*Original Research Article*

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 (Nair *et al.,* 2019). Once introduced, heavy metals can persist in sediments and biological tissues, leading to prolonged exposure for both aquatic organisms and their predators, including humans (Gulati *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 (Reference), 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 (Kumar *et al.,* 2020). The tropical monsoon climate with an average annual rainfall of ~3,000 mm significantly affects the region’s hydrology and salinity regime (Indian Meteorological Department, 2023).

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 (Menon *et al.,* 2022; Prasad & Nandan, 2016).

**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. 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).

**2.3 Health risk assessment**

**2.3.1 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.

**2.3.2 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.

**2.4 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.

**2.5 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**

Chart 1: MPI Values among Fish Species across various seasons.

The analysis of the Metal Pollution Index (MPI) across various fish species and seasons reveals significant variations. Chart 1,2 illustrates how MPI values fluctuate among species across Pre-Monsoon, Monsoon, and Post-Monsoon seasons. During the Pre-Monsoon season, E. suratensis exhibited the highest MPI value at 0.1085, followed by O. placidus at 0.2126, indicating notable metal presence. In the Monsoon season, O. placidus again had a high index at 0.0144, while E. suratensis showed a significant decrease, likely due to environmental factors affecting metal accumulation. In the post-monsoon season, E. suratensis maintained a notable index at 0.0883, while O. placidus showed a decline. These variations suggest that environmental factors significantly influence metal accumulation in fish. Higher MPI values in E. suratensis and O. placidus could be due to their feeding habits, habitat preferences, and metabolic processes (Yin *et al.,* 2024). Decreases in MPI during the Monsoon might be due to increased water flow, pollutant dilution, and changes in metal availability. Persistent elevated MPI values in some species suggest potential resistance or slow metal elimination.

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

Table. 1, 2, and 3 present the Target Hazard Quotient (THQ) values for Heavy Metals (HM) (Cd, Pb, Ni, Cr, Cu, Zn) in various fish species during the pre-monsoon, monsoon, and post-monsoon seasons. During the pre-monsoon season, C. malabaricus shows the highest THQ values for both adults and children, indicating significant health risks associated with consuming this species due to elevated heavy metal accumulation (Pal & Maiti, 2018). Conversely, S. serrata exhibits the lowest THQ values, suggesting lower health risks from heavy metal exposure compared to other species. During the monsoon season C. malabaricus continues to show the highest THQ values, indicating ongoing health risks associated with its consumption due to elevated heavy metal levels (Tabezar *et al.,* 2023). In contrast, S. serrata maintains the lowest THQ values among the sampled species, indicating reduced health risks during this season. In the post-monsoon season, M. cephalus displays the highest THQ values, indicating potential health risks from consuming this species due to heavy metal bioaccumulation. P. monodon exhibits the lowest THQ values, suggesting reduced health risks associated with its consumption, possibly due to lower heavy metal accumulation or habitat preferences with lower contamination levels(Saha *et al.,* 2016). These findings underscore the variability in heavy metal accumulation among fish species across different seasons, influencing the health risks associated with their consumption. Factors such as habitat, feeding habits, and metabolic processes contribute to these variations.

Chart 2: CR Values among Fish Species During Pre-Monsoon Season.

*C. malabaricus* exhibits the highest carcinogenic risk values among fish species during the pre-monsoon season for both adults (0.000313203) and children (0.000332466), indicating significant carcinogen exposure risk. This risk may result from bioaccumulation of carcinogenic elements like Cd, Pb, Ni, and Cr in their tissues or from contaminated habitats (Lin *et al.,*2024). Conversely, *P. indicus* shows the lowest carcinogenic risk values (Adults: 9.10926E-06, Children: 9.6695E-06), suggesting a lower risk due to lesser accumulation of these elements or cleaner habitats. The variability in carcinogenic risk among species highlights the importance of monitoring fish consumption to mitigate cancer risks. Choosing fish with lower carcinogenic risk values can help reduce potential health hazards.

Chart 3: CR Values among Fish Species During Monsoon Season.

S. argus exhibits the highest carcinogenic risk values among fish species during the monsoon season for both adults (7.41338E-05) and children (7.86932E-05), indicating potential health risks from its consumption. Factors such as bioaccumulation of carcinogenic substances like Cd, Pb, Ni, and Cr, habitat preferences, and dietary habits may contribute to these elevated risk values (Tabezar *et al.,* 2023). Conversely, P. monodon and P. indicus show the lowest carcinogenic risk values, suggesting a relatively lower cancer risk associated with their consumption during the monsoon season (Lin *et al.,* 2023 ). This may result from lower accumulation of carcinogens in their tissues or their presence in less contaminated environments.

Overall, the study reveals significant variability in carcinogenic risk values among different fish species during the monsoon season, highlighting the importance of monitoring and regulating fish consumption to mitigate health risks. Consumers may reduce potential health risks by choosing fish species with lower carcinogenic risk values.

Chart 4: CR Values among Fish Species during Post Monsoon Season.

L. calcarifer shows the highest carcinogenic risk values among fish species during the post-monsoon season for both adults (5.7229E-05) and children (6.07487E-05), indicating potential health risks from consuming this species (Ray & Vashishth, 2024). Factors such as bioaccumulation of Cd, Pb, Ni, and Cr in their tissues contribute to these elevated risks. In contrast, S. serrata exhibits the lowest carcinogenic risk values (adults: 7.82911E-05, children: 8.31062E-05), suggesting a lower health risk associated with consuming this species. These findings highlight variability in carcinogenic risk among fish species due to differences in contaminant accumulation, emphasizing the need for monitoring and regulating consumption to mitigate health risks.

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 one-way ANOVA results revealed statistically significant variation in heavy metal concentrations among the different fish species sampled (F = 79.46, p =0.001). This indicates that the accumulation levels of metals varied considerably between species, possibly due to differences in trophic level, habitat preference, and metabolic activity (Ilyas *et al.,* 2023). Additionally, a significant variation was observed across the seasons and/or elements (F = 2.62, p = 0.026), suggesting that environmental factors such as seasonal changes, water quality, and exposure levels also influence the bioaccumulation patterns of heavy metals in fish tissues(Bhuyain *et al.,*2022).

**4. Conclusion**

This study presents a detailed evaluation of heavy metal bioaccumulation in key fish species from the Vembanad Backwaters, integrating multivariate statistical analyses and risk assessment indices. The significant variation in metal concentrations across seasons and species, as confirmed by ANOVA, highlights the dynamic nature of contamination patterns in this ecologically sensitive region.

The application of Metal Pollution Index (MPI), Target Hazard Quotient (THQ), and Carcinogenic Risk (CR) metrics revealed potential human health risks associated with the consumption of certain fish species, particularly from areas exhibiting elevated contamination levels. These findings emphasize the need for continuous monitoring and regulatory intervention to safeguard public health.

Aligned with the Sustainable Development Goals—particularly SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 14 (Life below Water)—the outcomes contribute to the growing body of evidence supporting ecosystem-based fisheries management and risk-informed policymaking. This research provides a scientific basis for establishing region-specific fish consumption advisories and pollution control measures, thereby enhancing the environmental resilience and food safety of the Vembanad ecosystem.

Please summarize the conclusion into a few comprehensive meaningful sentences

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