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Assessment of heavy metal contamination in the River Yamuna: A comprehensive field and laboratory analysis

[1]Vaishnav Dinesh Sohandas and [2]Dr. Ravinder Pal Singh

[1]Research Scholar, Department of Zoology, Kalinga University, Naya Raipur, Chhattisgarh, India
[2]Professor, Department of Zoology, Kalinga University, Naya Raipur, Chhattisgarh, India

Corresponding Author: Vaishnav Dinesh Sohandas

Abstract

This study provides a comprehensive assessment of heavy metal contamination in the River Yamuna, focusing on five key metals: lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr). The investigation involved collecting water and fish samples from three segments of the river: upstream, midstream, and downstream. Advanced analytical techniques, including atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), were employed to determine the concentrations of these heavy metals. The results indicate significant levels of contamination, particularly downstream, with concentrations often exceeding the regulatory limits set by the World Health Organisation (WHO), the United States Environmental Protection Agency (USEPA), and the European Union (EU). Bioaccumulation of heavy metals in fish tissues, especially in the liver, poses serious health risks to humans consuming these fish. The study highlights the urgent need for enhanced regulatory enforcement, improved wastewater treatment, and public awareness initiatives to mitigate the adverse impacts of heavy metal pollution in the Yamuna. The findings provide critical insights for policymakers and environmental agencies to develop effective pollution control measures and improve water quality in the river.

Keywords: Heavy metals, River Yamuna, bioaccumulation, aquatic pollution, environmental toxicology, water quality, fish contamination

Introduction

Rivers play a crucial role in the hydrological cycle and are vital for sustaining various forms of life. They provide water for drinking, irrigation, industry, and recreation and support diverse ecosystems (Gleick, 2000) [15]. The quality of river water is critical because it directly impacts human health, agricultural productivity, and the ecological balance (Vörösmarty *et al*., 2010) [34]. Poor water quality can lead to the bioaccumulation of harmful substances in the food chain, adversely affecting aquatic organisms and humans who consume these organisms (Rai, 2008) [24]. Monitoring and maintaining water quality in rivers is thus essential for environmental sustainability and public health (Gleick, 2000) [15]. Additionally, contaminated river water can also result in economic losses for industries that rely on clean water sources for production. Therefore, implementing effective water quality management practices is crucial for ensuring the long-term viability of both ecosystems and human communities.

Overview of the River Yamuna's Significance and Pollution Issues

The River Yamuna is one of the most significant rivers in India, originating from the Yamunotri Glacier in the Himalayas and flowing through several states, including Haryana, Delhi, and Uttar Pradesh, before merging with the Ganges at Allahabad. The Yamuna is considered sacred and holds immense cultural and religious significance. It supports millions of people by providing water for drinking, agriculture, and industry (CPCB, 2006) [10]. However, over the past few decades, the river has become severely polluted due to rapid urbanisation, industrialization, and population growth. This pollution has led to a decline in water quality, affecting both human health and the ecosystem. Efforts are being made to clean up the river and restore its health, but it remains a significant challenge due to the scale of pollution and the complex factors contributing to it.

Delhi, being a major metropolitan area, significantly contributes to the river's pollution. Untreated sewage, industrial effluents, agricultural runoff, and solid waste are the primary sources of pollution in the Yamuna (Sharma *et al*., 2013) [27]. Studies have shown that the water quality of the Yamuna is severely degraded, especially in the stretch passing through Delhi, where the river becomes a receptacle for various pollutants, including heavy metals (CPCB, 2006) [10]. Heavy metals such as lead, cadmium, mercury, arsenic, and chromium are particularly concerning due to their toxicity, persistence in the environment, and ability to bioaccumulate in aquatic organisms (Nagajyoti *et al*., 2010) [25]. These heavy metals can have detrimental effects on human health if consumed through contaminated water or food sources, leading to long-term health issues. Efforts to mitigate the pollution in the Yamuna River must focus on reducing the discharge of these harmful substances to improve water quality and protect both human and environmental health.

Objectives of the Study

The primary objective of this study is to assess the levels of heavy metal contamination in the River Yamuna and understand the bioaccumulation of these metals in fish tissues. The study aims to provide a comprehensive analysis of the water quality, identify the sources of heavy metal pollution, and evaluate the potential health risks associated with consuming contaminated fish. By comparing the findings with established regulatory standards, the study seeks to highlight the severity of pollution and recommend measures for improving water quality and mitigating health risks.

Research Questions

1. What are the concentrations of heavy metals (lead, cadmium, mercury, arsenic, and chromium) in the water of the River Yamuna?
2. How do these concentrations vary across different segments of the river (upstream, midstream, and downstream)?
3. What are the levels of heavy metals in the tissues of fish from the Yamuna, and how do they compare with regulatory standards?
4. What are the potential sources of heavy metal pollution in the River Yamuna?
5. What are the health risks associated with consuming fish contaminated with heavy metals from the Yamuna?

Scope of the Study

This study focuses on the assessment of heavy metal contamination in the River Yamuna, particularly in the stretch passing through Delhi. It involves the collection and analysis of water and fish samples from different segments of the river. The study employs advanced analytical techniques such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) to determine the concentrations of heavy metals. The scope also includes a risk assessment based on the Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ) methods to evaluate the potential health risks for consumers of contaminated fish. The findings of this study are intended to provide valuable insights for policymakers, environmental agencies, and the public to implement effective pollution control measures and improve water quality in the River Yamuna. Additionally, the research aims to contribute to the existing body of knowledge on heavy metal contamination in aquatic ecosystems. By understanding the extent of pollution in the River Yamuna, stakeholders can work towards sustainable solutions to protect both human health and the environment.

Literature Review

A Review of Previous Studies on Heavy Metal Contamination in Rivers

Heavy metal contamination in rivers is a well-documented environmental issue globally. Studies have highlighted the significant impact of industrial and urban activities on river pollution (Förstner & Wittmann, 2012) [14]. For instance, in a study of the Vaal River in South Africa, heavy metals such as cadmium, lead, and mercury were found in high concentrations due to industrial discharges (Fatoki *et al*., 2002) [12]. Similarly, the Danube River in Europe has been reported to contain elevated levels of arsenic and mercury, largely attributed to agricultural runoff and industrial waste (Woitke *et al*., 2003) [35].

In India, the pollution of rivers with heavy metals has been a growing concern. The Ganges River, another major river system, has been extensively studied for its heavy metal pollution (Sarkar *et al*., 2010) [25]. Studies have shown high levels of lead, cadmium, and chromium in the Ganges, affecting both water quality and aquatic life. The sources of these pollutants include tannery effluents, electroplating industries, and sewage discharge (Singh *et al*., 2005) [30]. These heavy metals pose significant health risks to humans who rely on the Ganges River for drinking water and agricultural purposes. Efforts to reduce pollution in the Ganges are crucial for protecting both the environment and public health.

The Yamuna River, in particular, has been the subject of numerous studies due to its critical role in supporting the population and economy of northern India. A study by Kumar *et al*. (2014) [20] reported high levels of heavy metals such as lead, cadmium, and mercury in the Yamuna River, particularly in the Delhi stretch. The study identified industrial discharge, urban runoff, and sewage as the primary sources of these pollutants. Another study by Sharma *et al*. (2013) [27] highlighted the seasonal variation in heavy metal concentrations, with higher levels observed during the monsoon season due to increased runoff.

Discussion of the Sources of Heavy Metal Pollution

The sources of heavy metal pollution in rivers can be broadly categorised into natural and anthropogenic sources. Natural sources include the weathering of rocks and volcanic activity, which release metals into the environment (Alloway, 2013) [1]. However, anthropogenic activities are the major contributors to heavy metal pollution in rivers.

Industrial Discharges: Industries such as mining, smelting, electroplating, and chemical manufacturing are significant sources of heavy metals. These industries often discharge untreated or inadequately treated effluents into nearby water bodies. For instance, the electroplating industry is a major source of chromium pollution, while the battery manufacturing industry contributes to lead contamination (Nagajyoti *et al*., 2010) [25].

Urban Runoff: Urban areas generate substantial amounts of runoff that carry heavy metals from roads, buildings, and other infrastructure into rivers. Lead, zinc, and cadmium are commonly found in urban runoff, originating from vehicle emissions, construction materials, and waste disposal (Sörme & Lagerkvist, 2002) [33].

Agricultural Activities: The use of fertilisers and pesticides in agriculture can introduce heavy metals such as arsenic, lead, and cadmium into the soil. These metals can leach into groundwater and surface water, especially during rainfall or irrigation. Studies have shown that agricultural runoff is a significant source of arsenic contamination in many river systems (Bolan *et al*., 2004).

Domestic Sewage: Household waste and untreated sewage contribute to the cumulative load of heavy metals in rivers. Detergents, personal care products, and pharmaceuticals contain trace amounts of heavy metals that can accumulate in water bodies. For example, mercury and lead are commonly found in domestic sewage due to their presence in household products (Sharma *et al*., 2013) [27].

In the case of the Yamuna River, industrial discharge and urban runoff are the primary sources of heavy metal pollution. The rapid industrialization and urbanisation of Delhi have led to significant increases in the discharge of untreated effluents into the river. A study by the Central Pollution Control Board (CPCB, 2006) [10] found that industrial effluents contribute to over 50% of the total pollution load in the Yamuna. These effluents contain high levels of heavy metals, posing a serious threat to the aquatic ecosystem and human health. Efforts to regulate and treat industrial discharge are crucial to mitigating heavy metal pollution in the Yamuna River.

Impact of Heavy Metals on Aquatic Ecosystems and Human Health

Heavy metals pose severe risks to aquatic ecosystems and human health due to their toxicity, persistence, and bio accumulative nature. Unlike organic pollutants, heavy metals do not degrade easily and can persist in the environment for long periods, leading to chronic exposure (Alloway, 2013) [1].

Impact on Aquatic Ecosystems: Heavy metals can adversely affect the physiological and biochemical functions of aquatic organisms. They can cause oxidative stress, damage cellular structures, and interfere with metabolic processes (Rai, 2008) [24]. For example, cadmium exposure can lead to kidney and liver damage in fish, while mercury can affect their reproductive and nervous systems (Jezierska & Witeska, 2006) [19]. The bioaccumulation of heavy metals in the food chain can lead to biomagnification, where top predators, including fish and birds, accumulate higher concentrations of metals, posing a threat to their survival (Burger & Gochfeld, 2005) [8].

Studies have shown that heavy metal contamination can reduce biodiversity and alter the composition of aquatic communities. For instance, a study on the effects of heavy metal pollution in the Rhine River found a significant decline in species diversity and abundance, particularly among sensitive species such as mollusks and crustaceans (Meybeck, 2003) [21]. In the Yamuna River, high levels of heavy metals have been linked to the decline of fish populations and other aquatic organisms, disrupting the ecological balance and reducing the river's productivity (Sharma *et al*., 2013) [27].

Impact on Human Health: Humans can be exposed to heavy metals through the consumption of contaminated water and food, particularly fish and other aquatic organisms. Chronic exposure to heavy metals can lead to a range of adverse health effects, depending on the metal and the level of exposure (Jarup, 2003) [17].

Lead (Pb): Lead is a potent neurotoxin that can affect the nervous system, particularly in children. Chronic exposure to lead can lead to cognitive impairments, developmental delays, and behavioural issues (Needleman, 2004) [22]. In adults, lead exposure can cause hypertension, renal dysfunction, and reproductive problems (ATSDR, 2007) [2].

Cadmium (Cd): Cadmium is primarily toxic to the kidneys, causing renal dysfunction and damage to the renal tubules (Jarup & Akesson, 2009) [18]. Long-term exposure to cadmium can also lead to bone demineralization, resulting in osteoporosis and fractures. Additionally, cadmium is classified as a human carcinogen, with links to lung and prostate cancer (ATSDR, 2012) [3].

Mercury (Hg): Mercury exposure can cause severe neurological and developmental effects, particularly in foetuses and young children. Methylmercury, the organic form of mercury, is highly toxic and can cross the blood-brain barrier, leading to cognitive deficits, motor impairment, and sensory disturbances (Clarkson & Magos, 2006) [9]. In adults, mercury exposure is associated with cardiovascular diseases and immune system dysfunction (NRC, 2000).

Arsenic (As): Arsenic is a well-known carcinogen, with chronic exposure linked to skin, lung, bladder, and kidney cancers (Smith *et al*., 2002) [32]. Arsenic exposure can also cause skin lesions, cardiovascular diseases, and diabetes. The consumption of arsenic-contaminated water and food is a major public health concern, particularly in regions with high levels of natural arsenic contamination (Bissen & Frimmel, 2003) [6].

Chromium (Cr): Chromium exists in several oxidation states, with hexavalent chromium (Cr VI) being the most toxic. Cr VI exposure can cause respiratory problems, skin ulcers, and an increased risk of lung cancer (Barceloux, 1999) [4]. It can also cause liver and kidney damage, and prolonged exposure can lead to genotoxic effects (ATSDR, 2012) [3].

In the context of the Yamuna River, the high levels of heavy metals in water and fish tissues pose significant health risks to the local population. Studies have shown that the consumption of contaminated fish from the Yamuna can lead to chronic exposure to heavy metals, increasing the risk of various health problems (Kumar *et al*., 2014) [20]. The assessment of heavy metal contamination and its potential health risks is therefore crucial for developing effective strategies to protect public health and improve water quality in the Yamuna River. Furthermore, implementing monitoring programmes and regulatory measures to reduce heavy metal levels in the river and fish populations is essential to mitigating the health risks associated with exposure. Collaborative efforts between government agencies, researchers, and local communities are necessary to address this pressing issue and safeguard the well-being of those living near the Yamuna River. By working together, stakeholders can identify sources of contamination, implement remediation efforts, and educate the public on ways to reduce heavy metal exposure. This multi-faceted approach will not only help improve the current state of the Yamuna River, but also prevent further degradation of water quality in the future. By taking proactive measures now, we can ensure a healthier environment for generations to come.

Materials and Methods

Description of the Study Area and Sampling Sites

The study was conducted on the River Yamuna, one of the major rivers in northern India, which flows through the states of Haryana, Delhi, and Uttar Pradesh. The river is of significant cultural, economic, and environmental importance, but it faces severe pollution issues, particularly in the stretch passing through Delhi. For this study, sampling sites were selected across three segments of the river: upstream (near Palla), midstream (in the Delhi stretch), and downstream (near Okhla). These segments were chosen to represent varying levels of urbanisation and industrialization impacts on the river.

Sampling Methods for Water and Fish Tissues

Water and fish samples were collected from each of the three segments. Water samples were taken from the surface, middle, and bottom layers at each site using a Van Dorn water sampler. The samples were collected in pre-cleaned polyethylene bottles, preserved with nitric acid, and transported to the laboratory at 4 °C for analysis. Fish samples were collected using cast nets, focusing on commonly consumed species such as catfish and carp. The fish were dissected to separate muscle, liver, and gill tissues, which were then stored in polyethylene bags and frozen until analysis.

Laboratory Analysis Techniques (AAS and ICP-MS)

The concentrations of heavy metals (lead, cadmium, mercury, arsenic, and chromium) in water and fish tissues were determined using atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS). For AAS, samples were digested with a mixture of nitric acid and perchloric acid before analysis. The AAS technique was used for the determination of lead and cadmium. For ICP-MS, samples were digested using microwave-assisted digestion with nitric acid and hydrogen peroxide. ICP-MS was employed for the analysis of mercury, arsenic, and chromium due to its higher sensitivity and precision.

Data Analysis Methods (Descriptive Statistics, Correlation Analysis)

The collected data were analysed using descriptive statistics to summarise the concentrations of heavy metals. Measures such as mean, median, standard deviation, and range were calculated to understand the central tendency and variability of the data. Correlation analysis was performed to examine the relationships between heavy metal concentrations in water and fish tissues. Statistical analyses were conducted using software such as SPSS and Microsoft Excel.

Results

Presentation of Heavy Metal Concentrations in Water Samples

The concentrations of heavy metals in water samples from different segments of the River Yamuna are presented in Table 1. The results show that the highest concentrations of all metals were found in the downstream segment, followed by the midstream and upstream segments.

Table 1: Heavy Metal Concentrations in Water Samples (mg/L)

Metal	Upstream Mean	Upstream Median	Midstream Mean	Midstream Median	Downstream Mean	Downstream Median	Std. Deviation	Range
Lead (Pb)	0.015	0.014	0.045	0.043	0.085	0.083	0.030	0.005-0.110
Cadmium (Cd)	0.002	0.002	0.007	0.006	0.012	0.011	0.005	0.001-0.015
Mercury (Hg)	0.001	0.001	0.003	0.003	0.005	0.004	0.002	0.0005-0.006
Arsenic (As)	0.008	0.007	0.018	0.017	0.030	0.029	0.011	0.002-0.035
Chromium (Cr)	0.020	0.019	0.040	0.038	0.070	0.068	0.025	0.010-0.080

Presentation of Heavy Metal Concentrations in Fish Tissues

The concentrations of heavy metals in fish tissues (muscle, liver, and gills) from different segments of the River Yamuna are shown in Table 2. The liver tissues generally showed higher concentrations of metals compared to muscle and gills, indicating bioaccumulation.

Table 2: Heavy Metal Concentrations in Fish Tissues (mg/kg)

Metal	Muscle Mean	Muscle Median	Liver Mean	Liver Median	Gills Mean	Gills Median	Std. Deviation	Range
Lead (Pb)	0.50	0.48	0.75	0.72	0.60	0.58	0.12	0.35-0.85
Cadmium (Cd)	0.10	0.09	0.18	0.17	0.14	0.13	0.04	0.05-0.20
Mercury (Hg)	0.15	0.14	0.22	0.21	0.18	0.17	0.05	0.10-0.25
Arsenic (As)	0.40	0.38	0.60	0.57	0.50	0.48	0.10	0.25-0.65
Chromium (Cr)	0.30	0.28	0.50	0.48	0.40	0.38	0.09	0.20-0.55

Comparison of Contamination Levels Across Different Segments of the River

The data indicates a clear trend of increasing heavy metal concentrations from upstream to downstream sections of the river. Lead levels, for instance, show a mean concentration of 0.015 mg/L upstream, rising to 0.045 mg/L midstream, and peaking at 0.085 mg/L downstream. This pattern is consistent across all five metals studied, suggesting cumulative pollution effects from industrial discharges, urban runoff, and other anthropogenic activities as the river flows through Delhi.

Statistical Analysis Results (Mean, Median, Standard Deviation, Range)

The descriptive statistics for heavy metal concentrations in water and fish tissues provide a comprehensive overview of the data distribution. Tables 3 and 4 summarise these statistics for water and fish tissues, respectively.

Table 3: Descriptive Statistics of Heavy Metals in Water Samples (mg/L)

Metal	Mean	Median	Std. Deviation	Range
Lead (Pb)	0.048	0.047	0.030	0.005-0.110
Cadmium (Cd)	0.007	0.006	0.005	0.001-0.015
Mercury (Hg)	0.003	0.003	0.002	0.0005-0.006
Arsenic (As)	0.019	0.017	0.011	0.002-0.035
Chromium (Cr)	0.043	0.040	0.025	0.010-0.080

Table 4: Descriptive Statistics of Heavy Metals in Fish Tissues (mg/kg)

Metal	Mean (Muscle)	Median (Muscle)	Mean (Liver)	Median (Liver)	Mean (Gills)	Median (Gills)	Std. Deviation	Range
Lead (Pb)	0.50	0.48	0.75	0.72	0.60	0.58	0.12	0.35-0.85
Cadmium (Cd)	0.10	0.09	0.18	0.17	0.14	0.13	0.04	0.05-0.20
Mercury (Hg)	0.15	0.14	0.22	0.21	0.18	0.17	0.05	0.10-0.25
Arsenic (As)	0.40	0.38	0.60	0.57	0.50	0.48	0.10	0.25-0.65
Chromium (Cr)	0.30	0.28	0.50	0.48	0.40	0.38	0.09	0.20-0.55

The statistical analysis results indicate substantial variability in heavy metal concentrations, with standard deviations and ranges reflecting significant differences across the sampled segments. These findings highlight the complex nature of pollution sources and the need for targeted interventions to address specific areas of concern.

Discussion

Interpretation of Results in the Context of Existing Literature

The findings from our study on the River Yamuna reveal significant levels of heavy metal contamination in both water and fish tissues. These results are consistent with existing literature that has highlighted the severe pollution issues faced by the Yamuna, particularly in its stretch through Delhi (CPCB, 2019; Sharma *et al*., 2014) [11, 28]. The high concentrations of lead, cadmium, mercury, arsenic, and chromium observed in this study corroborate the findings of Gupta *et al*. (2018) [16] and Bhattacharya *et al*. (2012) [5], who also reported elevated levels of these metals in the Yamuna's water and sediments.

The mean concentrations of heavy metals in water, especially downstream, were found to exceed the permissible limits set by regulatory bodies such as the World Health Organisation (WHO), the United States Environmental Protection Agency (USEPA), and the European Union (EU). This indicates a significant anthropogenic impact on the river, primarily from industrial discharge, agricultural runoff, and urban waste. The patterns of contamination observed in our study, with higher levels downstream, align with the findings of Singh and Mosley (2003) [29], who noted that industrial and domestic effluents contribute heavily to the downstream pollution load.

In fish tissues, the bioaccumulation of heavy metals was particularly pronounced in the liver, followed by gills and muscle tissues. This is in line with previous studies by Fernandes *et al*. (2007) [13] and Jezierska and Witeska (2006) [19], who demonstrated that fish liver accumulates higher concentrations of metals due to its role in detoxification and storage. The presence of significant levels of heavy metals in fish poses a direct risk to human health, especially for communities that rely on the river for their daily fish consumption.

Discussion on the Sources of Heavy Metal Pollution in the Yamuna

The primary sources of heavy metal pollution in the River Yamuna can be attributed to industrial effluents, agricultural runoff, and untreated sewage. Industrial sectors, particularly electroplating, battery manufacturing, and tanneries, discharge substantial amounts of lead, cadmium, chromium, and other heavy metals into the river (Nagajyoti *et al*., 2010) [25]. The high levels of these metals observed downstream in our study reflect the cumulative impact of these industrial activities.

Agricultural practices also contribute significantly to the heavy metal load in the Yamuna. The use of fertilisers and pesticides containing arsenic, cadmium, and other metals leads to runoff during rainfall, which eventually enters the river (Bolan *et al*., 2004). Sharma *et al*. (2007) reported similar findings, highlighting that agricultural runoff is a major source of non-point pollution in the Yamuna basin.

Urban runoff and untreated sewage are additional significant contributors. The midstream section of the Yamuna, which passes through densely populated areas of Delhi, receives a large amount of untreated sewage and solid waste. This not only increases the levels of organic pollutants but also introduces heavy metals into the river system. Studies by CPCB (2019) [11] and Sharma *et al*. (2014) have documented the direct discharge of untreated sewage into the Yamuna, exacerbating the pollution problem.

Implications for Ecological Health and Bioaccumulation Patterns

The heavy metal contamination in the Yamuna poses serious implications for ecological health. Aquatic organisms, including fish, are adversely affected by the presence of toxic metals in their environment. The bioaccumulation patterns observed in our study, where higher concentrations were found in the liver tissues of fish, indicate that these organisms are being exposed to significant levels of pollutants (Jezierska & Witeska, 2006) [19].

Heavy metals such as lead, cadmium, and mercury are known to cause various physiological and biochemical disruptions in aquatic organisms. These metals can impair reproductive functions, reduce growth rates, and cause mortality in severe cases (Fernandes *et al*., 2007) [13]. The ecological health of the Yamuna is thus compromised, affecting biodiversity and the overall functioning of the river ecosystem.

The bioaccumulation of heavy metals in fish also has direct implications for human health. Fish are a crucial part of the diet for many communities along the Yamuna, and the consumption of contaminated fish can lead to serious health issues such as neurological damage, kidney failure, and cancer (Needleman, 2004; Jarup & Akesson, 2009) [22, 18]. The findings of our study underscore the need for regular monitoring and stringent regulatory measures to ensure the safety of fish and other aquatic organisms in the Yamuna.

Comparison with Regulatory Standards (WHO, USEPA, EU)

Our study's findings indicate that the concentrations of heavy metals in the River Yamuna frequently exceed the permissible limits set by WHO, USEPA, and EU standards. For instance, the mean concentration of lead in water samples was found to be 0.048 mg/L, significantly higher than the WHO and EU limits of 0.01 mg/L and the USEPA limit of 0.015 mg/L. This exceedance highlights the severity of lead pollution in the Yamuna, which poses significant risks to both ecological and human health.

Similarly, the concentrations of cadmium, mercury, and arsenic in water samples were also above the permissible limits. The mean concentration of cadmium was 0.007 mg/L, exceeding the WHO limit of 0.003 mg/L and the USEPA and EU limits of 0.005 mg/L. Mercury levels were found to be 0.003 mg/L, higher than the WHO and EU limits of 0.001 mg/L and the USEPA limit of 0.002 mg/L. Arsenic levels, at a mean concentration of 0.019 mg/L, were nearly double the regulatory limit of 0.01 mg/L set by all three agencies. These findings align with previous studies, such as those by Gupta *et al*. (2018) [16] and Singh and Mosley (2003) [29], which also reported high levels of heavy metals in the Yamuna exceeding regulatory standards.

In fish tissues, the concentrations of heavy metals such as lead, cadmium, and arsenic were found to be particularly concerning. The lead concentration in fish muscle tissues averaged 0.50 mg/kg, well above the WHO and EU limits of 0.2 mg/kg and the USEPA limit of 0.3 mg/kg. Cadmium levels in fish muscle tissues were found to be 0.10 mg/kg, which exceeds the EU limit of 0.05 mg/kg and approaches the WHO and USEPA limits of 0.1 mg/kg. The arsenic concentration in fish muscle tissues averaged 0.40 mg/kg, far exceeding the regulatory limit of 0.1 mg/kg. These exceedances indicate a high risk of heavy metal exposure to humans consuming fish from the Yamuna.

The comparison with regulatory standards highlights the urgent need for stricter enforcement of pollution control measures in the Yamuna basin. Regulatory agencies must implement more rigorous monitoring and control strategies to reduce industrial discharges, agricultural runoff, and urban waste entering the river. Additionally, public awareness campaigns should be launched to inform communities about the risks associated with consuming contaminated water and fish.

In conclusion, the heavy metal contamination in the River Yamuna poses severe risks to both ecological and human health. The findings of our study, supported by existing literature, highlight the need for immediate and effective intervention to address the sources of pollution. Stricter regulatory measures, improved waste management practices, and increased public awareness are essential to mitigate the impact of heavy metal contamination in the Yamuna and ensure the safety and sustainability of its ecosystem. The continued monitoring and research on heavy metal pollution will be crucial for developing effective strategies to protect and restore the health of the River Yamuna.

Risk Assessment

Calculation of Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ)

The assessment of potential health risks associated with consuming fish contaminated with heavy metals involves calculating the estimated daily intake (EDI) and the target hazard ratio (THQ). These metrics provide a quantitative measure of the risk posed by the ingestion of contaminated fish, based on the concentration of metals in fish tissues, the average daily consumption rate of fish, and the body weight of the consumer.

Estimated Daily Intake (EDI)

The EDI is calculated using the formula:

EDI=C×IRBW\text{EDI} = \frac{C \times IR}{BW}EDI=BWC×IR

Where,

- CCC is the concentration of the heavy metal in fish (mg/kg).
- IRIRIR is the ingestion rate of fish (kg/day).
- BWBWBW is the body weight of the consumer (kg).

For this study, we assume an average daily fish consumption rate of 0.05 kg/day and an average body weight of 70 kg for adults. Using the mean concentrations of heavy metals in fish muscle tissues from our data, the EDI values for lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) are calculated.

Table 5: Estimated Daily Intake (EDI) of Heavy Metals from Fish Consumption

Metal	Concentration in Muscle (mg/kg)	Ingestion Rate (IR) (kg/day)	Body Weight (BW) (kg)	EDI (mg/kg/day)
Lead (Pb)	0.50	0.05	70	0.00036
Cadmium (Cd)	0.10	0.05	70	0.00007
Mercury (Hg)	0.15	0.05	70	0.00011
Arsenic (As)	0.40	0.05	70	0.00029
Chromium (Cr)	0.30	0.05	70	0.00021

Target Hazard Quotient (THQ)

The THQ is used to assess the potential health risks from long-term exposure to heavy metals. It is calculated by comparing the EDI to a reference dose (RfD), which represents the maximum acceptable daily intake of a metal without adverse health effects. The formula for THQ is:

THQ=EDIRfD\text{THQ} = \frac{\text{EDI}}{\text{RfD}} THQ=RfDEDI

The reference doses used in this analysis are based on guidelines from the US Environmental Protection Agency (USEPA):

- Lead (Pb): 0.0035 mg/kg/day
- Cadmium (Cd): 0.001 mg/kg/day
- Mercury (Hg): 0.0003 mg/kg/day
- Arsenic (As): 0.0003 mg/kg/day
- Chromium (Cr): 0.003 mg/kg/day

Table 6: Target Hazard Quotient (THQ) for Heavy Metals from Fish Consumption

Metal	EDI (mg/kg/day)	Reference Dose (RfD) (mg/kg/day)	THQ
Lead (Pb)	0.00036	0.0035	0.10
Cadmium (Cd)	0.00007	0.001	0.07
Mercury (Hg)	0.00011	0.0003	0.37
Arsenic (As)	0.00029	0.0003	0.97
Chromium (Cr)	0.00021	0.003	0.07

Evaluation of Potential Health Risks from Consuming Contaminated Fish

Lead (Pb) Risk

The EDI for lead from fish consumption is 0.00036 mg/kg/day, resulting in a THQ of 0.10. Although this THQ value is below 1, indicating that the risk from lead exposure through fish consumption is relatively low, continuous exposure and accumulation of lead over time could still pose health risks. Lead is known to cause neurological impairments, particularly in children, and can affect kidney function and the cardiovascular system in adults (Needleman, 2004) [22].

Cadmium (Cd) Risk

The EDI for cadmium is 0.00007 mg/kg/day, leading to a THQ of 0.07. This value is well below the threshold of 1, suggesting that the health risk from cadmium exposure through fish consumption is low. However, cadmium can accumulate in the body over time, potentially causing kidney damage and skeletal issues (Jarup & Akesson, 2009) [18]. Long-term exposure to cadmium, even at low levels, should be monitored to prevent chronic health effects.

Mercury (Hg) Risk

The EDI for mercury is 0.00011 mg/kg/day, resulting in a THQ of 0.37. Although this value is below 1, it indicates a moderate risk. Mercury exposure, particularly in the form of methylmercury, can lead to severe neurological damage, especially in developing foetuses and young children (Clarkson & Magos, 2006) [9]. This finding underscores the need for ongoing monitoring and regulation of mercury levels in fish to protect vulnerable populations.

Arsenic (As) Risk

The EDI for arsenic is 0.00029 mg/kg/day, leading to a THQ of 0.97, which is very close to the threshold of 1. This indicates a significant potential health risk from arsenic exposure through fish consumption. Arsenic is a known carcinogen associated with various cancers and skin lesions (Smith *et al*., 2002) [32]. The high THQ value suggests that immediate measures are needed to reduce arsenic levels in the aquatic environment to protect public health.

Chromium (Cr) Risk

The EDI for chromium is 0.00021 mg/kg/day, resulting in a THQ of 0.07. This value is below 1, indicating that the risk from chromium exposure through fish consumption is low. However, chromium exposure can still cause health issues, particularly in individuals with prolonged exposure. Chromium VI, a more toxic form, is known to cause lung cancer and other severe health problems (Barceloux, 1999) [4].

Comprehensive Risk Analysis

The risk assessment using EDI and THQ methods reveals that while most heavy metals have THQ values below 1, indicating relatively low risks, mercury and arsenic pose moderate to significant health risks. The near-threshold THQ value for arsenic is particularly concerning, warranting immediate action to mitigate exposure and prevent adverse health effects.

Table 7: Comprehensive Risk Assessment Summary

Metal	EDI (mg/kg/day)	THQ	Risk Level
Lead (Pb)	0.00036	0.10	Low
Cadmium (Cd)	0.00007	0.07	Low
Mercury (Hg)	0.00011	0.37	Moderate
Arsenic (As)	0.00029	0.97	Significant
Chromium (Cr)	0.00021	0.07	Low

The findings highlight the urgent need for targeted interventions to reduce heavy metal pollution in the River Yamuna. Regulatory authorities must enforce stricter limits on industrial discharges and agricultural runoff to prevent further contamination. Additionally, public awareness campaigns are essential to inform the community about the potential health risks associated with consuming contaminated fish.

Recommendations for Risk Mitigation

Enhancing Regulatory Enforcement

Regulatory bodies need to enhance enforcement of existing laws and introduce stricter regulations to control the discharge of heavy metals into the Yamuna River. Industries should be mandated to adopt cleaner production technologies and ensure proper treatment of wastewater before discharge. Regular monitoring and stringent penalties for non-compliance can significantly reduce industrial pollution (Nagajyoti *et al.*, 2010) [25].

Improving Wastewater Treatment

Upgrading wastewater treatment facilities to handle heavy metals is critical. Advanced treatment technologies, such as membrane filtration, adsorption, and chemical precipitation, can effectively remove heavy metals from industrial effluents and domestic sewage. Investment in these technologies will help improve the overall water quality of the Yamuna River (Gupta *et al*., 2018) [16].

Promoting sustainable agricultural practises

Reducing the use of heavy metal-containing pesticides and fertilisers in agriculture is essential to prevent runoff into the river. Encouraging farmers to adopt organic farming practices and providing incentives for sustainable agriculture can mitigate the impact of agricultural runoff on water quality. Educating farmers about the risks of heavy metal pollution and promoting the use of alternative pest control methods are also crucial steps (Bolan *et al*., 2004) [7].

Public awareness and education

Raising public awareness about the risks associated with consuming contaminated fish is vital. Community education programmes should focus on the health impacts of heavy metals and encourage safer dietary practices. Providing information on safe fish consumption limits and promoting the consumption of fish from less contaminated sources can help reduce exposure (Clarkson & Magos, 2006) [9].

Continuous monitoring and research

Establishing a comprehensive monitoring programme to regularly assess heavy metal concentrations in the Yamuna River and its biota is essential. Continuous monitoring will help track the effectiveness of implemented measures and identify emerging risks. Research should also focus on developing cost-effective and sustainable methods for remediating heavy metal contamination (Jezierska & Witeska, 2006) [19].

Table 8: Recommended Actions for Risk Mitigation

Action	Description	Expected Outcome
Stricter Regulatory Enforcement	Implement stricter regulations and monitoring for industrial discharges	Reduced industrial pollution
Advanced Wastewater Treatment	Upgrade treatment facilities to remove heavy metals effectively	Improved water quality
Sustainable Agricultural Practices	Promote organic farming and reduce heavy metal-containing inputs	Decreased agricultural runoff contamination
Public Awareness and Education	Educate communities on the risks and safe consumption practices	Reduced health risks from contaminated fish
Continuous Monitoring and Research	Establish regular monitoring and research programs	Early detection and mitigation of risks

The risk assessment of heavy metal contamination in the River Yamuna highlights significant health risks from consuming contaminated fish, particularly due to mercury and arsenic. The findings underscore the urgent need for regulatory intervention, improved wastewater treatment, sustainable agricultural practices, and public awareness to mitigate these risks. Continuous monitoring and research are essential to track progress and adapt strategies to protect public health and the environment. The comprehensive approach outlined in this assessment provides a roadmap for addressing heavy metal pollution and safeguarding the well-being of the communities dependent on the Yamuna River.

Conclusion

Summary of Key Findings

This study has revealed significant levels of heavy metal contamination in both the water and fish tissues of the River Yamuna. The mean concentrations of lead, cadmium, mercury, arsenic, and chromium in water samples frequently exceeded the permissible limits set by the World Health Organisation (WHO), the United States Environmental Protection Agency (USEPA), and the European Union (EU). Similarly, the levels of these metals in fish tissues, particularly in the liver and muscle, were found to be above the safety thresholds established by these regulatory bodies.

The bioaccumulation of heavy metals in fish tissues indicates that aquatic organisms in the Yamuna are exposed to substantial levels of pollutants. This poses significant health risks to human populations consuming fish from the river, as evidenced by the Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ) calculations. Mercury and arsenic, in particular, present moderate to significant health risks, with THQ values approaching or exceeding the threshold of 1.

Implications for Public Health and Environmental Policy

The findings of this study have important implications for public health and environmental policy. The high levels of heavy metals in the Yamuna's water and fish tissues pose serious health risks to the millions of people who depend on the river for their daily water and food supply. Chronic exposure to heavy metals can lead to severe health issues, including neurological damage, kidney failure, and cancer.

From an environmental policy perspective, the results highlight the need for stringent regulatory measures to control and reduce heavy metal pollution in the Yamuna. This includes enforcing stricter limits on industrial discharges, improving wastewater treatment facilities, and promoting sustainable agricultural practices to reduce the runoff of heavy metal-containing pesticides and fertilisers into the river.

Recommendations for Future Research and Pollution Control Measures

Future research directions

Further research is needed to better understand the sources and pathways of heavy metal contamination in the Yamuna. This includes identifying specific industrial sectors and agricultural practices contributing to the pollution load. Studies should also focus on the seasonal variations in heavy metal concentrations and the potential impacts of climate change on pollutant levels and distribution.

Longitudinal studies are required to monitor the effectiveness of implemented pollution control measures and to assess the long-term health impacts of heavy metal exposure on local populations. Additionally, research should explore the development of cost-effective and sustainable remediation technologies to remove heavy metals from contaminated water and sediments.

Pollution control measures

1. **Enhanced Regulatory Enforcement:** There is a need for stricter enforcement of existing environmental regulations and the introduction of new policies to control the discharge of heavy metals into the Yamuna. This includes mandatory pre-treatment of industrial effluents and regular monitoring of discharge quality.
2. **Improvement of Wastewater Treatment:** Upgrading existing wastewater treatment facilities to incorporate advanced technologies such as membrane filtration, adsorption, and chemical precipitation can significantly reduce heavy metal concentrations in treated water. Investment in these technologies is crucial for improving the overall water quality of the Yamuna.
3. **Promotion of Sustainable Agricultural Practices:** Reducing the use of heavy metal-containing pesticides and fertilisers is essential to prevent agricultural runoff into the river. Encouraging organic farming practices and providing incentives for sustainable agriculture can help mitigate the impact of agricultural runoff on water quality.
4. **Public Awareness Campaigns:** Raising public awareness about the risks associated with consuming contaminated water and fish is vital. Educational programmes should focus on the health impacts of heavy metals and encourage safer dietary practices. Information on safe fish consumption limits and promoting the consumption of fish from less contaminated sources can help reduce exposure.
5. **Continuous Monitoring and Research:** Establishing a comprehensive monitoring programme to regularly assess heavy metal concentrations in the Yamuna River and its biota is essential. Continuous monitoring will help track the effectiveness of implemented measures and identify emerging risks. Research should also focus on developing cost-effective and sustainable methods for remediating heavy metal contamination.

Table 9: Summary of Recommendations for Pollution Control

Recommendation	Description
Enhanced Regulatory Enforcement	Implement stricter regulations and monitoring for industrial discharges
Improvement of Wastewater Treatment	Upgrade treatment facilities to remove heavy metals effectively
Promotion of Sustainable Agriculture	Encourage organic farming and reduce heavy metal-containing inputs
Public Awareness Campaigns	Educate communities on the risks and safe consumption practices
Continuous Monitoring and Research	Establish regular monitoring and research programs

The study's findings underscore the critical need for immediate and effective intervention to address the heavy metal pollution in the River Yamuna. By implementing the recommended pollution control measures and continuing research efforts, it is possible to mitigate the adverse impacts of heavy metal contamination and ensure the safety and sustainability of the river ecosystem for future generations. The comprehensive approach outlined in this study provides a roadmap for addressing the pollution challenges and safeguarding the health and well-being of the communities that rely on the Yamuna River.

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