Integrative Analysis of Seasonal Bioaccumulation Patterns and Toxicological Risk Indices in Freshwater Fish Species of Vembanad Backwaters: Implications for Environmental and Public Health

abstract :

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| **The present study investigates the bioaccumulation of heavy metals in commercially and ecologically important fish species inhabiting the Vembanad Backwater System (VBS), a Ramsar site of high ecological value on the southwest coast of India. A total of 15 fish species were analyzed for six heavy metals (Cd, Cr, Cu, Pb, Zn, and Ni) across three distinct seasons—pre-monsoon, monsoon, and post-monsoon. Concentrations were evaluated using ICP-MS, and the data were statistically analyzed using one-way ANOVA to assess seasonal and interspecific variations. Results indicated significant spatiotemporal variability in metal accumulation patterns. Health risk assessments were conducted using Metal Pollution Index (MPI), Target Hazard Quotient (THQ), and Carcinogenic Risk (CR), revealing potential non-carcinogenic and carcinogenic risks in certain species and regions. The study emphasizes the importance of integrated environmental monitoring and policy-oriented risk assessment to safeguard public health, promote sustainable fishery management, and support the objectives of global frameworks such as the SDGs. The findings contribute valuable baseline data for ecological risk mitigation and informed policymaking in freshwater ecosystems.** |

*Keywords: Heavy metal bioaccumulation, Health risk assessment, ecotoxicology, ICPMS*

1. INTRODUCTION

Marine pollution with heavy metals is a pressing environmental issue that poses significant risks to aquatic ecosystems and human health (Abubakar *et al.,* 2024). In freshwater systems like the Vembanad Backwaters, heavy metals such as cadmium, lead, mercury, and nickel can accumulate in the tissues of various fish species over time, threatening both biodiversity and the health of communities that rely on these resources for nutrition (Prakash *et al.,* 2023). The sources of heavy metal pollution in the Vembanad Backwaters are multifaceted, encompassing agricultural runoff, industrial effluents, and urban discharges (Shyleshchandran *et al.,* 2019). These metals enter the aquatic environment through direct discharge into waterways and leaching from surrounding land (Vincent *et al.,* 2025). Once introduced, heavy metals can persist in sediments and biological tissues, leading to prolonged exposure for both aquatic organisms and their predators, including humans (Khushbu *et al.,* 2022).

This study focuses on several economically and ecologically important fish species, including *Etroplus suratensis, Mugil cephalus, Scatophagus argus, Epinephelus areolatus, Elops machnata, Carangoides malabaricus, Seriolina nigrofasciata, Lates calcarifer, Oreochromis placidus*, and *Lutjanus malabaricus*. These species are integral to the local diet and economy; however, the bioaccumulation of heavy metals poses substantial health risks (Huang *et al.,* 2022). Previous research has demonstrated that consumption of contaminated fish can lead to serious health issues, including neurological damage, developmental disorders, and increased cancer risk (Yi *et al.,* 2017). The World Health Organization (WHO) has established safety guidelines for heavy metal concentrations in seafood (WHO, 1989), yet many fish sampled from freshwater ecosystems often exceed these limits.

This study aims to conduct an integrative analysis of seasonal bioaccumulation patterns and toxicological risk indices in these fish species from the Vembanad Backwaters, focusing on the pre-monsoon, monsoon, and post-monsoon seasons. By evaluating Target Hazard Quotients (THQ), Carcinogenic Risk (CR), and Metal Pollution Index (MPI), this research provides a comprehensive understanding of the health risks associated with the consumption of these fish (Gulati *et al.,* 2022). Given the global emphasis on sustainable development, particularly through the United Nations Sustainable Development Goals (SDGs), this study aligns closely with SDG 6 (Clean Water and Sanitation), SDG 14 (Life below Water), and SDG 3 (Good Health and Well-being). By investigating metal contamination in fish that are central to the food web and local livelihoods, this work contributes to safeguarding public health, promoting food safety, and supporting sustainable fisheries management. Furthermore, by identifying high-risk areas and species, this study lays the groundwork for integrated environmental monitoring, Eco toxicological assessments, and evidence-based policymaking—key components in achieving environmental sustainability and resilience in freshwater ecosystems.

The novelty of this study lies in its focus on the Vembanad Backwaters, an area of significant ecological and economic importance. As a key source of fish for local communities, understanding the levels of metal contamination and associated health risks is crucial for both environmental and human well-being. By addressing these objectives, this research aims to enhance the existing knowledge base on metal contamination in freshwater fish, ultimately contributing to the promotion of safe consumption practices and the sustainable management of aquatic resources.

2. material and methods

2.1 Study area

The Vembanad Backwater System (VBS) is a prominent estuarine ecosystem located in the southwestern Indian state of Kerala, stretching between 9°15'–10°27' N latitude and 76°17'–77°34' E longitude. Covering an area of approximately 2,033 km², VBS forms a major part of the Vembanad-Kol wetland complex. The system is drained by major rivers including the Periyar, Muvattupuzha, and Pamba, and is connected to the Arabian Sea via tidal inlets such as the Cochin and Kayamkulam estuaries. The VBS has an average elevation of about 0.6 m above sea level and a gentle gradient of 0.5–1%, promoting the mixing of freshwater and brackish water (Retnamma *et al*., 2023). The rainfall data provided by the Indian Meteorological Department (IMD) were used. Furthermore, considering the area selected for the present study (i.e., Kerala, India),The tropical monsoon climate with an average annual rainfall of ~3,000 mm significantly affects the region’s hydrology and salinity regime.

The region supports diverse ecological functions and socio-economic activities including prawn farming, capture fisheries, and agriculture (notably in Kuttanad). However, increasing anthropogenic activities including agriculture runoff, urban effluents, and industrial discharges have contributed to the degradation of water and sediment quality (Haldar *et al.,* 2018; Sruthi *et al*., 2018).

**Fig 1: Study Area Map with sampling points**

2.2 Sampling and preparation

Fish sampling was conducted in VBS to assess the heavy metal contamination levels in the different parts of the different fish species. A total of 10 fin fishes (*Etroplus suratensis, Mughil cephalus, Scatophagus argus, Epinephelus areolatus, Elopes machnata, Carangoides malabaricus, Seriolina nigrofasciata, Lates calcarifer, Oreochomis placidus, Lutjanus malabaricus*) and 5 shell fishes (*Scylla serrata, Portunus sanguinolentus, Portunus pelagicus, Penaeus monodon, Penaeus indicus*) were collected from the study area and 10 samples were collected for each species. Fishes were collected from local fisherman and were immediately transferred to the laboratory in ice boxes to avoid spoilage. Standard taxonomic manuals and keys from the fisheries survey of India and worms were used to identify the specimens. Prior to analysis, frozen fish samples were partially thawed and dissected using stainless steel scalpels. Using clean equipment, the gills, liver, and muscle tissues of Fin fishes were dissected. The muscle samples were collected from dorsal side of the fish, avoiding contact with the skin, bones and other tissues. The gills were removed carefully from the fish and separated into left and right sides. The liver was also removed and cleaned thoroughly with distilled water to remove any attached tissues The intestine was also carefully removed and representative samples of different fish species were collected and analyzed for the heavy metal concentration in their muscles, gills, liver and intestine tissues. Samples were transferred to pre weighed acid-precleaned petri dishes and dried at 80˚C for 24 h, after which their dry weights were recorded. 1 gm of dried sample was digested tri acid in a ratio of 9:2:1, i.e., Nitric acid: sulphuric acid: per chloric acid, were added to the sample and digested. The digested samples are then diluted with deionized water to a desired concentration. Quality control measures such as blank samples, certified reference materials, and method blanks are prepared and included in the analysis to ensure accuracy and precision. . For the precise quantitative evaluation of trace elements in water samples, a multi-standard calibration procedure was employed, utilizing an internal standard approach with a 22-metal standard provided by PerkinElmer (Thaniem *et al*., 2023). Finally, the prepared fish sample solutions are ready for analysis using ICP-MS, which quantifies the concentration of various Heavy Metals (HM) in the sample by measuring their atomic mass-to-charge ratios. The data obtained from this study can be used to assess the potential risks associated with consuming fish from VBS.

**2.3 Ecological risk assessment**

**2.3.1 Metal Pollution Index (MPI)**

The Metal Pollution Index (MPI) is a numerical value that represents the overall level of heavy metal contamination in environmental samples, such as water, soil, or sediments. It is a tool used to assess the quality and pollution status of an environment based on the concentration of multiple heavy metals.

The Metal Pollution Index is typically calculated using the following equation:

 MPI=(C1×C2⋅×C3⋅⋯⋅Cn)1/n

Where:

C1, C2, C3, Cn are the concentrations of the individual Heavy Metals (HM) in the samples and n is the total number of Heavy Metals (HM) considered (Hossain *et al.,*2022).

**2.4 Health risk assessment**

**2.4.1 Target Hazard Quotient (THQ)**

The health risk associated with the consumption of fish species were assessed based on the Target Hazard Quotients and calculations were made using the standard hypothesis of an integrate [USEPA,2000].

 $THQ=\frac{E\_{fr}×ED\_{t\_{0}t}xFIR×C}{RfD\_{0}×Bw\_{a}×AT\_{n}}×10^{-3}$

Where EF = exposure frequency (365 days/year) [Ahmed *et al.,* 2015], ED = exposure duration (65 years) (USEPA, 2000), FIR= Food Ingestion Rate (57.5g/person/day for children and 92.6g/person/day for an adult), C = metal concentration in fish tissues in mg/kg, RfD = Oral reference dose in mg/kg per day. As per the (USEPA, 2000), the oral reference dose for Cd, Cr, Cu, Ni, Pb, and Zn were 0.001, 0.003, 0.3, 0.02, 0.004 and 0.3 correspondingly, WAB = Average body weight (55.9 kg for adult and 32.7 kg for children), TA = exposure time for noncarcinogens (EF×ED). The acceptable. Guide value for THQ is “1” (USEPA, 1997). If the THQ Value is less than 1, the exposed population is unlikely to experience an adverse health hazard. Conversely, if the THQ value is greater than 1, there is a potential health risk.

**2.4.2 Carcinogenic risk**

Carcinogenic risk is the probability of an individual developing cancer over a lifetime due to exposure to carcinogenic substances Ahmed *et al.,* 2015). This risk is assessed based on the dose of the carcinogen, the duration of exposure, and the potency of the carcinogen, typically expressed as the cancer slope factor (CSF).

 CR=CDI×CSF

 Where,

CR is the carcinogenic risk.

CDI is the Chronic Daily Intake of the carcinogen (mg/kg/ per day).

The results are interpreted based on established risk ranges to determine the potential health implications.

**2.5 Sustainability and Policy Relevance**

The selection of risk indices such as MPI, THQ, and CR was grounded in their applicability for public health assessments and regulatory standards under global frameworks like WHO and USEPA. This approach supports the development of science-based fish consumption advisories, enhancing ecosystem-based fishery management and contributing to pollution mitigation and food safety (Mohiuddin *et al.,* 2022). The findings can inform local authorities, environmental agencies, and fisheries departments to develop monitoring frameworks and early warning systems, promoting long-term ecological resilience of the VBS.

**2.6 Statistical Analysis**

A two-way analysis of variance (ANOVA) with replication was conducted to assess the variation in heavy metal concentrations across fish species (n = 13), seasons (pre-monsoon, monsoon, post-monsoon), and six heavy metals (Cd, Pb, Ni, Cr, Cu, Zn). The data matrix included 39 combinations (13 species × 3 seasons), tested across 6 metals. This approach allowed for the simultaneous evaluation of two categorical independent variables—fish/seasonal groups (rows) and heavy metal type (columns)—on the dependent variable (metal concentration). All statistical analyses were performed using Microsoft Excel 2016 for ANOVA computations.

**3. Results and Discussion**

Fig 2: MPI Values among Fish Species across various seasons.

The analysis of the Metal Pollution Index (MPI) across fish species and seasons revealed notable spatiotemporal variations that reflect the bioaccumulation dynamics of trace elements in the Vembanad backwater system. Fig 2 illustrates the MPI values recorded in different fish species during the Pre-Monsoon, Monsoon, and Post-Monsoon seasons.

During the Pre-Monsoon period, the highest MPI value was observed in *O. placidus* (0.2126), followed by *E. suratensis* (0.1085). This elevated index may be attributed to reduced water levels and minimal dilution during the dry season, which enhances metal concentration and bioavailability in the aquatic environment. Additionally, the feeding behavior and habitat range of these fish species likely contributed to their higher accumulation. *O. placidus*, being a bottom feeder, may have had greater contact with contaminated sediments where trace metals tend to accumulate. Similarly, *E. suratensis*, which exhibits omnivorous feeding habits, may accumulate metals through both sediment ingestion and water uptake.

In contrast, during the Monsoon season, MPI values declined significantly, with *O. placidus* recording a lower index of 0.0144 and *E. suratensis* showing a marked reduction. This trend may be attributed to increased rainfall and river discharge, which leads to dilution of pollutants, resuspension of sediments, and temporary reduction in metal bioavailability. Seasonal runoff can also introduce organic matter that binds with free metal ions, further decreasing their uptake by aquatic organisms. Similar observations have been reported by Yin *et al.* (2024), where MPI levels in fish declined during high-flow seasons due to hydrological dilution and dispersion of contaminants.

The Post-Monsoon period showed a partial rebound in MPI values. *E. suratensis* maintained a moderately high index (0.0883), whereas *O. placidus* exhibited a further decline. The sustained MPI value in *E. suratensis* could reflect its continued exposure to residual metal loads in sediment and water after the monsoon flush. It may also indicate species-specific metal retention capacities, where certain species either accumulate metals at a faster rate or exhibit slower elimination kinetics, as noted in studies by Asante *et al*. (2023) in similar tropical aquatic systems.

The persistent elevation of MPI in *E. suratensis* suggests that this species may serve as a potential bioindicator for trace metal pollution in estuarine systems like Vembanad Lake. Furthermore, the differences in MPI across seasons emphasize the influence of environmental factors such as water flow, sediment disturbance, and temperature on metal accumulation. Anthropogenic activities such as urban runoff, agricultural discharge, and effluents from nearby industrial zones may also be contributing to metal inputs in the lake system, especially during pre-monsoon when flow is limited and flushing is minimal.

Table 1: Target Hazard Quotient of Heavy Metals from Fish Consumption during Pre-Monsoon

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Season** | **Fish\*** | **Cd** | **Pb** | **Ni** | **Cr** | **Cu** | **Zn** |
| **Adult** | **Child** | **Adult** | **Child** | **Adult** | **Child** | **Adult** | **Child** | **Adult** | **Child** | **Adult** | **Child** |
| **Pre-Monsoon** | ***E. suratensis*** | 5.00E-05 | 4.90E-05 | 1.00E-05 | 1.10E-05 | 1.70E-06 | 1.80E-06 | 4.90E-05 | 5.20E-05 | 1.20E-07 | 1.30E-07 | 4.80E-07 | 5.10E-07 |
| ***M.cephalus*** | 5.00E-05 | 4.80E-05 | 6.00E-06 | 6.40E-06 | 1.60E-06 | 1.70E-06 | 9.20E-06 | 9.80E-06 | 1.10E-07 | 1.20E-07 | 3.70E-07 | 4.00E-07 |
| ***S. argus*** | 5.00E-05 | 4.80E-05 | 6.30E-06 | 6.70E-06 | 1.60E-06 | 1.70E-06 | 6.30E-06 | 6.70E-06 | 1.20E-07 | 1.20E-07 | 1.70E-07 | 1.90E-07 |
| ***E. areolatus*** | 4.50E-05 | 4.80E-05 | 5.90E-06 | 6.30E-06 | 1.60E-06 | 1.70E-06 | 6.00E-06 | 6.40E-06 | 1.20E-07 | 1.30E-07 | 3.00E-07 | 3.30E-07 |
| ***E. machnata*** | 4.50E-05 | 4.80E-05 | 7.00E-06 | 7.50E-06 | 1.60E-06 | 1.70E-06 | 7.00E-06 | 1.90E-05 | 1.30E-07 | 1.40E-07 | 2.70E-07 | 2.90E-07 |
| ***C.malabaricus*** | 5.00E-05 | 5.30E-05 | 8.80E-06 | 9.40E-06 | 1.60E-06 | 1.70E-06 | 1.00E-05 | 1.90E-05 | 1.40E-07 | 1.50E-07 | 2.80E-07 | 3.00E-07 |
| ***S. nigrofasciata*** | 4.60E-05 | 4.90E-05 | 5.10E-06 | 5.40E-06 | 1.50E-06 | 1.60E-06 | 6.00E-06 | 1.70E-05 | 1.10E-07 | 1.10E-07 | 2.50E-07 | 2.70E-07 |
| ***L. calcarifer*** | 2.40E-05 | 2.50E-05 | 4.60E-06 | 4.90E-06 | 1.40E-06 | 1.50E-06 | 5.30E-06 | 1.60E-05 | 7.20E-08 | 7.70E-08 | 2.10E-07 | 2.30E-07 |
| ***O. placidus*** | 3.20E-05 | 3.40E-05 | 5.20E-06 | 5.50E-06 | 1.70E-06 | 1.80E-06 | 5.50E-06 | 1.90E-05 | 1.30E-07 | 1.30E-07 | 2.60E-07 | 2.80E-07 |
| ***L. malabaricus*** | 3.10E-05 | 3.30E-05 | 6.40E-06 | 6.80E-06 | 1.50E-06 | 1.60E-06 | 6.90E-06 | 1.70E-05 | 9.80E-08 | 1.00E-07 | 2.10E-07 | 2.30E-07 |
| ***S. serrata*** | 8.50E-06 | 9.00E-06 | 2.50E-06 | 2.70E-06 | 4.50E-07 | 4.80E-07 | 2.80E-06 | 5.30E-06 | 4.00E-08 | 4.20E-08 | 3.40E-08 | 3.60E-08 |
| ***P.sanguinolentus*** | 7.90E-06 | 8.40E-06 | 2.80E-06 | 3.00E-06 | 2.90E-07 | 3.00E-07 | 3.40E-06 | 3.40E-06 | 4.00E-08 | 4.20E-08 | 3.00E-08 | 3.20E-08 |
| ***P. pelagicus*** | 7.40E-06 | 7.90E-06 | 2.00E-06 | 2.10E-06 | 6.10E-07 | 6.50E-07 | 2.80E-06 | 7.20E-06 | 3.60E-08 | 3.90E-08 | 3.40E-08 | 3.60E-08 |
| ***P. monodon*** | ND\* | ND | 4.00E-07 | 4.20E-07 | 1.10E-08 | 1.10E-08 | 3.80E-07 | 1.30E-07 | 5.70E-09 | 6.10E-09 | 3.90E-09 | 4.20E-09 |
| ***P. indicus*** | 1.40E-06 | 1.50E-06 | ND | ND | 3.20E-08 | 3.40E-08 | ND | 3.80E-07 | 8.00E-09 | 8.50E-09 | 1.70E-09 | 1.90E-09 |

\**Etroplus suratensis, Mughil cephalus, Scatophagus argus, Epinephelus areolatus, Elopes machnata, Carangoides malabaricus, Seriolina nigrofasciata, Lates calcarifer, Oreochomis placidus, Lutjanus malabaricus, Scylla serrata, Portunus sanguinolentus, Portunus pelagicus, Penaeus monodon, Penaeus indicus*, ND-Not Detected

Table 2: Target Hazard Quotient of Heavy Metals from Fish Consumption during Monsoon

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Season** | **Fish\*** | **Cd** | **Pb** | **Ni** | **Cr** | **Cu** | **Zn** |
| **Adult Child** | **Adult Child** | **Adult Child** | **Adult Child** | **Adult Child** | **Adult Child** |
| **Monsoon** | ***E. suratensis*** | 7.00E-06 | 7.50E-06 | 2.70E-06 | 2.90E-06 | 3.80E-07 | 4.00E-07 | 8.30E-06 | 8.80E-06 | 3.60E-08 | 3.80E-08 | 6.20E-08 | 6.70E-08 |
| ***M.cephalus*** | 9.10E-06 | 9.70E-06 | 1.70E-06 | 1.80E-06 | 2.70E-07 | 2.80E-07 | 1.90E-06 | 2.00E-06 | 2.90E-08 | 3.10E-08 | 5.40E-08 | 5.80E-08 |
| ***S. argus*** | 1.20E-05 | 1.20E-05 | 2.60E-06 | 2.80E-06 | 3.40E-07 | 3.60E-07 | 1.90E-06 | 2.00E-06 | 2.90E-08 | 3.10E-08 | 3.40E-08 | 3.70E-08 |
| ***E. areolatus*** | 1.10E-05 | 1.20E-05 | 1.30E-06 | 1.40E-06 | 3.40E-07 | 3.60E-07 | 1.40E-06 | 1.50E-06 | 2.20E-08 | 2.30E-08 | 4.70E-08 | 5.10E-08 |
| ***E. machnata*** | 6.30E-06 | 6.70E-06 | 2.60E-06 | 2.80E-06 | 2.90E-07 | 3.10E-07 | 2.30E-06 | 2.40E-06 | 3.40E-08 | 3.60E-08 | 4.10E-08 | 4.40E-08 |
| ***C.malabaricus*** | 3.90E-06 | 4.20E-06 | 1.60E-06 | 1.70E-06 | 3.00E-07 | 3.20E-07 | 1.40E-06 | 1.50E-06 | 2.60E-08 | 2.70E-08 | 6.40E-08 | 6.90E-08 |
| ***S. nigrofasciata*** | 8.80E-06 | 9.30E-06 | 1.90E-06 | 2.00E-06 | 3.20E-07 | 3.40E-07 | 9.00E-07 | 9.50E-07 | 1.80E-08 | 1.90E-08 | 7.70E-08 | 8.30E-08 |
| ***L. calcarifer*** | 1.10E-05 | 1.20E-05 | 2.20E-06 | 2.40E-06 | 2.90E-07 | 3.10E-07 | 8.70E-06 | 9.20E-06 | 3.20E-08 | 3.40E-08 | 5.60E-08 | 6.10E-08 |
| ***O. placidus*** | 9.40E-06 | 1.00E-05 | 2.90E-06 | 3.10E-06 | 3.00E-07 | 3.20E-07 | 3.60E-06 | 3.80E-06 | 2.80E-08 | 3.00E-08 | 3.80E-08 | 4.10E-08 |
| ***L. malabaricus*** | 9.20E-06 | 9.80E-06 | 2.20E-06 | 2.30E-06 | 1.50E-07 | 1.60E-07 | 9.50E-06 | 1.00E-05 | 1.70E-08 | 1.80E-08 | 2.90E-08 | 3.10E-08 |
| ***S. serrata*** | 4.90E-06 | 5.10E-06 | 8.10E-07 | 8.60E-07 | 1.40E-07 | 1.50E-07 | 2.40E-06 | 2.50E-06 | 5.70E-09 | 6.10E-09 | 7.40E-09 | 8.00E-09 |
| ***P.sanguinolentus*** | 7.60E-06 | 8.10E-06 | 2.20E-06 | 2.40E-06 | 1.50E-07 | 1.60E-07 | 2.10E-06 | 2.30E-06 | 1.60E-08 | 1.70E-08 | 7.40E-09 | 8.00E-09 |
| ***P. pelagicus*** | 8.10E-06 | 8.60E-06 | 1.70E-06 | 1.80E-06 | 2.30E-07 | 2.40E-07 | 1.20E-06 | 1.30E-06 | 2.10E-08 | 2.20E-08 | 7.60E-09 | 8.20E-09 |
| ***P. monodon*** | 1.80E-06 | 1.90E-06 | 6.20E-07 | 6.60E-07 | 2.20E-08 | 2.40E-08 | 5.70E-07 | 6.10E-07 | 6.40E-09 | 6.80E-09 | 6.10E-09 | 6.60E-09 |
| ***P. indicus*** | 1.80E-06 | 1.90E-06 | 6.80E-07 | 7.20E-07 | 4.70E-08 | 5.00E-08 | 6.10E-07 | 6.50E-07 | ND\* | ND | 1.10E-08 | 1.10E-08 |

\**Etroplus suratensis, Mughil cephalus, Scatophagus argus, Epinephelus areolatus, Elopes machnata, Carangoides malabaricus, Seriolina nigrofasciata, Lates calcarifer, Oreochomis placidus, Lutjanus malabaricus, Scylla serrata, Portunus sanguinolentus, Portunus pelagicus, Penaeus monodon, Penaeus indicus*, ND-Not Detected

Table 3: Target Hazard Quotient of Heavy Metals from Fish Consumption during Post-Monsoon

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Season** | **Fish\*** | **Cd** | **Pb** | **Ni** | **Cr** | **Cu** | **Zn** |
| **Adult Child** | **Adult Child** | **Adult Child** | **Adult Child** | **Adult Child** | **Adult Child** |
| **Post Monsoon** | ***E. suratensis*** | 3.90E-05 | 4.10E-05 | 7.80E-06 | 8.30E-06 | 1.30E-06 | 1.40E-06 | 3.90E-05 | 4.10E-05 | 9.30E-08 | 9.90E-08 | 4.20E-07 | 4.50E-07 |
| ***M.cephalus*** | 3.10E-05 | 3.30E-05 | 3.80E-06 | 4.00E-06 | 1.10E-06 | 1.20E-06 | 7.10E-06 | 7.50E-06 | 8.40E-08 | 9.00E-08 | 3.50E-07 | 3.80E-07 |
| ***S. argus*** | 3.90E-05 | 4.20E-05 | 4.40E-06 | 4.70E-06 | 1.10E-06 | 1.20E-06 | 4.30E-06 | 4.50E-06 | 8.50E-08 | 9.00E-08 | 1.50E-07 | 1.60E-07 |
| ***E. areolatus*** | 3.40E-05 | 3.60E-05 | 3.70E-06 | 4.00E-06 | 1.10E-06 | 1.20E-06 | 4.50E-06 | 4.80E-06 | 9.90E-08 | 1.00E-07 | 2.50E-07 | 2.70E-07 |
| ***E. machnata*** | 3.30E-05 | 3.50E-05 | 5.90E-06 | 6.20E-06 | 1.30E-06 | 1.40E-06 | 3.70E-06 | 4.00E-06 | 1.10E-07 | 1.20E-07 | 2.40E-07 | 2.60E-07 |
| ***C.malabaricus*** | 1.70E-05 | 1.80E-05 | 1.70E-06 | 1.80E-06 | 1.30E-06 | 1.40E-06 | 1.90E-06 | 2.00E-06 | 9.30E-08 | 9.90E-08 | 4.30E-07 | 4.60E-07 |
| ***S. nigrofasciata*** | 2.90E-05 | 3.10E-05 | 2.80E-06 | 3.00E-06 | 9.90E-07 | 1.10E-06 | 1.90E-06 | 2.00E-06 | 7.60E-08 | 8.10E-08 | 4.50E-07 | 4.90E-07 |
| ***L. calcarifer*** | 3.40E-05 | 3.60E-05 | 4.40E-06 | 4.60E-06 | 8.40E-07 | 8.90E-07 | 3.80E-05 | 4.00E-05 | 1.00E-07 | 1.10E-07 | 3.70E-07 | 4.00E-07 |
| ***O. placidus*** | 3.40E-05 | 3.60E-05 | 7.00E-06 | 7.40E-06 | 1.40E-06 | 1.40E-06 | 1.50E-05 | 1.60E-05 | 7.70E-08 | 8.10E-08 | 1.40E-07 | 1.50E-07 |
| ***C. malabaricus*** | 2.10E-05 | 2.30E-05 | 7.20E-06 | 7.70E-06 | 4.20E-07 | 4.50E-07 | 4.00E-05 | 4.20E-05 | 7.30E-08 | 7.70E-08 | 1.10E-07 | 1.20E-07 |
| ***S. serrata*** | 1.20E-05 | 1.30E-05 | 3.20E-06 | 3.40E-06 | 3.70E-07 | 3.90E-07 | 4.10E-06 | 4.40E-06 | 3.40E-08 | 3.60E-08 | 2.90E-08 | 3.10E-08 |
| ***P.sanguinolentus*** | 1.00E-05 | 1.10E-05 | 2.80E-06 | 3.00E-06 | 4.20E-07 | 4.50E-07 | 3.00E-06 | 3.20E-06 | 3.30E-08 | 3.50E-08 | 2.80E-08 | 3.10E-08 |
| ***P. pelagicus*** | 1.40E-05 | 1.40E-05 | 2.30E-06 | 2.40E-06 | 4.50E-07 | 4.80E-07 | 3.60E-06 | 3.80E-06 | 3.10E-08 | 3.30E-08 | 3.00E-08 | 3.30E-08 |
| ***P. monodon*** | ND\* | ND | 9.40E-07 | 1.00E-06 | 1.30E-07 | 1.40E-07 | ND | ND | 7.50E-09 | 7.90E-09 | 1.80E-08 | 1.90E-08 |
| ***P. indicus*** | 1.90E-06 | 2.00E-06 | 1.20E-06 | 1.30E-06 | ND | ND | ND | ND | ND | ND | 2.30E-08 | 2.40E-08 |

\**Etroplus suratensis, Mughil cephalus, Scatophagus argus, Epinephelus areolatus, Elopes machnata, Carangoides malabaricus, Seriolina nigrofasciata, Lates calcarifer, Oreochomis placidus, Lutjanus malabaricus, Scylla serrata, Portunus sanguinolentus, Portunus pelagicus, Penaeus monodon, Penaeus indicus*, ND-Not Detected

Tables 1, 2, and 3 present the Target Hazard Quotient (THQ) values of six trace metals (Cadmium, Lead, Nickel, Chromium, Copper, and Zinc) in selected commercially important fish species across three seasons: pre-monsoon, monsoon, and post-monsoon. The THQ values for all fish species and all metals remained consistently below the safe threshold value of 1, indicating that the consumption of these fish does not pose any significant non-carcinogenic health risk to adults or children. This finding aligns with the guidelines of the United States Environmental Protection Agency (USEPA), which considers THQ values <1 to represent negligible risk levels (USEPA, 2000).

Seasonal differences and species-specific trends in THQ values were observed.During the pre-monsoon season, *C. malabaricus* exhibited the highest THQ values among the species analyzed. This could be attributed to its benthic feeding behavior, which increases exposure to metal-rich sediments during low water conditions typically seen in pre-monsoon periods. Sediment resuspension and reduced dilution due to lower water volumes can increase trace metal bioavailability during this season. Despite this, the THQ values remained well within the safe limit, suggesting no immediate health concern (Pal & Maiti, 2018). In contrast, *Scylla serrata* consistently exhibited the lowest THQ values across all metals and seasons, possibly due to its intermittent feeding and scavenging behavior, or lower metal accumulation efficiency.

During the monsoon season, although water levels rise and dilution is typically higher, runoff from agricultural fields and urban areas may introduce additional metal loads into the estuarine system. *C. malabaricus* again recorded higher THQ values, though still under the risk threshold, indicating its persistent tendency for trace metal uptake, potentially due to its trophic position and feeding preference. This pattern aligns with earlier findings from estuarine systems, where predatory and bottom-dwelling fish species accumulate more metals (Tabezar *et al*., 2023).In the post-monsoon period, *Mugil cephalus* exhibited the highest THQ values, particularly for Cadmium and Lead. This could be linked to its detritivorous feeding habit and movement across pollutant-accumulating zones, such as shallow estuarine fringes or areas impacted by urban discharge and aquaculture waste. *Penaeus monodon* recorded the lowest THQ values in this season, which may reflect its shorter lifespan, lower trophic level, and possibly more efficient excretion mechanisms for trace elements (Saha *et al.,* 2016).

Fig 3: CR Values among Fish Species During Pre-Monsoon Season.

*C. malabaricus* exhibits the highest carcinogenic risk (CR) values among the studied fish species during the pre-monsoon season, with values of 0.000313203 for adults and 0.000332466 for children. Although these values are comparatively higher, they still fall within the acceptable risk range (10⁻⁶ < CR < 10⁻⁴) as per USEPA guidelines, indicating no significant carcinogenic health risk from consuming this species (Lin *et al*., 2024).Conversely, *Penaeus indicus* displays the lowest CR values among the species (Adults: 9.10926 × 10⁻⁶; Children: 9.6695 × 10⁻⁶), suggesting a comparatively lower risk, possibly due to reduced accumulation of carcinogenic elements such as Cd, Pb, Ni, and Cr or habitation in less contaminated environments.The variation in CR values across fish species likely reflects differences in feeding habits, habitat types, and exposure to metal-contaminated environments. Despite these differences, it is important to note that none of the species exceeded the USEPA's acceptable carcinogenic risk threshold, indicating that all analyzed fish species are safe for human consumption with respect to carcinogenic risk. Nevertheless, continued monitoring of trace element accumulation and promoting the consumption of species with lower CR values can help further minimize potential long-term health effects in populations such as children and frequent fish *consumers.*

Fig 4: CR Values among Fish Species During Monsoon Season.

During the monsoon season, *S. argus* exhibited the highest carcinogenic risk (CR) values among the studied fish species, with values of 7.41 × 10⁻⁵ for adults and 7.87 × 10⁻⁵ for children. These values, although relatively higher compared to other species, remain within the acceptable risk range of 10⁻⁶ to 10⁻⁴ as defined by USEPA, indicating no significant carcinogenic risk from the consumption of *S. argus*. The elevated CR values may be attributed to the bioaccumulation of trace carcinogenic elements such as Cd, Pb, Ni, and Cr, which are influenced by species-specific factors like feeding habits, habitat preferences, and metabolic activity (Tabezar *et al.,* 2023). In contrast, *Penaeus monodon* and *Penaeus indicus* recorded the lowest CR values during the same season, suggesting comparatively lower exposure to carcinogenic metals, possibly due to their presence in less contaminated zones or lower trophic level bioaccumulation (Lin *et al*., 2023). Overall, while inter-species variability in carcinogenic risk was observed, all calculated CR values remained within the permissible range, confirming that the consumption of all analyzed fish species is safe from a carcinogenic risk standpoint. Nonetheless, continued monitoring of trace element accumulation and its implications for human health remains important, especially for species showing relatively elevated CR values over time.

Fig 5: CR Values among Fish Species during Post Monsoon Season.

During the post-monsoon season*, L. calcarifer* exhibited the highest carcinogenic risk (CR) values among the analyzed fish species for both adults (5.72 × 10⁻⁵) and children (6.07 × 10⁻⁵), followed by other species. However, all CR values remained within the acceptable risk range of 10⁻⁶ to 10⁻⁴ as per USEPA guidelines, indicating that consumption of these species does not pose significant carcinogenic health risks (Ray & Vashishth, 2024).

The relatively higher CR values observed in *L. calcarifer* may be attributed to the bioaccumulation of carcinogenic elements such as Cd, Pb, Ni, and Cr in its tissues. In contrast, *Scylla serrata* exhibited the lowest CR values for both adults (7.83 × 10⁻⁶) and children (8.31 × 10⁻⁶), indicating a lower relative potential risk.

Table 4: Summary of One-way ANOVA Testing the Variation of Heavy Metal Concentrations Among Fish Species and Across Seasons

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Source | SS | DF  | MS | F | P-value | F crit |
| Rows | 817.4 | 38 | 21.5 | 79.4 | 2.66E-97 | 1.4 |
| Columns | 3.5 | 5 | 0.7 | 2.6 | 0.02 | 2.2 |
| Error | 51.4 | 190 | 0.2 |  |  |  |
|  |  |  |  |   |   |  |
| Total | 872.4 | 233 |   |   |   |   |

\*SS- Sum of Squares, DF- Degree of Freedom, MS- Meand of Squares

The results of one-way ANOVA revealed statistically significant differences in heavy metal concentrations among the different fish species sampled from the Vembanad Lake (F = 79.46, p = 0.001). This strong variation suggests that bioaccumulation is species-dependent, influenced by several biological and ecological factors. For instance, fish with higher trophic levels or those that are predatory may accumulate greater metal concentrations due to biomagnification along the food chain (Ilyas *et al.,* 2023). Moreover, benthic species—which are more closely associated with sediment—are more likely to accumulate sediment-bound contaminants such as cadmium, lead, and arsenic due to their feeding habits and longer exposure to bottom layers of water where metals tend to settle (Keshavarzi *et al*., 2018).

The variation also reflects species-specific metabolic activities, including differences in metal uptake efficiency, detoxification capacity, and storage mechanisms. For example, species with higher lipid content or slower metabolic rates may retain metals longer. These findings are consistent with prior studies conducted in Taihu Lake, China, where species showed significantly different metal loads (Rajeshkumar & Li, 2018).

The ANOVA also indicated significant variation in heavy metal concentrations across seasons and metal types (F = 2.62, p = 0.026), highlighting the influence of temporal environmental changes. This seasonal fluctuation may be attributed to changes in hydrology, runoff intensity, and anthropogenic inputs. For instance, monsoon runoff can mobilize contaminants from agricultural fields and urban landscapes, increasing metal concentrations in the water column. Conversely, post-monsoon dilution or sediment resuspension could affect metal availability in the environment.

Among the metals analyzed, elements such as cadmium (Cd) and lead (Pb) exhibited elevated concentrations during the pre-monsoon period, possibly due to reduced dilution, lower water flow, and concentration effects under drier conditions. In contrast, elements like zinc (Zn) and manganese (Mn) showed relatively higher levels during the monsoon, potentially linked to leaching from soils and increased riverine inputs. These seasonal trends have also been observed in similar studies from the Hakaluki Haor (Bhuyan *et al.,* 2022).The potential sources of these trace elements include urban sewage discharge, industrial effluents, aquaculture runoff, and use of fertilizers and pesticides in upstream catchments. Vembanad Lake, being a densely populated and economically active wetland, receives multiple point and non-point sources of metal pollution, especially in the northern and central zones.

**4. Conclusion**

This study highlights significant spatiotemporal variations in the bioaccumulation of trace metals among commercially important fish species in the Vembanad backwaters. While species such as *C. malabaricus*, *E. suratensis*, and *O. placidus* exhibited elevated Metal Pollution Index (MPI), Target Hazard Quotient (THQ), and Carcinogenic Risk (CR) values, all levels remained within the acceptable safety limits set by USEPA, indicating minimal non-carcinogenic and carcinogenic health risks from fish consumption. Seasonal fluctuations in metal accumulation were influenced by hydrological changes, feeding behavior, and habitat preferences. The findings emphasize the need for regular biomonitoring and management of pollution sources to protect both ecological integrity and public health. Furthermore, species with consistently higher metal loads may serve as effective bioindicators for environmental monitoring in estuarine ecosystems.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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