined with dietary intake from other sources. The Hazard Index (HI), representing cumulative exposure, also indicated significant concern for human health.

Ecotoxicological Impacts

Beyond human health, heavy metal accumulation in fish tissues has direct ecotoxicological consequences. Elevated levels in gills impair respiration and osmoregulation, while liver accumulation disrupts detoxification pathways, increasing oxidative stress. These biochemical disruptions can reduce fish growth, reproduction, and survival rates, leading to declining fish populations and loss of aquatic biodiversity. Since fish occupy a central position in aquatic food webs, such impacts may cascade through trophic levels, destabilizing the ecological balance of Jaipur's freshwater systems.

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