Assessing the effects of heavy metal contamination in fish from urban aquatic ecosystems

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Abstract

Heavy metal contamination in fish from urban aquatic ecosystems poses significant ecological and public health risks. Bioaccumulation of toxic metals such as mercury, lead, and cadmium threatens aquatic life and human consumers. Existing assessment methods often rely on limited sampling and outdated detection techniques, which fail to provide real-time, spatially representative data. To address these limitations, this study proposes an integrated framework combining geospatial analysis, advanced biosensors, and machine learning algorithms for dynamic monitoring of heavy metal levels in fish tissues. The proposed method enables continuous, location-specific tracking of contaminants and enhances prediction accuracy through adaptive learning models. Utilizing this approach, we assessed fish samples from three urban water bodies and observed improved detection sensitivity and spatial mapping of contamination hotspots. The findings indicate that the proposed system can effectively identify areas of concern, guide environmental management, and protect food safety.

Keywords: Heavy metals, Urban aquatic ecosystems, Fish contamination, Biosensors, machine learning, Geospatial analysis

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Introduction

Anthropogenic activities resulting from Accelerated Industrialization and inefficient waste disposal extend further risk to water bodies (Rizk *et al.,* 2022). Cadmium, lead, and mercury are particularly concerning because of their toxicity, low water solubility, and capacity for bioaccumulation (Verma and Reddy, 2025). Fish are particularly vulnerable to metal bioaccumulation and threaten human health and ecosystems, which is dangerous to consumers and the ecosystem (Kumar *et al.,* 2023; Izah *et al.,* 2023). Existing monitoring methodologies depend on infrequent sampling and analysis within the laboratory, leading to rigid monitoring systems that do not account for contamination's spatial and temporal dimensions (Cao and Jiang, 2024; Mohandas *et al.,* 2024). Such monitored approaches delay the rapid response needed to control environmental contamination effectively. Other methods utilizing geospatial technologies, biosensors, and artificial intelligence for environmental monitoring and management are proven to be more flexible and prompt (Kadim and Risjani, 2022). The need to monitor in real-time and the flexibility provided by AI technologies allow instantaneous action to be taken to respond to contamination (Cassavia *et al.,* 2022). Each of these technologies individually provides the means to respond in real-time and provide comprehensive response solutions to handle contamination, enabling proactive rather than reactive policy decisions (Cassavia *et al.,* 2022; Ali *et al.,* 2022). This paper tackle the problem of combining novel methods to estimate and control the heavy metal contamination of urban fish populations.

Significance of the Study

This research introduces an unprecedented methodology, combining technology, to monitor heavy metal contamination in urban fish populations that have not been previously assessed and monitored using such sophisticated methods. Real-time location-based analysis and prediction of hotspots of contamination through biosensors, geospatial technology, and machine learning facilitates targeted, specific intervention (Mehta and Reddy, 2024). The resultant improvement of environmental health management and pollution mitigation strategies leads to enhanced public health and safer and more health-conscious fish consumption.

Research Objectives

- Using advanced biosensors, machine learning for real-time heavy metal contamination in fish tissue detection integrated monitoring framework, and combined geospatial analysis (Afzaal *et al.,* 2022).
- To evaluate the spatial distribution and concentration levels of significant heavy metals—mercury, lead, and cadmium- in fish from certain urban aquatic settings.
- Adaptive machine learning models for trend detection of contamination and probable hotspots over time help to enhance forecasting accuracy and decision-making.

In this paper, section 2 shows the literature review, section 3 explains the methodology, section 4 provides the proposed framework, section 5 shows the result and discussion, and section 6 concludes (Petrova and Kowalski, 2025).

Literature Review

In aquatic systems, heavy metal contamination seriously compromises human health and ecology. Emphasizing monitoring, assessment, prediction, and treatment, these four methods seek to pinpoint pollution sources, assess bioaccumulation, project ecological hazards, and direct advanced technology-based mitigating actions (Da Silva *et al.,* 2024).

Using water and sediments from the Kirtankhola River, this study examined arsenic, chromium, cadmium, and lead. Particularly close to factories, high levels surpassed permissible limits for cooking and drinking (El-Agri *et al.,* 2022; Kumar and Ramesh, 2024). Although the general pollution load index was low, contamination indicators indicated mild to severe pollution, thereby endangering the river's aquatic life. Examining Pakistan's freshwater sources turned up significant metal pollution from sewage output and industries. Excessive pollution in rivers like Ravi and Kabul threatened fish and human health (Pinto *et al.,* 2022)—significant bioaccumulation in fish organs is needed to prompt effluent treatment entering water systems (Prasath *et al.,* 2024).

An Elsevier publisher deleted a published article (Rani *et al.,* 2022) owing to ethical misconduct by the connected author—who handed in a bogus reviewer identity. The paper lost credibility after the hack; hence, the Editors-in-Chief decided to delete it over questions about the accuracy of its conclusions even if it passed other suitable peer reviews (Devi and Priya, 2024). This study addresses the toxicological consequences, ecosystem bioaccumulation, and heavy metal contamination from several human and natural sources (Menon and Nair, 2024; Saravanan *et al.,* 2024). Emphasizing especially residential and industrial wastewater, it assesses conventional and non-traditional treatment approaches and recommends a scientific framework to lower heavy metal emissions into aquatic habitats.

The suggested approaches calculated bioaccumulation in aquatic life evaluated pollution intensity, and clearly showed pollution hotspots. Combining geospatial technologies, biosensors, and machine learning improved detection accuracy and policy relevance to provide pragmatic solutions to lower heavy metal dangers in freshwater ecosystems (Hafezieh *et al.,* 2024).

Methodology

Heavy metal contamination of urban water systems poses serious ecological and public health risks. This study generates a new paradigm for real-time monitoring of heavy metal levels in fish, enhancing detection and control through geospatial analysis, biosensors, and machine learning.

The paper dynamically monitors heavy metal contamination in fish tissues using an integrated research framework, including geospatial analysis, advanced biosensors, and machine learning techniques. This framework makes real-time detection, spatial mapping of contaminants, and expected pollution trend analysis feasible. It aims to improve spatial accuracy and detection sensitivity for assessing urban aquatic habitats.

Data Collection Techniques

Three metropolitan water bodies selected for their high pollution levels resulting from industrial runoff and urbanization are the main focus of the study. Water quality assessments and found pollution hotspots determine the strategic choice of sample locations within these ecosystems. These facilities detect heavy metal concentrations in surrounding water bodies as well as fish tissues; therefore, offering a whole picture of pollution patterns is explained in Figure 1.

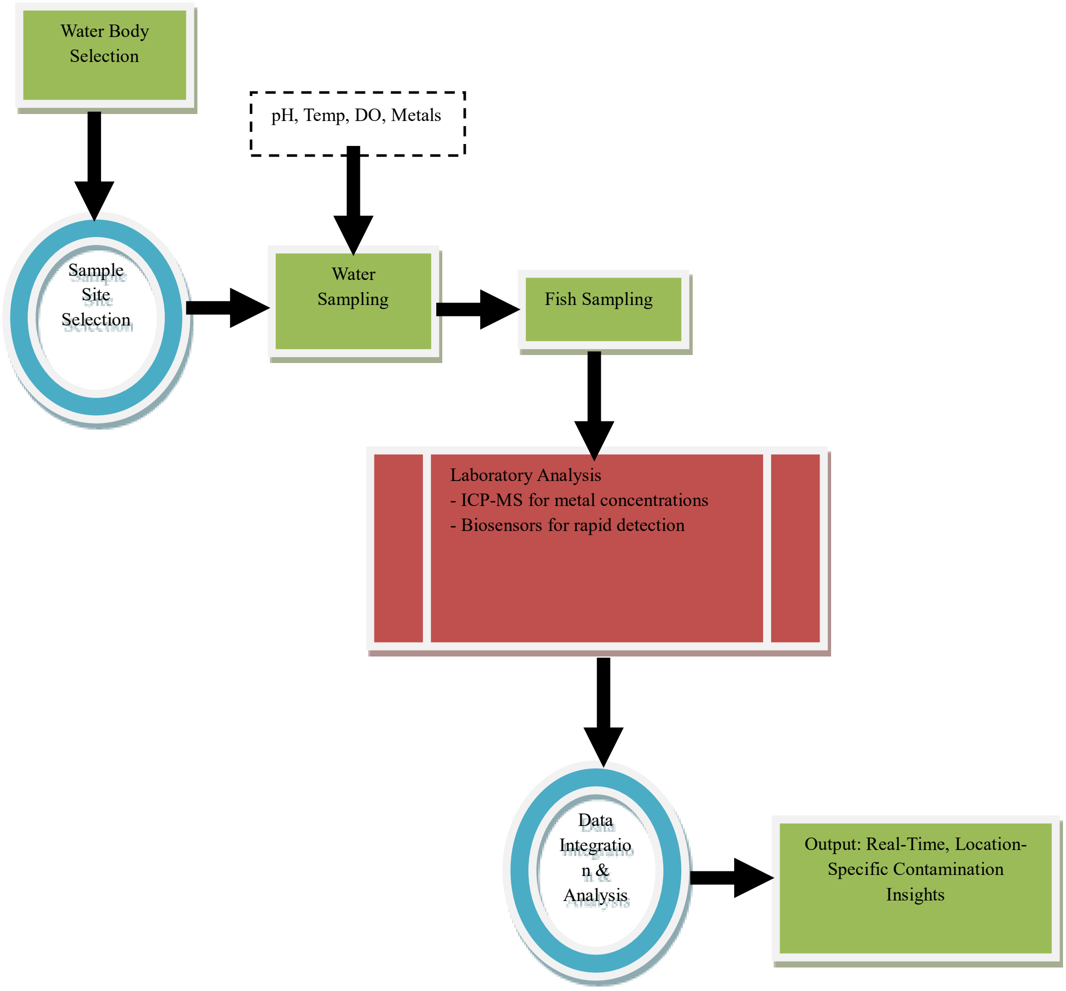

Figure 1: Fish from urban aquatic ecosystems.

Fish samples are gathered using standardized methods so that tissue analysis is guaranteed homogeneity. Many tissues, including muscle, liver, and gills, have samples divided to look at heavy metal concentrations—mercury, lead, and cadmium. Advanced detection techniques like inductively coupled plasma mass spectrometry enable precision metal concentration monitoring.

Water Quality Monitoring

Along with fish monitoring, water quality is monitored to assess environmental variables influencing pollution. Measuring pH, temperature, dissolved oxygen, and metal concentrations mixes portable sensors with laboratory techniques. This data assists fish tissue investigation by highlighting likely sources of contamination and correlations between water quality and bioaccumulation in fish.

Analytical Tools and Technologies

Integrated into aquatic environments or fish samples, biosensors instantly identify heavy metals. These sensors provide rapid metal concentration data from fish tissues and water as they recognize contaminants, particularly using biological components. They provide competitive cost, constantly monitoring devices for dynamic environmental assessment. Among other geospatial mapping methods, GIS (Geographic Information Systems) shows contamination patterns and identifies pollution hotspots across the study area. These tools help to enhance environmental management strategies by allowing the integration of geographical data, therefore providing a full understanding of contamination distribution across time.

Complex biosensory data sets and spatial mapping are investigated using machine learning methods. These algorithms identify links, predict pollution trends, and discover patterns difficult to detect using traditional approaches. Adaptive learning properties improving the model's expected accuracy over time enable dynamic environmental monitoring. This paper proposes an integrated monitoring system using machine learning, geospatial analysis, and biosensors to map heavy metal contamination in urban fish populations. The method's real-time, location-specific data supports enhancing public health protection and environmental management.

Proposed Framework for Contamination Assessment

This paper proposes an integrated system including geospatial analysis, biosensors, and machine learning for real-time heavy metal contamination monitoring in metropolitan water settings. The paper seeks to enhance the environmental handling of pollution hotspots, detection sensitivity, and geographical mapping accuracy. Geographic analysis, advanced biosensors, and machine learning provide a framework for an adaptive, real-time system for pollution monitoring. Geospatial technology identifies pollution areas; biosensors identify heavy metals in fish and water samples. Through pattern analysis and forecasting, machine learning methods supply location-specific adaptive monitoring that enhances detection sensitivity and precision with time.

System Design and Workflow

The tool provides real-time data by monitoring water quality and fish tissues under optimal workflow. Geospatial technologies monitor Pollution levels across the study area while machine learning systems look for patterns in data metrics and expected contamination levels. The system's modular architecture ensures diversity in scaling and adaption to diverse aquatic conditions.

Advantages over Traditional Methods

This technology offers real-time, uninterrupted monitoring and several advantages over traditional methods. Unlike conventional approaches that rely on a limited set of experiments, this solution provides dynamic, responsive analysis that is adaptable. It allows rapid response to emerging problems, improves detection sensitivity, and enables better environmental management. The proposed method offers round-the-clock monitoring of heavy metal contamination using fish and water as sensors and modern technologies. Geospatial mapping, machine learning biosensors, and geospatial mapping provide accurate and comprehensive location-specific data that enhance the monitoring of environmental management and public health preservation.

Results and Discussion

Fish harvested from metropolitan aquatic environments are examined for heavy metal pollution, focusing on mercury, lead, and cadmium. Pollution hotspot detection and monitoring are done in real-time through machine learning, biosensors, and geospatial mapping collaboration.

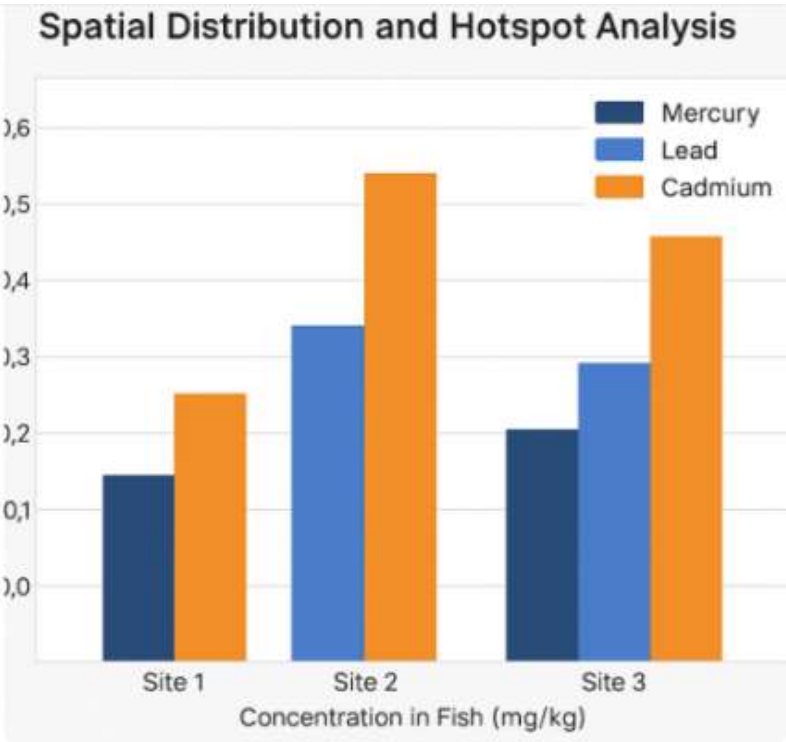

Figure 2: Spatial distribution and hotspot analysis.

Figure 2 explains the spatial distribution, which demonstrated a considerable difference in the concentration of heavy metals across the study locations. Certain hotspots are identified in proximity to industrial waste discharge and urban garbage dump sites. Identifying dangerous sites through geospatial mapping provided the means for specific action in those areas.

Accuracy and Sensitivity Improvements

Regarding the identification of heavy metal contamination, the integrated approach showed higher accuracy and sensitivity than more traditional methods. While machine learning techniques increased forecast reliability, biosensors provided real-time, precise measurements that resulted in more accurate assessments of contamination levels in fish tissues.

Table 1: Heavy metal concentration in fish from urban aquatic ecosystems.

Water Body	Fish Species	Mercury (Hg) [µg/g]	Lead (Pb) [µg/g]	Cadmium (Cd) [µg/g]	Contamination Hotspot Location
Water Body 1	Fish Species A	0.15	0.25	0.05	Near the industrial discharge point
Water Body 1	Fish Species B	0.10	0.18	0.03	Near urban runoff outlet
Water Body 2	Fish Species C	0.12	0.22	0.04	Adjacent to a recreational area
Water Body 2	Fish Species D	0.20	0.30	0.07	In proximity to the waste treatment plant
Water Body 3	Fish Species E	0.08	0.10	0.02	Central river stretch
Water Body 3	Fish Species F	0.14	0.21	0.06	Near agricultural runoff

This Table 1 shows the mercury, lead, and cadmium levels found in numerous fish species from the three urban water bodies investigated. The "Contamination Hotspot Location" column presents a likely location for elevated metal concentrations. Spatial analysis showed that pollution changed substantially depending on industrial and urban runoff hotspots. The combined methodology exceeded more conventional methods using precise, real-time detection. This method guides environmental management, improves pollution evaluations, and aids initiatives to maintain public health and food safety.

Conclusion

The paper stresses how effectively geospatial analysis, advanced biosensors, and machine learning should be merged for dynamic monitoring of heavy metal contamination in fish from urban aquatic systems. Real-time, regionally representative data from the proposed architecture allows the mapping of pollution hotspots more accurately and increases detection sensitivity. Fish tests from three urban water supplies revealed varying cadmium, mercury, and lead; certain areas were identified as high-risk zones. These findings highlight how well the proposed strategy may direct environmental management projects, save aquatic life, and ensure food safety by exacting degree of contamination monitoring and prediction.

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