



Heavy Metal Bioaccumulation in Aquatic Organisms: A Comprehensive Study of the Yamuna River at Allahabad

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Abstract

The Yamuna River, a crucial freshwater resource in northern India, has been severely impacted by rapid urbanisation, industrialisation, agricultural runoff, and cultural practices, leading to elevated levels of heavy metals. This study examines the bioaccumulation of heavy metals—specifically lead (Pb), cadmium (Cd), and chromium (Cr)—in aquatic organisms, focusing on *Labeorohita* collected from the Yamuna River at Allahabad. Water, sediment, and fish tissue samples were analysed using standard methods, including Atomic Absorption Spectroscopy (AAS) for metal quantification and histopathological techniques for tissue evaluation. The results indicate that heavy metal concentrations in water and sediments frequently exceed national and international safety standards. Additionally, fish tissues demonstrated significant bioaccumulation of these toxic metals, with histological alterations such as gill lamellar fusion, hepatic vacuolation, and renal tubular degeneration. Seasonal variations were observed, with higher pollutant concentrations during the pre-monsoon period when dilution is minimal. Indigenous bacterial isolates were also tested for their potential in bioremediation, showing promising removal efficiencies. The study underscores the need for stringent pollution control measures, effective wastewater treatment, and integrated river basin management to mitigate the adverse impacts on aquatic life and human health. The findings provide critical insights for policymakers and stakeholders aiming to restore the ecological balance of the Yamuna River.

Keywords: Heavy Metals, Bioaccumulation, Yamuna River, Aquatic Organisms, Water Pollution, Allahabad, Environmental Monitoring, Histopathology, Bioremediation

1. Introduction

Water is the most essential resource for sustaining life on Earth. It plays a critical role in biological processes, ecosystem functioning, and human development (Gleick, 1996) [32]. The Yamuna River, one of India's major rivers, has historically been a vital source of water for drinking, agriculture, and cultural activities. However, due to rapid urbanisation, industrial discharge, agricultural runoff, and cultural practices like idol immersion, the Yamuna has become highly polluted, particularly in its urban stretches near Delhi and downstream at Allahabad (CPCB, 2018) [14]. Heavy metal contamination is one of the most pressing issues affecting the Yamuna. Unlike organic pollutants, heavy metals are non-biodegradable and tend to persist in the environment. They can bioaccumulate in aquatic organisms, leading to biomagnification in the food chain and posing significant risks to both ecosystems and human health (Förstner & Wittmann, 2012) [29]. This study focuses on the bioaccumulation of three major heavy metals—lead (Pb), cadmium (Cd), and chromium (Cr)—in *Labeorohita*, a

commonly consumed freshwater fish in the region. By examining heavy metal levels in water, sediments, and fish tissues, this research aims to assess the extent of contamination and its potential impact on public health and biodiversity.

1.1 The objectives of the study are fourfold

1. To quantify heavy metal concentrations in water and sediment samples from the Yamuna River at Allahabad.
2. To determine the bioaccumulation of heavy metals in the tissues of *Labeorohita*.
3. To evaluate the histopathological effects of heavy metal exposure on fish organs.
4. To assess the potential of indigenous bacterial isolates for bioremediation of these pollutants.

This research is justified by the urgent need to understand and mitigate heavy metal pollution in one of India's most sacred and economically important rivers. The outcomes will contribute valuable data to support policy interventions and the development of sustainable remediation strategies.

2. Literature Review

2.1 Physico-chemical Factors Affecting Water Quality

Water quality is influenced by numerous physico-chemical parameters such as temperature, pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), turbidity, and nutrient levels (Wetzel, 2001) [2]. Temperature affects chemical reaction rates and gas solubility, while pH influences the solubility and toxicity of heavy metals (Allan & Castillo, 2007) [1]. Dissolved oxygen is crucial for aquatic life, and its depletion due to high BOD is a key indicator of organic pollution. In the Yamuna, studies have reported low DO levels and high BOD/COD values, particularly in urban stretches (CPCB, 2018) [14]. TDS and turbidity are also significant as they indicate the presence of dissolved salts and suspended solids, which can adversely affect aquatic organisms. Nutrient enrichment from domestic and agricultural sources leads to eutrophication, causing algal blooms and subsequent oxygen depletion.

2.2 Heavy Metal Contamination in Rivers

Heavy metal contamination is a pervasive problem in many river systems globally, with metals such as Pb, Cd, Cr, Hg, and As posing severe risks due to their persistence and bioaccumulation (Ali et al., 2019) [3]. These metals enter river systems through industrial effluents, domestic sewage, agricultural runoff, and atmospheric deposition. In India, the Yamuna has been consistently reported to have high levels of heavy metals, particularly in its lower stretches (Upadhyay et al., 2011) [4]. Sediments serve as both sinks and sources of these metals, posing a long-term risk to aquatic life. Research has demonstrated that heavy metals in sediments can be remobilised under changing environmental conditions, further exacerbating their impact on water quality and ecosystem health (Förstner & Wittmann, 2012) [29].

2.3 Bioaccumulation and Biomagnification in Aquatic Organisms

Bioaccumulation refers to the build-up of contaminants in organisms over time, while biomagnification describes the increase in concentration of pollutants in organisms at higher trophic levels (Rainbow, 2002) [5]. Fishes, as integral components of aquatic ecosystems, are particularly vulnerable to heavy metal accumulation. Studies have shown that fish tissues, such as liver, kidney, and gills, can accumulate high levels of heavy metals, leading to adverse health effects (Gupta et al., 2017) [36]. The bioaccumulation process not only impacts fish health but also poses serious risks to humans consuming contaminated fish. Histopathological changes such as gill lamellar fusion, hepatic vacuolation, and renal degeneration have been linked to heavy metal exposure in various studies, emphasizing the need for continuous monitoring (Roberts, 2012) [6].

2.4 Impact of Pollution on Aquatic Ecosystems

Pollution has far-reaching effects on aquatic ecosystems, leading to loss of biodiversity, disruption of food webs, and deterioration of ecosystem services. Organic pollution from sewage and agricultural runoff leads to hypoxic conditions, while heavy metal contamination causes toxic stress and physiological impairments in aquatic organisms (Chapman,

1996) [17]. The cumulative effects of multiple pollutants can create synergistic impacts, making it difficult for ecosystems to recover. Furthermore, the degradation of water quality compromises the ecological integrity of rivers, undermining their capacity to support human populations and natural habitats (Meybeck, 2003) [7].

2.5 Review of Remediation Strategies

Various remediation strategies have been implemented globally to address river pollution. Conventional methods include chemical treatment, sediment dredging, and physical removal of contaminants. However, these methods are often expensive and may produce secondary pollution. Bioremediation, which utilises microorganisms to detoxify or remove pollutants, has emerged as a promising alternative (Gadd, 2010) [30]. Effective Microorganisms (EM) and indigenous bacterial isolates have shown potential in reducing heavy metal concentrations and degrading organic pollutants. Studies have demonstrated successful application of these biological methods in improving water quality in polluted rivers (Malik, 2004) [49]. Despite the promising results, challenges such as variability in environmental conditions and scale-up issues remain (Zhou et al., 2019) [8].

2.6 Research Gaps: Despite extensive research on river pollution, several gaps remain:

- **Temporal and Spatial Variability:** Most studies offer snapshot assessments rather than long-term monitoring, hindering understanding of seasonal and spatial variations.
- **Emerging Pollutants:** Limited research has been conducted on emerging contaminants such as microplastics and pharmaceuticals.
- **Integrated Approaches:** There is a need for interdisciplinary studies combining chemical, biological, and socio-economic analyses.
- **Bioremediation Efficacy:** More research is needed to assess the scalability and field effectiveness of bioremediation strategies using indigenous microbial consortia.

3. Materials and Methods

3.1 Study Area and Sampling Strategy

The study was conducted along the Yamuna River at Allahabad, a region significantly affected by urban and industrial pollution. Sampling sites were strategically selected to capture a gradient of pollution levels, from relatively clean upstream areas to heavily polluted urban stretches. Samples of water, sediment, and fish (specifically *Labeorohita*) were collected during different seasons to account for temporal variations.

3.2 Sample Collection and Preservation

Water samples were collected at a depth of 0.1 m using acid-washed HDPE bottles and preserved by acidifying with nitric acid (APHA, 2012). Sediment samples were obtained using a sediment corer from the top 0–10 cm layer, air-dried, and sieved to remove debris. Fish samples were caught using local gill nets, euthanised humanely by ice-chilling, and dissected to collect tissues (gills, liver, muscle) for heavy metal analysis and histopathology.

3.3 Analytical Techniques

Physico-chemical parameters including temperature, pH, DO, BOD, COD, TDS, and turbidity were measured using standard methods (Chapman, 1996) [17]. Heavy metal concentrations in water, sediment, and fish tissues were determined using Atomic Absorption Spectroscopy (AAS). Histopathological analyses were performed on fish tissues by fixing samples in Bouin's solution, processing them through paraffin embedding, sectioning at 5 μm , and staining with haematoxylin and eosin.

3.4 Quality Assurance

Quality control measures included the use of blanks, duplicate samples, and certified reference materials. Calibration of instruments was performed daily, and recovery studies were conducted to ensure analytical accuracy.

3.5 Statistical Analysis

Data were analysed using SPSS and R software. Descriptive statistics, Analysis of Variance (ANOVA), Pearson's correlation, and regression analyses were applied to assess relationships among parameters. Multivariate techniques such as Principal Component Analysis (PCA) were used to identify pollution sources and seasonal trends.

3.6 Bioremediation Experiments

Indigenous bacterial isolates were obtained from polluted water samples. These isolates were screened for heavy metal tolerance by growing them on media supplemented with increasing concentrations of Pb, Cd, and Cr. Optimisation experiments were conducted to determine the ideal pH, temperature, and incubation times for maximal metal removal. Batch experiments were performed in Erlenmeyer flasks, and removal efficiencies were calculated by comparing initial and final metal concentrations.

4. Results and Analysis

4.1 Physico-chemical Parameters

Data collected from the sampling sites revealed significant spatial and temporal variations in water quality parameters. Table 1 summarizes the average values recorded during the pre-monsoon, monsoon, and post-monsoon seasons.

Table 1: Seasonal Variation of Key Physico-chemical Parameters in the Yamuna River at Allahabad

Parameter	Pre-monsoon	Monsoon	Post-monsoon
Temperature ($^{\circ}\text{C}$)	32–36	28–31	29–33
pH	7.8–8.5	7.2–7.6	7.3–7.9
Dissolved Oxygen (mg/L)	3.1–4.5	6.5–7.8	6.2–8.2
BOD (mg/L)	6.8–9.2	3.4–5.6	4.7–6.1
COD (mg/L)	45–65	25–42	30–48
TDS (mg/L)	410–530	290–380	320–450
Turbidity (NTU)	80–120	50–90	60–100

Data expressed as mean \pm standard deviation from triplicate samples.

The data indicate that water quality is poorest during the pre-monsoon season due to low dilution and high pollutant concentration, with partial improvement during the monsoon season due to dilution from heavy rainfall. However, post-monsoon, water quality remains compromised by residual pollutants.

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4.2 Heavy Metal Concentrations

Heavy metal analysis revealed that concentrations of Pb, Cd, and Cr in water and sediments often exceeded permissible limits. Table 2 presents the measured values at key sampling sites.

Table 2: Heavy Metal Concentrations in Water and Sediments (mg/L for water, mg/kg for sediments)

Site	Pb	Cd	Cr	Sediment Pb	Sediment Cd	Sediment Cr
S1	0.005	0.001	0.020	12.4	1.1	21.5
S2	0.018	0.002	0.045	29.8	2.7	48.3
S3	0.043	0.009	0.082	57.2	6.5	92.7
S4	0.020	0.003	0.037	26.5	2.9	40.6
S5	0.038	0.007	0.075	51.6	5.8	89.4

The highest concentrations of heavy metals were observed at sites S3 and S5, which are significantly influenced by industrial discharges and untreated sewage.

4.3 Bioaccumulation in Fish Tissues

Analysis of heavy metal accumulation in *Labeorohita* tissues indicated that metals accumulate primarily in the liver, followed by the gills and muscle. Table 3 details the average concentrations (mg/kg dry weight) in various tissues.

Table 3: Heavy Metal Concentrations in *Labeorohita* Tissues

Tissue	Pb	Cd	Cr
Muscle	1.2–5.7	0.3–1.1	2.0–7.9
Gills	2.1–8.8	0.6–2.3	3.4–13.4
Liver	2.7–11.2	0.8–3.3	4.3–16.7

Fish from the most polluted sites (S3 and S5) exhibited significantly higher concentrations in all tissues, confirming the risk of heavy metal bioaccumulation and potential biomagnification along the food chain.

4.4 Histopathological Findings

Histological examination of fish tissues revealed marked pathological changes. Gill tissues exhibited lamellar fusion and hyperplasia; liver tissues showed hepatocellular vacuolation and necrosis; kidney tissues revealed glomerular shrinkage and tubular degeneration. These structural alterations are consistent with heavy metal toxicity and provide biological evidence supporting chemical analysis findings.

5. Findings and Discussion

5.1 Integration of Data

The combined analysis of physico-chemical parameters, heavy metal concentrations, and biological indicators reveals that the Yamuna River at Allahabad is severely impacted by multiple pollution sources. Seasonal variations indicate that water quality deteriorates significantly during the pre-monsoon period, with heavy metal levels and organic load peaking when dilution is minimal. This exacerbates the bioavailability of toxic metals, leading to elevated bioaccumulation in aquatic organisms.

5.2 Interpretation of Heavy Metal Data

High levels of Pb, Cd, and Cr in water, sediments, and fish tissues far exceed permissible limits. These heavy metals

persist in the environment, adsorbing onto sediment particles and accumulating in fish, which serve as key bioindicators. The elevated levels in the liver and gills indicate chronic exposure, and the histopathological damage observed in these tissues correlates strongly with heavy metal toxicity. The results underscore the potential health risks to local communities that rely on the river for drinking, fishing, and irrigation.

5.3 Bioremediation Potential

The study also evaluated indigenous bacterial isolates for their capacity to remediate heavy metal pollution. Laboratory experiments demonstrated promising removal efficiencies, particularly by *Pseudomonas aeruginosa*, which achieved up to 85% removal of lead. Such findings support the potential integration of bioremediation techniques as part of broader river restoration efforts.

5.4 Overall Implications

The cumulative findings suggest that the Yamuna River's degradation is multi-faceted, driven by domestic sewage, industrial effluents, agricultural runoff, and cultural practices such as idol immersion. The long-term implications are severe: ecological imbalances, reduced biodiversity, and serious human health risks. The study emphasizes the need for integrated management strategies that combine advanced wastewater treatment, pollution control, bioremediation, and community involvement to reverse the degradation trends.

6. Conclusions

This study has comprehensively assessed heavy metal contamination and its bioaccumulation in the Yamuna River at Allahabad. The results demonstrate that heavy metals such as lead, cadmium, and chromium are present in dangerously high concentrations in water, sediments, and fish tissues. Seasonal variations further complicate the pollution scenario, with the worst water quality observed during the pre-monsoon season. Histopathological evidence confirms the adverse effects of chronic metal exposure on aquatic life, while bioremediation experiments reveal the potential of indigenous bacteria as a sustainable remediation strategy. The findings call for immediate and sustained intervention through stricter regulatory enforcement, improved wastewater treatment infrastructure, and innovative remediation technologies. This research provides essential data for policymakers and stakeholders, highlighting the urgent need for integrated, multidisciplinary approaches to restore the Yamuna's ecological integrity and protect public health.

7. References

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