DOI: https://doi.org/10.70749/ijbr.v3i10.2541

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://ijbr.com.pk
ISSN: 2960-2793/ 2960-2807

Assessment of Heavy Metal Contamination in Aquatic Fauna Using Atomic Absorption Spectroscopy

Muhammad Raza Malik[1], Pariyah Shayman[2], Muhammad Ansuf Imran[3], Alizzah Amanat[4], Muhammad Tanveer[5], Muhammad Dilshad[6]

[1]Department of Chemistry, University of the Punjab, Lahore, Pakistan.
[2]Lahore Grammar School, Defence, Lahore, Pakistan.
[3]International School, Lahore, Pakistan.
[4]University of Okara, Okara, Pakistan.
[5]Fisheries Research and Training Institute, Lahore, Pakistan.
[6]Directorate General of Archaeology, Tourism and Museums Department, Punjab, Pakistan.

ARTICLE INFO

Keywords: Heavy Metals, Fish Bioaccumulation, Atomic Absorption Spectroscopy, Environmental Pollution, Health Risk Assessment, Aquatic Ecosystems, Ecotoxicology, Industrial Discharge.

Correspondence to: Muhammad Raza Malik,
Department of Chemistry, University of the Punjab, Lahore, Pakistan.
Email: chemistofpu@gmail.com

Declaration

Authors' Contribution: All authors equally contributed to the study and approved the final manuscript.

Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History

Received: 01-08-2025 Revised: 02-10-2025
Accepted: 18-10-2025 Published: 30-10-2025

ABSTRACT

This study investigates the extent of heavy metal contamination in freshwater fish tissues across industrial, urban, agricultural, and pristine sites using Atomic Absorption Spectroscopy (AAS) for precise quantification of lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg). A total of 150 samples were analyzed, revealing concentrations of all metals exceeding FAO permissible limits, with the liver showing the highest accumulation (Pb: 3.37 mg/kg; Cd: 1.02 mg/kg; Cr: 1.58 mg/kg; Hg: 0.57 mg/kg), followed by gills and muscle tissues. Spatial variation analysis indicated significantly elevated levels in industrial and urban drainage zones compared to reference sites, confirming anthropogenic sources such as metal plating, textile effluents, and agricultural runoff. Bioaccumulation Factor (BAF) and Health Risk Index (HRI) values were significantly higher ($p < 0.001$) in contaminated regions, with cumulative Hazard Index (HI = 5.55) surpassing safe limits, indicating substantial ecological and human health risks through fish consumption. The findings demonstrate that industrial and agricultural discharges are primary contributors to persistent aquatic pollution, leading to potential bioaccumulation and chronic toxicity. Therefore, this research underscores the urgent need for continuous biomonitoring, strict enforcement of effluent regulations, and adoption of sustainable pollution management strategies to mitigate heavy metal exposure and preserve aquatic ecosystem integrity.

INTRODUCTION

Aquatic ecosystems are increasingly threatened by the accumulation of heavy metals resulting from anthropogenic activities such as industrial discharge, mining, and agricultural runoff [1]. Unlike organic pollutants, heavy metals are non-biodegradable and persist in water bodies, where they accumulate in sediments and enter the food chain through aquatic organisms [2]. Fish and other aquatic fauna play a critical role in this process as they act as biological indicators that reflect the contamination status of their environment [3]. Once ingested, these metals can bioaccumulate in tissues such as gills, liver, and muscle, posing serious health risks to both aquatic life and humans who consume contaminated fish [4]. Atomic Absorption Spectroscopy (AAS) has emerged as one of the most reliable and precise analytical techniques for quantifying trace metal concentrations in biological samples [5]. It offers high sensitivity, reproducibility, and specificity for detecting metals such as lead, cadmium, chromium, mercury, zinc, and copper in aquatic tissues [6]. The method allows for direct comparison of pollutant levels with standard guidelines provided by agencies such as WHO, FAO, and EPA, ensuring consistency in environmental assessments [7].

1. Global Occurrence and Environmental Dynamics of Heavy Metal Contamination

Numerous studies across the world have consistently demonstrated the widespread presence of heavy metals in aquatic ecosystems, particularly in areas with high

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

industrialization and intensive agricultural practices [8]. Rapid urban expansion, mining, and improper waste management have further aggravated the problem by continuously introducing heavy metal residues into rivers, lakes, and estuaries. These contaminants, unlike organic pollutants, are non-biodegradable and persist for extended periods, binding with sediments and entering biological food chains. As a result, aquatic species such as fish, crustaceans, and mollusks have become important bioindicators of environmental metal exposure. Regions adjacent to industrial effluent discharge zones often report metal concentrations exceeding permissible environmental limits, highlighting the critical need for continuous ecological monitoring. The bioavailability and toxicity of these metals in aquatic environments are strongly influenced by several physicochemical parameters such as pH, temperature, salinity, and water hardness [9]. For instance, acidic pH levels increase metal solubility, enhancing their uptake by aquatic organisms, whereas higher water hardness can reduce metal toxicity through ionic competition. Seasonal variations in temperature and hydrological conditions also alter the chemical speciation of metals, affecting their interaction with sediments and aquatic biota. These environmental dynamics complicate the prediction of contamination patterns, emphasizing the need for precise analytical methods to accurately assess heavy metal distribution and behavior in aquatic habitats.

Furthermore, spatial differences in land use contribute to distinct contamination profiles across aquatic systems. Agricultural catchments often exhibit elevated concentrations of cadmium and zinc due to fertilizer and pesticide runoff, while industrial zones show higher levels of lead, chromium, and mercury [10]. The interaction of these multiple pollution sources results in cumulative environmental stress, which adversely affects biodiversity, alters trophic interactions, and threatens ecosystem resilience. Understanding these dynamics provides the foundation for developing targeted pollution control and remediation strategies tailored to specific environmental contexts.

2. Analytical Assessment of Heavy Metals Using Atomic Absorption Spectroscopy

To evaluate and quantify the extent of contamination, precise analytical techniques are indispensable. Atomic Absorption Spectroscopy (AAS) has emerged as a gold-standard method for determining trace levels of heavy metals in biological and environmental samples due to its high sensitivity, selectivity, and reproducibility [11]. AAS operates on the principle that ground-state metal atoms absorb light at specific wavelengths, and the amount of absorbed light is directly proportional to metal concentration in the sample. The method's robustness and cost-effectiveness make it particularly suitable for routine environmental monitoring programs in developing regions where advanced instrumentation such as ICP-MS may be unavailable. This study employs AAS to investigate the concentration of four major toxic metals—lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg)—in selected freshwater fish species collected from multiple locations. By focusing on these specific metals, which are known for their high toxicity and tendency to bioaccumulate, the analysis provides a representative overview of anthropogenic pollution levels within aquatic ecosystems. Fish tissues such as liver, gills, and muscle are analyzed since they exhibit differential metal accumulation patterns that reflect both short-term and long-term exposure to contaminants.

Moreover, the study establishes a strong correlation between measured heavy metal concentrations in fish tissues and key environmental parameters such as pH, dissolved oxygen (DO), and proximity to pollution sources [12]. These environmental factors play a crucial role in determining the chemical behavior, mobility, and bioavailability of metals in aquatic systems. For instance, lower pH levels increase metal solubility, enhancing their uptake through gill membranes and gastrointestinal tracts. Conversely, higher pH and elevated dissolved oxygen levels can promote metal precipitation or adsorption onto sediments, thereby reducing their bioavailability. The proximity of sampling sites to industrial effluent outlets, agricultural drainage channels, and urban runoff zones further amplifies contamination, as these locations often receive high concentrations of untreated waste containing heavy metals [13]. By integrating these environmental variables with bioaccumulation data, the study provides a clearer understanding of how physicochemical conditions influence the uptake and distribution of toxic metals in aquatic fauna.

This integrative analytical approach enhances the reliability and ecological relevance of the findings by linking field-level environmental dynamics with biological responses in fish. Such correlation-based assessments not only help identify pollution hotspots but also reveal the environmental mechanisms driving metal accumulation in different habitats. For example, areas characterized by low pH and limited dissolved oxygen were found to support higher metal bioavailability and subsequent tissue accumulation. These insights are critical for developing predictive models of contamination risk, enabling targeted interventions in high-risk zones [14]. Furthermore, understanding these environmental-bioaccumulation relationships supports more effective ecological risk assessment, informs the formulation of evidence-based environmental regulations, and promotes sustainable aquatic resource management practices. Ultimately, the study's comprehensive framework bridges environmental chemistry with ecotoxicology, providing valuable guidance for policymakers and conservationists seeking to mitigate heavy metal contamination in aquatic ecosystems.

Research Objectives

1. To determine the concentration levels of selected heavy metals (Pb, Cd, Cr, Hg) in aquatic fauna using Atomic Absorption Spectroscopy.
2. To analyze the spatial variation of heavy metal accumulation in fish species from different freshwater locations.
3. To assess the relationship between environmental pollution sources and bioaccumulation of heavy metals in aquatic fauna.

Heavy metal contamination in aquatic ecosystems represents one of the most critical environmental and

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

public health challenges of the modern era. Rapid industrialization, mining, urban runoff, and inadequate waste disposal have resulted in the continuous discharge of toxic metals such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) into water bodies, where they persist and bioaccumulate in sediments and aquatic organisms. Over time, this accumulation disrupts aquatic food chains, impairing the physiological and reproductive health of fish and other fauna. The human population faces indirect exposure through the consumption of contaminated seafood, leading to serious health risks such as neurotoxicity, renal failure, and carcinogenesis. In many developing regions, insufficient pollution monitoring and weak regulatory frameworks exacerbate these risks, leaving communities reliant on contaminated freshwater sources. Despite various studies, comprehensive data on the spatial distribution and bioaccumulation of heavy metals remain limited, particularly in freshwater ecosystems. This study addresses this gap by employing Atomic Absorption Spectroscopy (AAS) to quantify and assess heavy metal levels in selected fish species across multiple sites. The findings aim to provide empirical evidence that informs environmental management strategies, promotes policy development for pollution control, and enhances understanding of metal bioaccumulation processes in aquatic environments.

LITERATURE REVIEW

Sources and Environmental Behavior of Heavy Metals

Heavy metals enter aquatic systems primarily through anthropogenic activities such as industrial effluents, mining operations, sewage discharge, and agricultural runoff [15]. Once introduced, these metals interact with suspended particles and sediments, leading to long-term persistence in aquatic environments [16]. Natural processes such as weathering and volcanic activity also contribute, although their impact is relatively minor compared to industrial emissions [17]. The solubility and speciation of metals depend on physicochemical factors including pH, redox potential, and dissolved organic matter [18]. Research indicates that rivers and estuaries situated near densely populated or industrialized zones consistently exhibit the highest concentrations of heavy metal contaminants. Industrial activities such as electroplating, tanning, metal finishing, and textile processing release substantial quantities of toxic metals including chromium (Cr), lead (Pb), and cadmium (Cd) into adjacent water systems. These pollutants often enter waterways through untreated effluents or surface runoff, where they bind to suspended particles and settle in sediments. Over time, sediments act as long-term reservoirs of contamination, releasing metals back into the water column under changing environmental conditions such as pH shifts or oxygen depletion [19]. This persistent contamination not only alters the chemical composition of aquatic environments but also degrades water quality, posing serious ecological risks to both flora and fauna.

Once deposited in the aquatic ecosystem, heavy metals become bioavailable and are readily absorbed by benthic organisms such as mollusks, crustaceans, and worms. These primary consumers serve as a pathway for metal transfer to higher trophic levels, including fish and eventually humans. Through bioaccumulation and biomagnification, even trace levels of metals in water can result in dangerously high concentrations within the tissues of top predators. Such accumulation interferes with metabolic, neurological, and reproductive processes in aquatic fauna, while also threatening human health through the consumption of contaminated seafood. Consequently, understanding the sources, distribution, and ecological behavior of heavy metals in these environments is essential for effective pollution management and safeguarding aquatic biodiversity [20].

Bioaccumulation and Toxic Effects in Aquatic Organisms

Aquatic fauna absorbs heavy metals primarily through two major pathways — direct uptake from water and ingestion of contaminated food particles or sediments [21]. These metals occur in both dissolved and particulate forms, ensuring continuous exposure throughout the life cycle of aquatic organisms. Fish are particularly vulnerable due to their constant interaction with the aquatic environment through respiration and feeding [22]. The gill epithelium, being thin and highly vascularized, facilitates efficient ion exchange but also serves as a major entry point for dissolved metals. Simultaneously, ingestion of contaminated plankton, detritus, and benthic organisms introduces metals via the digestive tract, leading to internal accumulation. This dual mechanism of absorption explains why fish often exhibit higher concentrations of heavy metals compared to other aquatic species inhabiting the same environment [23]. Once absorbed, the distribution of metals within the fish body depends on the physiological and metabolic activity of specific organs [24]. The liver and kidneys generally accumulate higher metal concentrations because they are central to detoxification and excretory processes. Metals bind to metallothionein proteins within these organs, aiding in sequestration and reducing immediate toxicity [25]. However, continuous exposure overwhelms these protective systems, resulting in elevated metal retention and cellular stress. Muscle tissues, though exhibiting lower metal concentrations, are of major public health concern since they constitute the primary edible portion of fish consumed by humans [26]. Persistent accumulation across organs disrupts internal homeostasis and may cause chronic physiological alterations that compromise organismal survival.

Prolonged metal exposure leads to oxidative stress through the excessive generation of reactive oxygen species (ROS), damaging vital biomolecules such as proteins, lipids, and nucleic acids [27]. This oxidative imbalance hampers enzymatic activity, impairs mitochondrial respiration, and triggers apoptosis in sensitive tissues [28]. Cadmium interferes with calcium metabolism, resulting in skeletal deformities and inhibited growth, while mercury forms strong bonds with sulfhydryl groups in proteins, leading to enzyme inhibition and metabolic dysfunction [29]. These effects collectively reduce the metabolic efficiency and resilience of aquatic species, rendering them more susceptible to environmental fluctuations and pathogen attacks [30]. The neurotoxic potential of cadmium and mercury adds

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

further complexity to their ecological impact [31]. Both metals alter neurotransmitter synthesis and synaptic transmission, leading to behavioral abnormalities such as disorientation, erratic swimming, and impaired predator avoidance [32]. Chronic exposure has been shown to affect reproductive physiology, causing gonadal atrophy, reduced gamete quality, and diminished fertility [33]. Because these metals possess long biological half-lives, they persist in vital organs like the brain and liver, continuing to exert toxic effects even after environmental concentrations decline [34]. Such persistent bioaccumulation and neurotoxicity threaten not only the individual species but also the stability of entire aquatic food webs. Therefore, long-term monitoring and strict regulatory control of heavy metal emissions are essential to mitigate their impact on aquatic biodiversity and human health [35].

Atomic Absorption Spectroscopy in Heavy Metal Detection

Atomic Absorption Spectroscopy is a highly accurate method for determining trace metal concentrations in environmental and biological samples [36]. The principle is based on the absorption of light by free metal atoms in the gaseous state, which correlates directly with concentration [37]. Compared to other analytical techniques like ICP-MS or XRF, AAS is cost-effective, rapid, and suitable for routine environmental monitoring [38]. Studies utilizing Atomic Absorption Spectroscopy (AAS) have consistently verified its precision and reliability in detecting trace concentrations of toxic metals—often at microgram-per-liter levels—in fish tissues and other biological samples. The high sensitivity of AAS enables accurate quantification of elements such as lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr), even when present in minute amounts [39]. This capability is especially valuable for environmental biomonitoring, where detecting small variations in metal levels can reveal early signs of contamination. Furthermore, AAS provides element-specific analysis, allowing researchers to distinguish between multiple metals in complex biological matrices without significant cross-interference [40].

Beyond its detection sensitivity, the technique's robustness in differentiating contaminated from non-contaminated sampling sites makes it an essential analytical tool in aquatic pollution studies. Ongoing advancements in sample digestion protocols—such as microwave-assisted digestion—and improved matrix correction techniques have further enhanced the method's precision and reproducibility [41]. These improvements minimize analytical errors caused by organic content or sediment residues in biological tissues, ensuring more reliable results [42]. As a result, AAS remains a cornerstone technology in environmental toxicology, offering a cost-effective, reproducible, and scientifically validated approach for assessing heavy metal contamination in aquatic ecosystems [43].

METHODOLOGY

This study employs a quantitative experimental research design to assess the concentration and distribution of heavy metals in aquatic fauna using Atomic Absorption Spectroscopy (AAS). The quantitative approach allows for objective measurement and statistical evaluation of metal contamination across multiple freshwater sites, providing empirical data to determine whether industrial and agricultural activities significantly influence metal bioaccumulation in fish species. The study focuses on quantifying the levels of four major toxic metals—lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg)—in different fish tissues and evaluating their relationship with environmental exposure gradients.

The population and sampling framework of this study consists of fish species collected from five freshwater bodies exhibiting varying degrees of anthropogenic pressure, including urban-industrial discharge zones, agricultural runoff regions, and relatively unpolluted reference sites. A total of 150 fish specimens were collected through stratified random sampling to ensure representation from diverse environmental conditions. Each site contributed an equal number of specimens, and sampling was conducted during similar hydrological periods to maintain consistency. All fish samples were transported in sterile polyethylene containers, labeled appropriately, and preserved at −20°C to prevent biochemical alteration before analysis.

For sample preparation and laboratory analysis, fish specimens were dissected to obtain tissues including gills, liver, and muscle, which are known to exhibit varying affinities for heavy metal accumulation. Each tissue sample was rinsed with deionized water to remove external contaminants, then oven-dried at 105°C until a constant weight was achieved. Dried samples were ground into fine powder and subjected to acid digestion using a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 3:1 ratio. The digested samples were filtered and diluted with deionized water, followed by analysis using a Flame Atomic Absorption Spectrophotometer (FAAS). Standard calibration curves were prepared using certified reference solutions for Pb, Cd, Cr, and Hg to ensure analytical precision and reproducibility. Instrumental parameters were optimized for each element to achieve maximum sensitivity and accuracy.

For data collection and statistical analysis, quantitative data were recorded as mean metal concentrations (mg/kg dry weight) for each tissue and sampling location. Statistical software was used to perform Analysis of Variance (ANOVA) to test for significant differences in metal accumulation between tissue types and across different sites. Additionally, Pearson correlation analysis was applied to examine relationships between environmental factors (e.g., proximity to industrial sources, pH, and water temperature) and metal concentration levels in fish. The results were compared against World Health Organization (WHO) and Food and Agriculture Organization (FAO) permissible limits for heavy metals in edible fish tissue to determine contamination severity and potential human health risks. Descriptive statistics, including mean, standard deviation, and percentage distribution, were used to summarize the dataset.

The dependent variables in this study include the concentration of Pb, Cd, Cr, and Hg in fish tissues, while independent variables represent environmental exposure

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

factors such as site location, industrial influence, and water quality parameters. Strict quality assurance and control protocols were maintained throughout the analytical process, including the use of reagent blanks, duplicate analyses, and standard recovery tests. Ethical and environmental considerations were observed during fish collection to minimize ecological disturbance. The methodological framework ensures high reliability and validity of the results, providing a robust foundation for evaluating the extent of heavy metal contamination and its ecological implications.

DATA ANALYSIS

Table 1

Mean Concentrations of Heavy Metals in Fish Tissues (mg/kg, N = 150)

Metal	Gills (Mean±SD)	Liver (Mean±SD)	Muscle (Mean±SD)	FAO Permissible Limit (mg/kg)
Lead (Pb)	2.68 ± 0.41	3.37 ± 0.56	2.05 ± 0.33	2.0
Cadmium (Cd)	0.81 ± 0.18	1.02 ± 0.22	0.63 ± 0.14	0.5
Chromium (Cr)	1.27 ± 0.25	1.58 ± 0.31	1.06 ± 0.21	1.0
Mercury (Hg)	0.42 ± 0.09	0.57 ± 0.11	0.33 ± 0.08	0.3

Interpretation

The results indicate that all analyzed fish tissues exhibited varying levels of heavy metal accumulation, with concentrations generally exceeding the FAO permissible limits for safe human consumption. The liver consistently showed the highest accumulation across all metals, followed by gills and muscle tissues, reflecting the liver's central role in detoxification and metal sequestration. Lead and cadmium levels were notably elevated in hepatic samples, suggesting chronic exposure from industrial discharge and agricultural runoff. Similarly, mercury concentrations, although lower than other metals, surpassed safe thresholds in several specimens, indicating bioaccumulation through trophic transfer. Chromium levels also exceeded acceptable limits, particularly in fish collected near industrialized regions. The elevated mean values and low standard deviations imply a widespread contamination pattern rather than isolated incidents. These findings underscore the presence of persistent heavy metal pollution within the studied aquatic ecosystems and highlight potential risks to both ecological integrity and public health through dietary exposure.

Table 2

Spatial Variation of Heavy Metal Concentrations in Fish Across Sampling Sites (mg/kg, N = 150)

Sampling Site	Lead (Pb)	Cadmium (Cd)	Chromium (Cr)	Mercury (Hg)	Dominant Pollution Source
Site A Industrial Zone	3.42 ± 0.55	1.08 ± 0.19	1.76 ± 0.33	0.61 ± 0.14	Metal plating, textile effluents
Site B Urban Drainage Area	2.89 ± 0.48	0.93 ± 0.16	1.43 ± 0.29	0.52 ± 0.11	Domestic sewage, vehicular runoff
Site C Agricultural Runoff Zone	2.17 ± 0.39	0.86 ± 0.14	1.22 ± 0.25	0.41 ± 0.10	Pesticide and fertilizer leaching
Site D Semi-urban Transitional Zone	1.78 ± 0.31	0.63 ± 0.11	0.97 ± 0.21	0.34 ± 0.08	Mixed agricultural and domestic inputs
Site E – Reference (Rural Pristine Zone)	0.94 ± 0.22	0.37 ± 0.09	0.58 ± 0.15	0.19 ± 0.05	Minimal anthropogenic influence

Interpretation

The data reveal substantial spatial variation in heavy metal concentrations among the five freshwater sites, closely corresponding to the intensity of anthropogenic activities. Fish samples collected from the industrial and urban drainage zones (Sites A and B) exhibited the highest mean concentrations of all analyzed metals, particularly lead (3.42 mg/kg) and chromium (1.76 mg/kg), which far exceed permissible safety limits. Elevated cadmium and mercury levels at these sites further indicate contamination from untreated effluents and industrial waste discharge. Agricultural runoff zones (Site C) demonstrated moderate contamination, likely resulting from the leaching of fertilizers, pesticides, and irrigation residues containing trace metals. In contrast, fish from semi-urban transitional zones (Site D) showed relatively lower levels, reflecting partial dilution effects from mixed land-use patterns. The pristine reference site (Site E) recorded the lowest metal concentrations, confirming minimal anthropogenic impact and validating the comparative framework of this study. The observed spatial gradients highlight a clear correlation between local pollution sources and bioaccumulation intensity, emphasizing the need for targeted environmental monitoring and improved waste management practices in industrial and urban regions.

Table 3

Comparison of Bioaccumulation and Health Risk Indices Between Contaminated and Reference Sites (N = 150)

Parameter	Contaminated Sites (A–C)	Reference Sites (D–E)	t-value	p-value	Remarks / Observation
Mean Bioaccumulation Factor (BAF)	4.87 ± 0.72	2.14 ± 0.46	9.35	<0.001	Significantly higher accumulation at contaminated sites
Lead (Pb) – Health Risk Index (HRI)	1.62 ± 0.28	0.73 ± 0.15	8.24	<0.001	Potential non-carcinogenic risk from consumption
Cadmium (Cd) – HRI	1.48 ± 0.25	0.58 ± 0.13	7.91	<0.001	Chronic toxicity risk indicated
Chromium (Cr) – HRI	1.33 ± 0.22	0.64 ± 0.11	7.12	<0.001	Carcinogenic potential observed in industrial regions
Mercury (Hg) – HRI	1.12 ± 0.19	0.51 ± 0.09	6.85	<0.001	Elevated exposure risk due to biomagnification
Overall Hazard Index (HI)	5.55 ± 0.83	2.46 ± 0.52	10.17	<0.001	Cumulative exposure exceeds safe limits

Interpretation

The statistical analysis revealed a significant difference in bioaccumulation and health risk indices between contaminated and reference sites, confirming that industrial and agricultural regions pose greater ecological and human health risks. The mean Bioaccumulation Factor (BAF) at contaminated sites (4.87) was more than double that of reference locations (2.14), indicating a high potential for metal retention in aquatic fauna. Health Risk Index (HRI) values for all analyzed metals exceeded the critical threshold of 1.0 at contaminated sites, suggesting potential non-carcinogenic and chronic toxicity hazards through dietary exposure. Lead and cadmium exhibited the highest HRI values, reflecting their persistent release

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

from industrial effluents and agricultural chemicals. The cumulative Hazard Index (HI) also surpassed permissible limits, reinforcing the compounded risk of multi-metal exposure. Conversely, reference sites demonstrated significantly lower indices, validating the influence of anthropogenic activity on contamination intensity. These findings underscore the urgent need for regulatory intervention, continuous environmental monitoring, and the adoption of cleaner industrial practices to mitigate bioaccumulation and safeguard aquatic ecosystem health.

DISCUSSION

The findings of this study demonstrate a clear link between anthropogenic activities and heavy metal accumulation in aquatic fauna [44]. Elevated levels of lead, cadmium, chromium, and mercury were detected in all sampled fish tissues, with the liver showing the highest accumulation followed by gills and muscle [45]. This pattern corresponds with the liver's role in detoxification and storage of xenobiotics, while gills serve as primary sites for metal uptake from water [46]. Muscle tissue, though showing relatively lower concentrations, remains the main concern for human consumption, as its contamination directly reflects dietary exposure risks [47]. Spatial analysis revealed significant variation among the five sampling sites, with fish from industrial and urban regions exhibiting the highest concentrations of all analyzed metals [48]. These findings confirm that untreated industrial effluents, domestic wastewater, and agricultural runoff are major contributors to aquatic pollution [49]. The relatively lower metal levels observed in semi-urban and rural reference sites indicate the dilution effect and limited anthropogenic influence [50]. Chromium and lead levels were particularly high in industrial zones [51], reflecting emissions from electroplating, textile, and metal processing activities, while cadmium contamination was associated with agricultural fertilizers and pesticides [52].

Statistical analysis of the Bioaccumulation Factor (BAF) and Health Risk Index (HRI) showed significant differences ($p < 0.001$) between contaminated and reference sites [53]. BAF values were notably higher in polluted regions, confirming enhanced bioaccumulation potential [54]. HRI values for Pb, Cd, Cr, and Hg exceeded the safe threshold of 1.0 at industrial and agricultural sites, suggesting possible chronic toxicity risks to humans through fish consumption [55]. The cumulative Hazard Index (HI) also surpassed permissible limits, indicating combined metal exposure poses a greater health threat [56]. These findings highlight the urgent need for improved industrial waste management, stricter effluent monitoring, and routine biomonitoring of freshwater fish to safeguard both ecological balance and public health [57]. AAS proved highly effective for quantifying trace metal concentrations with accuracy and reproducibility [58]. The technique's sensitivity allowed detection even at microgram levels, reinforcing its role as a preferred method for environmental monitoring [59]. The observed contamination levels above permissible standards highlight urgent needs for pollution management, stricter effluent regulations, and sustainable water quality monitoring systems [60].

CONCLUSION

This study concludes that aquatic fauna inhabiting industrial and agricultural regions contain significantly elevated concentrations of toxic heavy metals, often surpassing internationally recognized safety limits for human consumption. The application of Atomic Absorption Spectroscopy (AAS) proved highly effective in accurately detecting and quantifying trace metal levels, reaffirming its value as a dependable analytical method in environmental toxicology and water quality assessment. Among the analyzed tissues, the liver exhibited the highest metal concentrations, underscoring its central role in detoxification and storage of pollutants, while gills and muscles also reflected measurable contamination. Spatial variation in metal accumulation patterns clearly indicated that areas exposed to industrial discharge, agricultural runoff, and urban effluents experience greater contamination pressure compared to pristine reference sites. These findings highlight the critical need for routine biomonitoring programs, stricter enforcement of pollution control regulations, and the adoption of cleaner industrial practices to minimize ecological degradation and protect public health from the long-term effects of heavy metal exposure through aquatic food chains.

Future Implications

Future research should prioritize the development of advanced, real-time, field-deployable metal detection technologies to complement conventional laboratory-based Atomic Absorption Spectroscopy (AAS), enabling rapid and continuous monitoring of aquatic environments. Incorporating a broader range of fish species, trophic levels, and seasonal variations would provide a more comprehensive understanding of bioaccumulation dynamics and pollutant transfer within aquatic food webs. Additionally, integrating spatial modeling and biomarker-based toxicity assessments could enhance predictive capabilities for environmental risk evaluation. Policymakers and environmental authorities should utilize these scientific insights to strengthen pollution control legislation, promote sustainable wastewater treatment systems, and implement eco-restoration strategies aimed at rehabilitating contaminated water bodies. Such collaborative, data-driven approaches will be essential for preserving aquatic biodiversity, ensuring food safety, and safeguarding public health against the growing threat of heavy metal contamination.

REFERENCES

1. Kassim, N. A., Ghazali, S. A. I. S. M., Bohari, F. L., & Abidin, N. A. Z. (2022). Assessment of heavy metals in wastewater plant effluent and lake water by using atomic absorption spectrophotometry. *Materials Today: Proceedings*, *66*, 3961-3964. https://doi.org/10.1016/j.matpr.2022.04.671
2. Conti, M. E., Tudino, M. B., Muse, J. O., & Cecchetti, G. (2002). Biomonitoring of heavy metals and their species in the marine environment: the contribution of atomic absorption spectroscopy and inductively coupled plasma spectroscopy. *Research Trends in Applied Spectroscopy*, *4*, 295-324.

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

3. Dalman, Ö., Demirak, A., & Balcı, A. (2006). Determination of heavy metals (Cd, Pb) and trace elements (Cu, Zn) in sediments and fish of the Southeastern Aegean Sea (Turkey) by atomic absorption spectrometry. *Food chemistry*, *95*(1), 157-162. https://doi.org/10.1016/j.foodchem.2005.02.009
4. Abrham, F., & Gholap, A. V. (2021). Analysis of heavy metal concentration in some vegetables using atomic absorption spectroscopy. *Pollution*, *7*(1), 205-216.
5. Aquisman, A. E., Assim, Z. B., Wahi, R. B., Kwabena, D. E., & Festus, W. (2019). Validation of the atomic absorption spectroscopy (AAS) for heavy metal analysis and geochemical exploration of sediment samples from the Sebangan River. *Adv Anal Chem*, *9*, 23-33.
6. Radulescu, C., Dulama, I. D., Stihi, C., Ionita, I., Chilian, A., Necula, C., & Chelarescu, E. D. (2014). Determination of heavy metal levels in water and therapeutic mud by atomic absorption spectrometry. *Romanian Journal of Physics*, *59*(9-10), 1057-1066.
7. Tsade, H. K. (2016). Atomic absorption spectroscopic determination of heavy metal concentrations in Kulufo River, Arbaminch, Gamo Gofa, Ethiopia. *J Environ Anal Chem*, *3*(177), 2. https://doi.org/10.4172/2380-2391.1000177
8. Assubaie, F. N. (2015). Assessment of the levels of some heavy metals in water in Alahsa Oasis farms, Saudi Arabia, with analysis by atomic absorption spectrophotometry. *Arabian Journal of Chemistry*, *8*(2), 240-245. https://doi.org/10.1016/j.arabjc.2011.08.018
9. Tokalioğlu, Ş., Kartal, Ş., & Elci, L. (2000). Determination of heavy metals and their speciation in lake sediments by flame atomic absorption spectrometry after a four-stage sequential extraction procedure. *Analytica Chimica Acta*, *413*(1-2), 33-40. https://doi.org/10.1016/s0003-2670(00)00726-1
10. Alkarkhi, F. A., Ismail, N., & Easa, A. M. (2008). Assessment of arsenic and heavy metal contents in cockles (Anadara granosa) using multivariate statistical techniques. *Journal of hazardous materials*, *150*(3), 783-789. https://doi.org/10.1016/j.jhazmat.2007.05.035
11. Akram, S., Najam, R., Rizwani, G. H., & Abbas, S. A. (2015). Determination of heavy metal contents by atomic absorption spectroscopy (AAS) in some medicinal plants from Pakistani and Malaysian origin. *Pakistan journal of pharmaceutical sciences*, *28*(5).
12. Opaluwa, O. D., Aremu, M. O., Logbo, L. O., Imagaji, J., & EOdiba, I. (2012). Assessment of heavy metals in water, fish and sediments from UKE stream, Nasarawa State, Nigeria. *Current World Environment*, *7*(2), 213. https://doi.org/10.12944/cwe.7.2.04
13. Milivojević, J., Krstić, D., Šmit, B., & Djekić, V. (2016). Assessment of heavy metal contamination and calculation of its pollution index for Uglješnica River, Serbia. *Bulletin of environmental contamination and toxicology*, *97*(5), 737-742. https://doi.org/10.1007/s00128-016-1918-0
14. Rajendiran, D., Harikrishnan, N., & Veeramuthu, K. (2025). Heavy metal concentrations and pollution indicators in the Ennore ecosystem, east coast of Tamilnadu, India using atomic absorption spectrometry study with statistical approach. *Scientific Reports*, *15*(1), 9161. https://doi.org/10.1038/s41598-025-93484-6
15. Tao, Y., Yuan, Z., Xiaona, H., & Wei, M. (2012). Distribution and bioaccumulation of heavy metals in aquatic organisms of different trophic levels and potential health risk assessment from Taihu lake, China. *Ecotoxicology and environmental safety*, *81*, 55-64. https://doi.org/10.1016/j.ecoenv.2012.04.014
16. Alina, M., Azrina, A., Mohd Yunus, A. S., Mohd Zakiuddin, S., Mohd Izuan Effendi, H., & Muhammad Rizal, R. (2012). Heavy metals (mercury, arsenic, cadmium, plumbum) in selected marine fish and shellfish along the Straits of Malacca. *International Food Research Journal*, *19*(1).
17. Mutiah, M., Siahaan, J., Loka, I. N., & Irawan, J. (2022). The efficiency of heavy metal analysis method in marine fish samples by atomic absorption spectrophotometry. *Jurnal Penelitian Pendidikan IPA*, *8*(2), 963-968. https://doi.org/10.29303/jppipa.v8i2.1489
18. Tüzen, M. (2003). Determination of heavy metals in soil, mushroom and plant samples by atomic absorption spectrometry. *Microchemical journal*, *74*(3), 289-297.
19. Altındağ, A., & Yiğit, S. (2005). Assessment of heavy metal concentrations in the food web of lake Beyşehir, Turkey. *Chemosphere*, *60*(4), 552-556. https://doi.org/10.1016/j.chemosphere.2005.01.009
20. Ihenetu, S. C., Njoku, V. O., Ibe, F. C., Li, G., Chinweuba, A., & Enyoh, C. C. E. (2022). Determination of pollutions in the surface of water samples from Ogbajarajara river, Nigeria by spectrophotometer and atomic absorption spectrometry before evaluation of health risk assessment. *Analytical Methods in Environmental Chemistry Journal*, *5*(1), 5-21. https://doi.org/10.24200/amecj.v5.i01.162
21. Rai, S. K., Xalxo, R., Patle, T. K., Verma, A., Chauhan, R., & Mahish, P. K. (2023). Analyzing contamination of heavy metals-AAS and fluorescence spectroscopy. In *Heavy metals in the environment: management strategies for global pollution* (pp. 167-204). American Chemical Society. https://doi.org/10.1021/bk-2023-1456.ch010
22. Choudhury, T. R., Acter, T., Alam, M. A., Sowrav, S. F. F., Rahman, M. S., Chowdhury, A. S., & Quraishi, S. B. (2024). Appraisal of heavy metal contamination and their source apportionment identification in five river water systems of the coastal areas in Bangladesh. *Regional Studies in Marine Science*, *70*, 103378. https://doi.org/10.1016/j.rsma.2024.103378
23. Tüzen, M. (2003). Determination of heavy metals in fish samples of the middle Black Sea (Turkey) by graphite furnace atomic absorption spectrometry. *Food chemistry*, *80*(1), 119-123. https://doi.org/10.1016/s0308-8146(02)00264-9
24. Lokeshwari, H., & Chandrappa, G. T. (2006). Impact of heavy metal contamination of Bellandur Lake on soil and cultivated vegetation. *Current science*, 622-627. https://doi.org/10.1111/j.1440-1770.2007.00337.x
25. Baki, M. A., Hossain, M. M., Akter, J., Quraishi, S. B., Shojib, M. F. H., Ullah, A. A., & Khan, M. F. (2018). Concentration of heavy metals in seafood (fishes, shrimp, lobster and crabs) and human health assessment in Saint Martin Island, Bangladesh. *Ecotoxicology and environmental safety*, *159*, 153-163. https://doi.org/10.1016/j.ecoenv.2018.04.035
26. Cobbinah, R. T., Boadi, N. O., Saah, S. A., Agorku, E. S., Badu, M., & Kortei, N. K. (2025). Cancer risk from heavy metal contamination in fish and implications for public health. *Scientific Reports*, *15*(1), 24162. https://doi.org/10.1038/s41598-025-08488-z
27. Abui, Y. M., Ezra, V., Bonet, R. A., & Amos, B. (2017). Assessment of heavy metals level of River Kaduna at Kaduna metropolis, Nigeria. *Journal of Applied Sciences and Environmental Management*, *21*(2), 347-352. https://doi.org/10.4314/jasem.v21i2.16
28. Jin, Y., Fu, B., & Wang, X. (2024). Quantifying heavy metal and radionuclide contamination in fish and water proximal to a uranium tailings facility: A Linshui River basin investigation, China. *Journal of Trace Elements in Medicine and Biology*, *85*, 127485. https://doi.org/10.1016/j.jtemb.2024.127485

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

29. Mastan, O. A., Coroian, A., Longodor, A. L., Mariş, Ş., & Mesaros, D. M. (2023, June). Assessment of Heavy Metal Contamination of Certain Types of Fish Meat. In *2023 17th International Conference on Engineering of Modern Electric Systems (EMES)* (pp. 1-4). IEEE. https://doi.org/10.1109/emes58375.2023.10171758
30. Addey, C. I., Ayoola, N. O., Omobolaji, A. A., & Tolulope, O. E. (2018). Heavy metals pollution index of surface water from Commodore channel, Lagos, Nigeria. *African Journal of Environmental Science and Technology*, *12*(6), 191-197.
31. Gopal, V., Krishnamurthy, R. R., Vignesh, R., Nathan, C. S., Anshu, R., Kalaivanan, R., ... & Abioui, M. (2023). Assessment of heavy metal contamination in the surface sediments of the Vedaranyam coast, Southern India. *Regional Studies in Marine Science*, *65*, 103081. https://doi.org/10.1016/j.rsma.2023.103081
32. Momodu, M. A., & Anyakora, C. A. (2010). Heavy metal contamination of ground water: The Surulere case study. *Res J Environ Earth Sci*, *2*(1), 39-43.
33. Bagheri, H., Afkhami, A., Saber-Tehrani, M., & Khoshsafar, H. (2012). Preparation and characterization of magnetic nanocomposite of Schiff base/silica/magnetite as a preconcentration phase for the trace determination of heavy metal ions in water, food and biological samples using atomic absorption spectrometry. *Talanta*, *97*, 87-95. https://doi.org/10.1016/j.talanta.2012.03.066
34. Zhong, W. S., Ren, T., & Zhao, L. J. (2016). Determination of Pb (Lead), Cd (Cadmium), Cr (Chromium), Cu (Copper), and Ni (Nickel) in Chinese tea with high-resolution continuum source graphite furnace atomic absorption spectrometry. *Journal of food and drug analysis*, *24*(1), 46-55. https://doi.org/10.1016/j.jfda.2015.04.010
35. Adji, B. K., Octodhiyanto, I., Rahmayanti, R., & Nugroho, A. P. (2022). Microplastic pollution in Rawa Jombor Reservoir, Klaten, Central Java, Indonesia: Accumulation in aquatic fauna, heavy metal interactions, and health risk assessment. *Water, Air, & Soil Pollution*, *233*(4), 112. https://doi.org/10.1007/s11270-022-05572-2
36. Onojake, M. C., & Frank, O. (2013). Assessment of heavy metals in a soil contaminated by oil spill: a case study in Nigeria. *Chemistry and Ecology*, *29*(3), 246-254.
37. Alinnor, I. J., & Obiji, I. A. (2010). Assessment of trace metal composition in fish samples from Nworie River. *Pakistan Journal of Nutrition*, *9*(1), 81-85. https://doi.org/10.3923/pjn.2010.81.85
38. Hossain, M. N., Rahaman, A., Hasan, M. J., Uddin, M. M., Khatun, N., & Shamsuddin, S. M. (2021). Comparative seasonal assessment of pollution and health risks associated with heavy metals in
39. Etemi, F. Z. (2018). Status assessment of heavy metals in water of the Lepenci River Basin, Kosova. *Journal of ecological engineering*. https://doi.org/10.12911/22998993/91273
40. Rahman, S. H., Khanam, D., Adyel, T. M., Islam, M. S., Ahsan, M. A., & Akbor, M. A. (2012). Assessment of heavy metal contamination of agricultural soil around Dhaka Export Processing Zone (DEPZ), Bangladesh: implication of seasonal variation and indices. *Applied sciences*, *2*(3), 584-601. https://doi.org/10.3390/app2030584
41. Muhammad, S., Shah, M. T., & Khan, S. (2011). Health risk assessment of heavy metals and their source apportionment in drinking water of Kohistan region, northern Pakistan. *Microchemical journal*, *98*(2), 334-343.
42. Marcovecchio, J. E., & Botté, S. E. (2007). Heavy metals, major metals, trace elements. In *Handbook of water analysis* (pp. 289-326). CRC Press. https://doi.org/10.1201/9781420006315-15
43. Ighariemu, V., Wegwu, M. O., & Chuku, L. C. (2023). Evaluation of heavy metals and health risk assessment of shellfish contaminated in Santa Barbara River, Niger Delta, Nigeria. *Current Research in Interdisciplinary Studies*, *2*(1), 1-20.
44. Dey, M., Akter, A., Islam, S., Dey, S. C., Choudhury, T. R., Fatema, K. J., & Begum, B. A. (2021). Assessment of contamination level, pollution risk and source apportionment of heavy metals in the Halda River water, Bangladesh. *Heliyon*, *7*(12). https://doi.org/10.1016/j.heliyon.2021.e08625
45. Ekpo, F. E., & Ukpong, E. J. (2014). Assessment of Heavy Metals Concentrations in water, Sediments and some common sea foods Callinectes amnicola and Tympanotonus fuscatus (crabs and periwinkles) from Uta Ewa Creek of Ikot Abasi, Akwa Ibom State, Nigeria. *Global Journal of Applied Environmental Sciences*, *4*(1), 99-106.
46. Varol, M. (2011). Assessment of heavy metal contamination in sediments of the Tigris River (Turkey) using pollution indices and multivariate statistical techniques. *Journal of hazardous materials*, *195*, 355-364. https://doi.org/10.1016/j.jhazmat.2011.08.051
47. Dural, M., Göksu, M. Z. L., & Özak, A. A. (2007). Investigation of heavy metal levels in economically important fish species captured from the Tuzla lagoon. *Food chemistry*, *102*(1), 415-421.
48. Ihedioha, J. N., Ukoha, P. O., & Ekere, N. R. (2017). Ecological and human health risk assessment of heavy metal contamination in soil of a municipal solid waste dump in Uyo, Nigeria. *Environmental geochemistry and health*, *39*(3), 497-515. https://doi.org/10.1007/s10653-016-9830-4
49. Akcay, H., Oguz, A., & Karapire, C. (2003). Study of heavy metal pollution and speciation in Buyak Menderes and Gediz river sediments. *Water research*, *37*(4), 813-822.
50. Harika, T. L., Al-Ghanim, K. A., Riaz, M. N., Krishnappa, K., Pandiyan, J., & Govindarajan, M. (2023). Fishing cat scats as a biomonitoring tool for toxic heavy metal contamination in aquatic ecosystems. *Toxics*, *11*(2), 173. https://doi.org/10.3390/toxics11020173
51. Fernandez-Maestre, R., Johnson-Restrepo, B., & Olivero-Verbel, J. (2018). Heavy metals in sediments and fish in the Caribbean coast of Colombia: assessing the environmental risk. *International journal of environmental research*, *12*(3), 289-301. https://doi.org/10.1007/s41742-018-0091-1
52. Muiruri, J. M., Nyambaka, H. N., & Nawiri, M. P. (2013). Heavy metals in water and tilapia fish from Athi-Galana-Sabaki tributaries, Kenya. *International Food Research Journal*, *20*(2).
53. Ogoyi, D. O., Mwita, C. J., Nguu, E. K., & Shiundu, P. M. (2011). Determination of heavy metal content in water, sediment and microalgae from Lake Victoria, East Africa. https://doi.org/10.2174/1874829501104010156
54. Diarra, I., & Prasad, S. (2021). The current state of heavy metal pollution in Pacific Island Countries: a review. *Applied Spectroscopy Reviews*, *56*(1), 27-51. https://doi.org/10.1080/05704928.2020.1719130
55. Velusamy, A., Kumar, P. S., Ram, A., & Chinnadurai, S. (2014). Bioaccumulation of heavy metals in commercially important marine fishes from Mumbai Harbor, India. *Marine pollution bulletin*, *81*(1), 218-224. https://doi.org/10.1016/j.marpolbul.2014.01.049
56. Lawal-Are, A. O., Adekugbe, A. L., & Odusoga, A. W. (2018). Assessment of heavy metal content in imported and local fish and crustacean species obtained within Lagos Metropolis. *Animal Research International*, *15*(2).
57. Olsen, S., Pessenda, L. C., Růžička, J., & Hansen, E. H. (1983). Combination of flow injection analysis with flame atomic-

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.

absorption spectrophotometry: determination of trace amounts of heavy metals in polluted seawater. *Analyst*, *108*(1289), 905-917. https://doi.org/10.1039/an9830800905

58. Niloy, H. K., Chowdhury, A. I., Islam, M. S., Pervez, A., Asseri, A. H., Alsohibany, K. S., ... & Uddin, M. S. (2024). Bioaccumulation of heavy metals in water and mollusks in the Karnafully estuary: Potential human health risk and environmental contamination. *Regional Studies in Marine Science*, *78*, 103752. https://doi.org/10.1016/j.rsma.2024.103752
59. Gupta, V., Kumar, D., Dwivedi, A., Vishwakarma, U., Malik, D. S., Paroha, S., ... & Gupta, N. (2023). Heavy metal contamination in river water, sediment, groundwater and human blood, from Kanpur, Uttar Pradesh, India. *Environmental Geochemistry and Health*, *45*(5), 1807-1818. https://doi.org/10.1007/s10653-022-01290-0
60. Nazir, R., Khan, M., Masab, M., Rehman, H. U., Rauf, N. U., Shahab, S., ... & Shaheen, Z. (2015). Accumulation of heavy metals (Ni, Cu, Cd, Cr, Pb, Zn, Fe) in the soil, water and plants and analysis of physico-chemical parameters of soil and water collected from Tanda Dam Kohat. *Journal of pharmaceutical sciences and research*, *7*(3), 89.

Copyright © 2025. IJBR Published by Indus Publishers
This work is licensed under a Creative Commons Attribution 4.0 International License.