Enviro Mind Solutions | Publishing
Journal of Environmental Science, Health & Sustainability

Article

Heavy metals in estuarine finfish and crustaceans and their associated health risks in the western Hooghly estuary, Indian Sundarbans

Debargha Chakraborty[1*], Dipanwita Das[2], A.C. Samal[1], S.C. Santra[1]

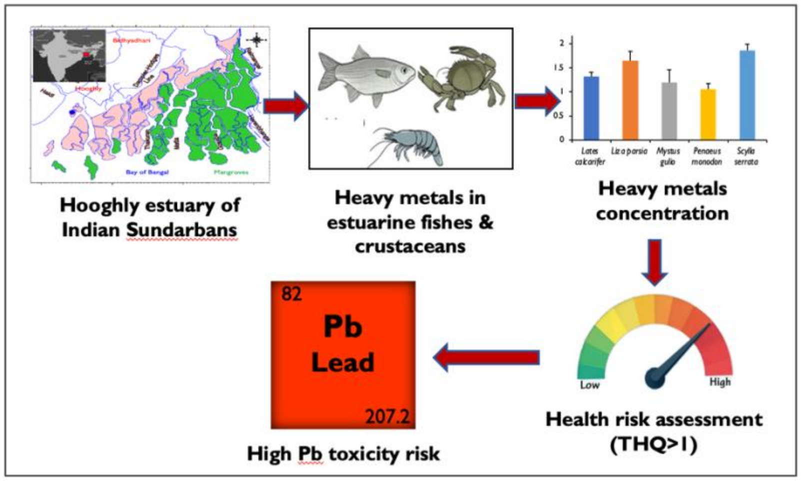
[1]Department of Environmental Science, University of Kalyani, Nadia-741235, West Bengal, India
[2]Amity Institute of Environmental Sciences, Amity University, Kolkata-700135, West Bengal, India

How to cite:

Chakraborty, D., Das, D., Samal, A.C., Santra, S.C., 2025. Heavy metals in estuarine finfish and crustaceans and their associated health risks in the western Hooghly estuary, Indian Sundarbans. Journal of Environmental Science, Health & Sustainability, 1, 1, 65–76. https://doi.org/10.63697/jeshs.2025.012

Article info:

Received: 21 February 2025
Revised: 11 April 2025
Accepted: 18 April 2025



Highlights

- Heavy metal concentrations were measured in finfish and crustaceans sampled from Indian Sundarbans.
- Cu, Fe, and Zn were the most abundant heavy metals in edible muscle tissues.
- Pb concentrations in *L. calcarifer*, *L. parsia*, and *M. gulio* exceeded the THQ threshold of 1.
- Pb toxicity risk could be present in individuals if fish is consumed for seven consecutive days.

Abstract

Mangroves are highly productive ecosystems that provide important social, economic, and environmental benefits. However, they are increasingly exposed to various contaminants, including heavy metals. The presence of heavy metals in such ecosystems can pose a serious threat to marine and aquatic life, including fish and crustaceans. Fish (*Lates calcarifer*, *Liza parsia* and *Mystus gulio*) and crustaceans (*Penaeus monodon* and *Scylla serrata*) were collected from local fishermen in Nayachar, West Bengal, in the Indian Sundarbans. Fe, Zn, Cu, Ni, Pb, Cr, Cd and As, concentrations were measured in the edible muscle tissues of these species using Atomic Absorption Spectroscopy (AAS). The concentration of heavy metals in the edible muscle tissues were observed in the following descending order: Fe > Zn > Cu > Pb > Ni > Cr > Cd > As. Results show a potential health risk from Pb both in terms of target hazard quotient (THQ) and provisional tolerable weekly intake (PTWI) for *Lates calcarifer*, *Liza parsia* and *Mystus gulio*. However, the consumption of these species didn't pose a serious health risk with respect to other measured heavy metals as both THQ and PTWI were within the established and/or recommended limits. Long-term exposure to these fish species could pose a significant toxicity risk to individuals who consume them regularly. Regular monitoring, identification of contamination sources and treatment are crucial to reduce any potential health risks to the local population and other consumers, as the Sundarbans is a major fish producing area in the state of West Bengal, India.

Keywords: Heavy Metals; Target Hazard Quotient; Provisional Tolerable Weekly Intake; Health Risk; Sundarbans.

Correspondence: debarghach@gmail.com (DC)

Handling Editor: Dr. Mohammad Mahmudur Rahman with assistance from Dr. Enfeng Liu.

1. Introduction

Mangrove ecosystems offer a wide range of social, economic, and ecological benefits (Su et al., 2021). However, they are subjected to overexploitation and mismanagement through practices like land reclamation, urban development, and recreational use (Eong, 1995; Akram et al., 2023). As a result, these ecosystems have been cleared for urban, industrial, and agricultural development (Moschetto et al., 2021). These ecosystems are also highly vulnerable to contamination, particularly from heavy metals and industrial chemicals, due to increasing anthropogenic activities, including nearby urban and industrial activities (MacFarlane, 2002; Nath et al., 2014). Major sources of heavy metal pollution in mangrove environments include urban and agricultural runoff, industrial effluents, boating, chemical spills, sewage discharges, domestic waste leachate, and mining activities (Peters et al., 1997; Proshad et al., 2024).

Heavy metals are common environmental contaminants that pose a significant risk to the health and survival of various aquatic and marine organisms, including fish and crustaceans (Lorenzon et al., 2001; Zaynab et al., 2022; Santhosh et al., 2024). They are particularly hazardous due to their toxicity, persistence, and capacity to bioaccumulate in the food chain (MacFarlane and Burchett, 2000). Heavy metals can enter finfish and shellfish through different routes, such as through food or non-food particles, gills, and water consumption (Mitra et al., 2012). Aquatic organisms absorb heavy metals at concentrations much higher than those in their surrounding environment (Sharma et al., 2025). As a result, measuring heavy metal concentrations in these organisms serves a dual purpose, such as assessing environmental contamination and evaluating potential health risks associated with their consumption.

The accumulation of heavy metals in aquatic organisms, especially seafood, is a potential health concern, as it provides essential nutrients such as the source of protein, low saturated fat, and omega fatty acids (Dural et al., 2007; Zaynab et al., 2022; Younis et al., 2024). Fish from contaminated aquatic environments may pose a threat to public health in the long run (Abera and Adimas, 2024). The World Health Organization (WHO) has set standards for the safe concentration of heavy metals in seafood (WHO, 2006). However, several studies have found high concentrations of heavy metals in seafood (Connelly et al., 2019; Zaynab et al., 2022; Younis et al., 2024). Therefore, it is crucial to assess the concentration of heavy metals in finfish, shellfish and crustaceans to evaluate the potential health risks associate with their consumption (Cid Pérez et al., 2001;Younis et al., 2024).

The Sundarbans, the world's largest river delta, is formed at the confluence of the Ganges, the Brahmaputra and the Meghna. The Sundarbans is home to a variety of mangrove species, where the intricate network of roots provides a unique habitat for a wide array of aquatic organisms including juveniles (Islam and Bhuiyan, 2018; Samanta et al., 2021). Besides, mangrove sediments, mostly composed of fine particles, act as a sink for a variety of heavy metals (Praveena et al., 2010; Marchand et al., 2011; Chaudhuri et al., 2014). However, the excessive input of heavy metals into these environments can have harmful effects on the organisms living there due to their high bioavailability (Pandiyan et al., 2021). Thus, the consumption of fish and seafood caught from such environments could pose significant health risks to individuals.

Adding to the earlier studies on the Indian Sundarbans (Saha et al., 2006; Mitra and Ghosh, 2014; Bhattacharya et al., 2016; Bepari et al., 2021), this study aims to provide insights into Fe, Zn, Cu, Ni, Pb, Cr, Cd and As accumulation in selected finfish, shellfish and crustaceans through the estimation of both target hazard quotient (THQ) and provisional tolerable weekly intake (PTWI) values. THQ assesses the risk level for populations exposed to heavy metals through the consumption of fish and crustaceans (US EPA, 2000). On the other hand, PTWI indicates the tolerable weekly exposure of heavy metals through consumptions of food (Traven et al., 2023).

Therefore, locally available finfish, shellfish and crustaceans from Nayachar, in the Indian Sundarbans, one of the vulnerable locations in terms of heavy contamination, were collected to draw attention of healthcare professionals and the general public to the potential health risks associated with the consumption of contaminated seafood.

2. Materials and methods

2.1 Sampling location

The sampling site is located at the Nayachar island of Indian Sundarbans. Nayachar island is a recently formed landform due to ongoing siltation by the Hooghly River, near its confluence with the Haldi River (**Fig. 1**). The study area is also located near the Haldia port and industrial complex, which includes petrochemical processing, oil refineries and manufacturing. These industries are potential sources of heavy metal pollution (Bhattacharya et al., 2016), making the area most vulnerable to various aquatic species for their survival.

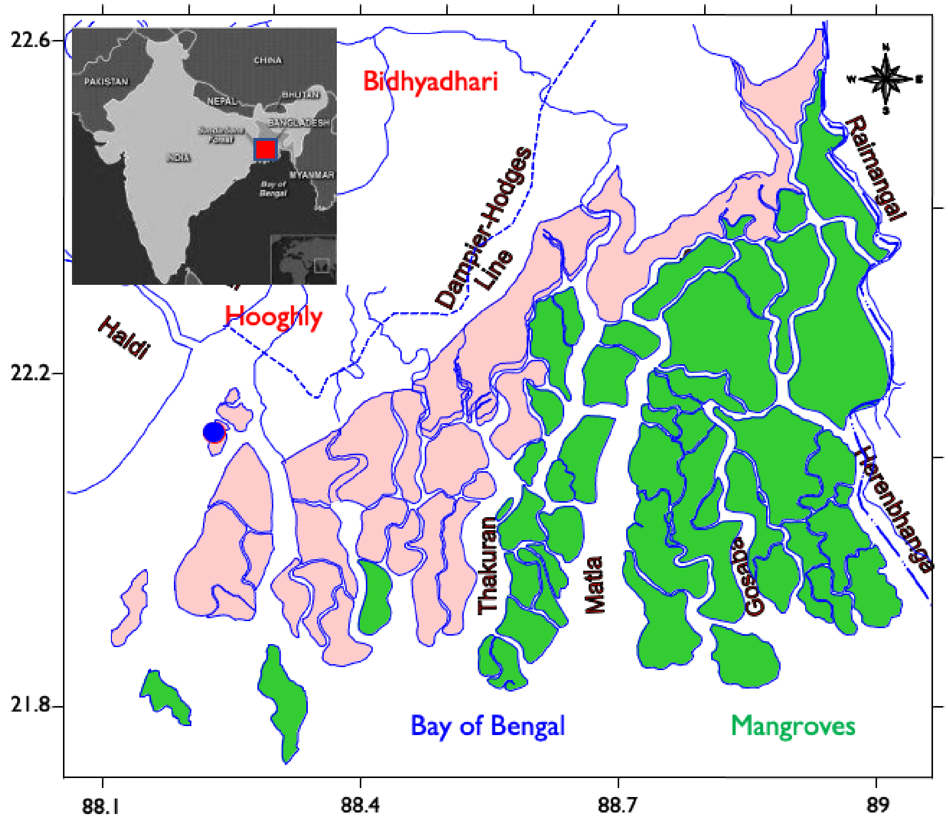


Figure 1. Map of Sundarbans showing the sampling location (blue circle). Inset map shows the location of Sundarbans in India.

2.2 Sample collection and preservation

Fish, such as *Lates calcarifer* (Bhetki), *Liza parsia* (Parse) and *Mystus gulio* (Nuna Tangra), and crustaceans, such as *Penaeus monodon* (Bagda) and *Scylla serrata* (Mud crab) were collected from the local fishermen. Upon collection the samples were stored in ice box (at 4°C) and transported to the laboratory for analysis. Three samples of each species were collected.

2.3 Sample processing and analysis

The tissue samples were digested following the procedure detailed in Kalay et al. (1999). Fe, Zn, Cu, Ni, Pb, Cr, Cd and As, were analyzed using Atomic Absorption Spectroscopy (AAS) techniques (Perkin Elmer AAnalyst 400) at the Department of Environmental Science, University of Kalyani.

2.4 Quality control

Standard Reference Materials (SRM) from the National Institute of Standards and Technology (NIST), USA, were analyzed using the same procedure at the beginning, during, and at the end of the measurements to maintain accuracy. Bovine liver (1577c) was used to ascertain and verify the efficiency of the metal estimation procedure. The recovery of all the measured elements were greater than 92% (**Table 1**).

2.5 Estimation of target hazard quotient

Target hazard quotient (THQ) assesses the risk level for populations exposed to heavy metals through the consumption of fish and crustaceans. It is based on the ratio between the exposure and reference dose (RfD) and is used to evaluate the likelihood of non-carcinogenic effects. A ratio below 1 indicates no significant exposure risk of heavy metals over the life, whereas a ratio equal to or exceeding the RfD suggests potential health concerns including the adverse effect for the exposed population. This approach is outlined in the U.S. Environmental Protection Agency (US EPA) Region III risk-based concentration table (US EPA, 2000).

Table 1. Heavy metal concentrations in Bovine liver (1577c) from the National Institute of Standards and Technology (NIST). The data are presented as means ± standard errors (in mg/kg dry wt.).

Heavy metals	Reference value	Measured value	Recovery (%)
Fe	197.9±0.65	182.6±2.56	92
Zn	181.1±1	170.5±5.62	94
Cu	275.2±4.6	263.8±9.41	95
Ni	44.5±9.2	43.1±7.52	96
Pb	62.8±1	59.4±6.77	94
Cr	53±14	51.3±9.31	98
Cd	97.0±1.4	94.8±5.62	97
As	19.6±1.4	18.9±1.85	96

THQ value is represented by the following equation:

$$THQ = \frac{EF \times ED \times FIR \times C}{RFD \times WAB \times TA} X\, 10^{-3}$$

Where, EF is the exposure frequency (365 days/year), ED is the exposure duration (70 years, equivalent to the average lifetime), FIR is the food ingestion rate (fish: 36 g/person/day; and crustaceans: 5.42 g/person/day), C is the metal concentration in seafood (mg/kg), RfD is the oral reference dose (Fe = 7×10^{-1} mg/kg/day, Zn = 3×10^{-1} mg/kg/day, Cu = 4×10^{-2} mg/kg/day, Ni = 2×10^{-2} mg/kg/day, Pb = 4×10^{-3} mg/kg/day, Cr = 3×10^{-3} mg/kg/day, Cd = 1×10^{-3} mg/kg/day, and As = 3×10^{-4} mg/kg/day), WAB is the average body weight (60 kg) and TA is the average exposure time for non-carcinogens (365 days/year × ED).

3. Results

3.1 Lates calcarifer

Lates calcarifer, commonly known as giant sea perch or Asian seabass, is an economically important fish found in the tropical and subtropical regions of the Asia–Pacific region (Ahmadi et al., 2022). This species belongs to the Centropomidae family and is widely distributed across the Indo-West Pacific region. Seabass are opportunistic predators with about 20% of their diet being planktons and the rest consisting of small shrimp, and fish. The mean concentrations (mg/kg dry wt.) of Fe, Zn, Cu, Ni, Pb, Cr, Cd and As in the edible muscle tissue were 318.3±28.65, 41.65±3.96, 28.56±3.58, 10.34±2.03, 12.66±1.65, 1.32±0.09, 1.25±0.23 and 0.21±0.03, respectively (**Fig. 2**).

3.2 Liza parsia

Liza parsia is a brackish water mullet widely distributed in the coastal region of Bay of Bengal, Southeast Asia, the Mediterranean, Eastern Europe and in many parts of Central and South America (Dayal et al., 2019). The fish is acclaimed for its taste and high nutritive value (Joarddar and Hossain, 2008). *Liza parsia* is mostly an herbivorous fish feeding on algae, plant parts, protozoans and crustaceans (Joarddar and Hossain, 2008). The mean concentrations (mg/kg dry wt.) of Fe, Zn, Cu, Ni, Pb, Cr, Cd and As in the edible muscle tissue were 312.78±36.58, 48.76±5.23, 32.68±3.56, 7.25±0.89, 10.25±1.23, 1.65±0.19, 1.12±0.20 and 0.35±0.04, respectively (**Fig. 2**).

3.3 Mystus gulio

Mystus gulio, known as the estuarine catfish, is a veracious bottom feeder, is euryphagous, feeding on a wide variety of food ranging from planktons to crustaceans. It has an overlapping diet to compete in all environments (Begum et al., 2008). The mean concentrations (mg/kg dry wt.) of Fe, Zn, Cu, Ni, Pb, Cr, Cd and As in the edible muscle tissue was 338.79±38.23, 86.62±7.35, 39.29±3.56, 12.45±1.57, 13.27±1.43, 2.20±0.26, 1.37±0.14 and 0.42±0.03, respectively (**Fig. 2**).

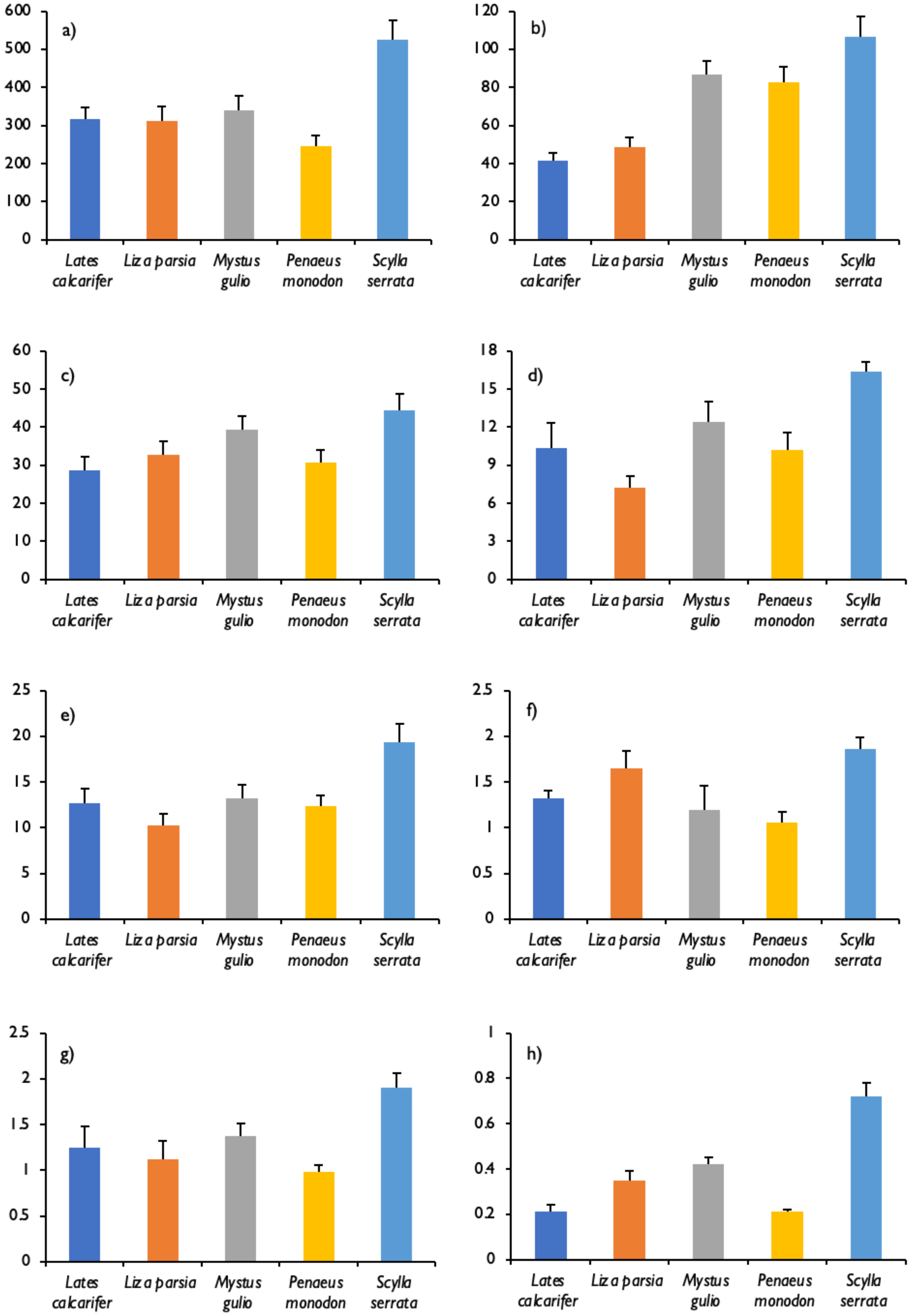


Figure 2. Heavy metal concentration (mg/kg) in edible muscle tissue of finfish and crustaceans: a) Fe, b) Zn, c) Cu, d) Ni, e) Pb, f) Cr, g) Cd, and h) As.

3.4 Penaeus monodon

Penaeus monodon is widely distributed in the Indo-Pacific, ranging from the eastern coast of Africa and Arabian Peninsula to Southeast Asia and Northern Australia (Vu et al., 2023). The major portion of the diet of the prawns consists of animal tissue, although vegetable matter too constitutes a part of their diet. *Penaeus monodon* in general cannot be considered detritus feeders. The mean concentrations (mg/kg dry wt.) of Fe, Zn, Cu, Ni, Pb, Cr, Cd and As in the edible muscle tissue were 246.71±26.23, 82.77±8.13, 30.67±3.45, 10.22±1.36, 12.33±1.21, 1.06±0.11, 0.98±0.08 and 0.21±0.01, respectively (**Fig. 2**).

3.5 Scylla serrata

Scylla serrata, commonly known as the mud crab, occurs in estuaries and other coastal embayment along the Indo-Pacific region (Waltham and Connolly, 2022). Mud crabs can be best described as opportunistic feeders, exhibiting carnivorous, herbivorous, scavenging, and cannibalistic behaviors. They have a diverse diet that includes bivalves, worms, fish, plant matter, and even smaller crabs. Their feeding behavior is influenced by the environmental conditions such as temperature and physiological factors such as their molting stage. The mean concentrations (mg/kg dry wt.) of Fe, Zn, Cu, Ni, Pb, Cr, Cd and As in the edible muscle tissue were 526.67±50.12, 106.46±11.03, 44.37±4.32, 16.41±0.71, 19.36±2.01, 1.86±0.13, 1.9±0.16 and 0.72±0.06, respectively (**Fig. 2**).

4. Discussion

4.1 Accumulation of heavy metals in fish and crustaceans

The concentration of heavy metals in the edible muscle tissues of the analyzed finfish and crustaceans followed the descending order: Fe > Zn > Cu > Pb > Ni > Cr > Cd > As. Fe, Zn and Cu are essential micronutrients involved in metabolic activities and enzymatic functions (Çoğun et al., 2008). Fe is a key component that facilitates hemoglobin activity in blood, while Zn and Cu contribute to growth and metabolic regulation in animals (Sun et al., 2023). Thus, relatively higher concentrations can be linked to their essential biological activities. In contrast, Pb, Cd, Cr and As are non-essential metals and/or metalloids which are toxic at low concentrations (Banaee et al., 2024). Pb, for instance is a neurotoxin which is reported to cause behavioral deficits in aquatic organisms, besides causing reduction in survival, growth and metabolism (Burger et al., 2008). Cd tends to accumulate in the liver and kidneys causing their dysfunction, skeletal damage and reproductive deficiencies (Banaee et al., 2024). Thus, relatively low concentration of these metals may be due to the presence of a developed system of their excretion (Pourang et al., 2004).

Among the studied fish and crustaceans, *Scylla serrata* had the maximum concentration of heavy metals followed by *Mystus gulio*, *Lates calcarifer*, *Liza parsia* and *Panaeus monodon*. The higher concentration of metals in *Scylla serrata* could be attributed to its feeding habits, as it is a detritus bottom feeder. Samal et al. (2013) observed that the estuarine sediments of Nayachar island tend to accumulate higher concentrations of heavy metals above background levels, potentially contributing to the bioaccumulation in benthic organisms like *S. serrata*. Likewise, Chakraborty et al. (2019) reported moderate enrichments of Cd, Pb, Cu, and Zn in sediments against the baseline and attributed that to the presence of industrial sources of heavy metals in the region.

4.2 Exposure of heavy metals through consumption of fish and crustaceans

The THQ value is a dimensionless index that reflects the potential health risks of long-term heavy metal exposure from the consumption of contaminated food, with values greater than 1 indicating a potential health concern (Lin et al., 2024). The THQ values for Pb in *L. calcarifer*, *L. parsia* and *M. gulio* exceeded 1 (**Table 2**), indicating a potential health risk to the exposed population. However, the THQ values based on seafood consumption indicate variability in contamination levels. The analyses revealed that contamination is inconsistent across different seafood types and metal contaminants. Additionally, the frequency and duration of seafood consumption remain uncertain, making it difficult to accurately assess long-term health risks. As for the other heavy metals in the studied fish and crustaceans, the THQ values remained below 1, indicating that the health risks from heavy metal exposure are negligible. Usese et al. (2017) reported THQ values greater than 2 for *Tympanotonus fuscatus* from Lagos lagoon, Nigeria, suggesting a potential for non-carcinogenic health effects in adults after prolonged consumption. The incremental lifetime cancer risks (ILCR) for adults from the consumption of Bagrid catfish (*Chrysichthys nigrodigitatus*) were found to be higher than the US EPA threshold, indicating a moderate carcinogenic risk (Usese et al., 2020). Likewise, Tanhan et al. (2023) reported high THQ value (8.97× 10−3) for Cr in *Penaeus monodon*. While others have shown both carcinogenic and non-carcinogenic risks to inhabitants who consume them regularly.

Table 2. Target hazard quotient (THQ) of different heavy metals in the study area.

Fish/Crustacean	Fe	Zn	Cu	Ni	Pb	Cr	Cd	As
Lates calcarifer	0.27	0.08	0.42	0.31	1.89	0.26	0.75	0.42
Liza parsia	0.26	0.09	0.49	0.21	1.53	0.33	0.67	0.70
Mystus gulio	0.29	0.17	0.58	0.37	1.99	0.44	0.82	0.84
Penaeus monodon	0.03	0.02	0.06	0.04	0.27	0.03	0.08	0.06
Scylla serrata	0.06	0.03	0.10	0.37	0.43	0.05	0.17	0.21

4.3 Tolerable intake of heavy metals due to consumption of fish and crustaceans

Seafood contaminated with heavy metals may pose health hazards to exposed populations (Hajeb et al., 2009; Pandion et al., 2022). Daily and weekly consumption rates of fresh fish muscle, 19.5 g and 136.2 g, respectively, were used to determine the weekly intake of heavy metals through the consumption of fish and crustaceans. The PTWI was then determined considering the fish ingestion rate and the concentration of heavy metals measured in the samples. Ingestion rate of crabs (37.74 g/week) was considered from food ingestion rate of FAO (2005). The estimated and established PTWI (mg/week) of heavy metals from the consumption of fish and crustaceans for a 60 kg individual during the study period are presented in **Table 3**.

Results indicate that there is no appreciable risk of heavy metal toxicity for Fe, Zn, Cu, Ni, Cr, Cd and As from the consumption of fish and crustaceans. However, comparison of the estimated PTWI with FAO/WHO standards revealed a potential toxicity risk from Pb if the seafood is consumed for seven successive days. This puts consumers in this geographical area at risk of heavy metal toxicity. Alarming levels of Pb in edible finfish from various places of Indian Sundarbans and estuarine zone of Hooghly River were also reported (Mitra and Ghosh, 2014). Likewise, Jolaosho et al. (2024) reported heavy metal accumulations in commercially available fish and shellfish species in Makoko, Nigeria.

Chowdhury and Maiti (2016) opined that the operation of various watercraft, such as fishing boats, trawlers, and transport vessels, contributed to the release of Pb into the surrounding water. In Nayachar Island, many residents rely on solar panels and rechargeable batteries to meet their energy needs. However, the inhabitants may be unaware of the impact of improper disposal of rechargeable batteries on our ecosystems. Leachates, such as Pb and Cd, can be introduced to the environments form these batteries (Kumar et al., 2019). Besides, Nayachar is situated opposite to the port and industrial complex of Haldia which can be a source of heavy metals. Chakraborty et al. (2019) reported moderate enrichments of Cd, Pb, Cu, and Zn in sediments and attributed that to the presence of industrial sources of heavy metals in the region.

Table 3. Estimated and established PTWI (mg/week) of heavy metals due to consumption of fishes and crustaceans for a 60 kg individual in the study area.

Fish/Crustacean	Fe	Zn	Cu	Ni	Pb	Cr	Cd	As
Lates calcarifer	43.35	5.67	3.88	1.40	1.72	0.17	0.17	0.02
Liza parsia	42.60	6.64	4.45	0.98	1.59	0.22	0.15	0.04
Mystus gulio	46.10	11.78	5.53	1.69	1.80	0.29	0.18	0.22
Penaeus monodon	33.60	11.27	4.17	1.39	1.47	0.14	0.13	0.02
Scylla serrata	19.92	4.06	1.68	0.61	0.73	0.07	0.07	0.02
Established PTWI (FAO/WHO, 2004)	336	420	210	70 – 80 μg/g (USFDA, 1993)	1.5	1.39 (WHO, 1996)	0.42	0.9

5. Conclusion

The Sundarbans estuarine regions are facing serious risks from heavy metal contamination, primarily due to industrial discharge, domestic and agricultural runoff, and land use practices. This can put the organisms, including humans, at risk due to heavy metal infusion in the food chain. The concentration of heavy metals in the edible muscle tissues of seafood were observed in the following order: Fe > Zn > Cu > Pb > Ni > Cr > Cd > As. The THQ values for Pb exceeded the safe threshold of 1 in three fish species—Lates calcarifer, Liza parsia, and Mystus gulio—indicating potential health risks from long-term exposure. The elevated Pb levels may be attributed to multiple anthropogenic activities, including industrial discharge, marine traffic, and improper disposal of lead-acid batteries in and around Nayachar Island. Among all the species studied, Scylla serrata (mud crab) exhibited the highest accumulation of heavy metals. While other heavy metals remained within acceptable limits, long-term consumption of these fish may still lead to cumulative toxicity. To safeguard this important fragile estuarine ecosystem, a concerted effort is needed from the part of decision makers and local communities to reduce contaminant input. Additionally, regular monitoring must be prioritized to identify the contamination sources and implementing effective remediation strategies to reduce heavy metal pollution.

6. Acknowledgement

The authors are thankful to University of Kalyani, Nadia, West Bengal for providing financial assistance and technical support to carry out this work.

7. Data availability statement

The data is presented in the manuscript as figures and tables. Raw data can be made available upon request from the corresponding author.

8. Author contributions

D. Chakraborty: conceptualization, formal analysis, investigation, methodology, visualization, writing – original draft, and writing – reviewing & editing. D. Das: formal analysis, investigation, methodology, visualization, and writing – original draft. A.C. Samal: formal analysis, investigation, methodology, visualization, and writing – original draft. S.C. Santra: conceptualization, funding acquisition, project administration, resources, supervision, and writing – reviewing & editing. All other approved the final version of the manuscript for publication.

9. Conflict of interest

The authors declare that they have no conflict of interest.

10. Ethical statement

The authors wish to state that this study doesn't involve human or animal subjects and therefore ethical approval is not required for this research. This study is part of the first author’s (Debargha Chakraborty) unpublished Ph.D. research.

11. Copyright statement

References

Abera, B.D., Adimas, M.A., 2024. Health benefits and health risks of contaminated fish consumption: current research outputs, research approaches, and perspectives. Heliyon, 10, e33905. https://doi.org/10.1016/j.heliyon.2024.e33905

Ahmadi, A., Bagheri, D., Hoseinifar, S.H., Morshedi, V., Paolucci, M., 2022. Beneficial role of polyphenols as feed additives on growth performances, immune response and antioxidant status of Lates Calcarifer (Bloch, 1790) juveniles. Aquaculture, 552, 737955. https://doi.org/10.1016/j.aquaculture.2022.737955

Akram, H., Hussain, S., Mazumdar, P., Chua, K.O., Butt, T.E., Harikrishna, J.A., 2023. Mangrove health: a review of functions, threats, and challenges associated with mangrove management practices. Forests, 14, 1698. https://doi.org/10.3390/f14091698

Banaee, M., Zeidi, A., Mikušková, N. Faggio, C., 2024. Assessing metal toxicity on crustaceans in aquatic ecosystems: a comprehensive review. Biological Trace Element Research, 202, 5743–5761. https://doi.org/10.1007/s12011-024-04122-7

Begum, M., Alam, M.J., Islam, M.A., Pal, H.K., 2008. On the food and feeding habit of an estuarine catfish (*Mystus gulio* Hamilton) in the south-west coast of Bangladesh. University Journal of Zoology, Rajshahi University, 27, 91–94.

Bepari, S.P., Pramanick, P., Zaman, S., Mitra, A., 2021. Comparative study of heavy metals in the muscle of two edible finfish species in and around Indian Sundarbans. Journal of Mechanics of Continua and Mathematical Sciences, 16, 9–18. https://doi.org/10.26782/jmcms.2021.10.00002

Bhattacharya, P., Samal, A.C., Bhattacharya, T., Santra, S.C., 2016. Sequential extraction for the speciation of trace heavy metals in Hoogly river sediments, India. International Journal of Experimental Research and Review, 6, 39–49.

Burger, J., Gaines, K.F., Boring, C.S., Stephens, W.L., Snodgrass, J., Dixon, C., McMohan, M., Shukla, S., Shukla, T., Gochfeld, M., 2002. Metal levels in fish from the Savannah River: potential hazards to fish and other receptors. Environmental Research, 89, 85–97. https://doi.org/10.1006/enrs.2002.4330

Chakraborty, D., Das, D., Samal, A.C., Santra, S.C., 2019. Prevalence and ecotoxicological significance of heavy metals in sediments of lower stretches of the Hooghly estuary, India. International Journal of Experimental Research and Review, 19, 1–17. https://doi.org/10.52756/ijerr.2019.v19.001

Chaudhuri, P., Nath, B., Birch, G., 2014. Accumulation of trace metals in grey mangrove *Avicennia marina* fine nutritive roots: The role of rhizosphere processes. Marine Pollution Bulletin, 79, 284–292. https://doi.org/10.1016/j.marpolbul.2013.11.024

Chowdhury, A., Maiti, S.K., 2016. Assessing the ecological health risk in a conserved mangrove ecosystem due to heavy metal pollution: a case study from Sundarbans Biosphere Reserve, India. Human and Ecological Risk Assessment: An International Journal, 22, 1519–1541. https://doi.org/10.1080/10807039.2016.1190636

Cid Pérez, B., Boia, C., Pombo, L., Rebelo, E., 2001. Determination of trace metals in fish species of the Ria de Aveiro (Portugal) by electrothermal atomic absorption spectrometry. Food Chemistry, 75, 93–100. https://doi.org/10.1016/S0308-8146(01)00184-4

Çoğun, H., Yüzereroğlu, T. A., Kargin, F., Firat, Ö., 2005. Seasonal variation and tissue distribution of heavy metals in shrimp and fish species from the Yumurtalik coast of Iskenderun Gulf, Mediterranean. Bulletin of Environmental Contamination and Toxicology, 75, 707–715. https://doi.org/10.1007/s00128-005-0809-6

Connelly, N.A., Lauber, T.B., McCann, P.J., Niederdeppe, J., Knuth, B.A., 2019. Estimated exposure to mercury from fish consumption among women anglers of childbearing age in the great lakes region. Environmental Research, 171, 11–17. https://doi.org/10.1016/j.envres.2019.01.005

Dayal, J.S., Ambasankar, K., Jannathulla, R., Kumuraguruvasagam, K.P., Kailasam, M., 2019. Nutrient and fatty acid composition of cultured and wild caught gold-spot mullet *Liza parsia* (Hamilton, 1822). Indian Journal of Fisheries, 66, 62–70.

Dural, M., Göksu, M., Özak, A.A., 2007. Investigation of heavy metal levels in economically important fish species captured from the Tuzla lagoon. Food Chemistry, 102, 415–421. https://doi.org/10.1016/j.foodchem.2006.03.001

Eong, O.J., 1995. The ecology of mangrove conservation and management. Hydrobiologia, 295, 343–351. https://doi.org/10.1007/BF00029141

FAO, 2005. Statistical databases. https://faostat.fao.org

FAO/WHO, 2004. Summary of evaluations performed by the Joint FAO/WHO expert committee on food additives (JECFA 1956–2003). ILSI Press International Life Sciences Institute.

Hajeb, P., Jinap, S., Ismail, A., Fatimah, A.B., Jamilah, B., Abdul Rahim, M., 2009. Assessment of mercury level in commonly consumed marine fishes in Malaysia. Food control, 20, 79–84. https://doi.org/10.1016/j.foodcont.2008.02.012

Islam, S.M.D-U., Bhuiyan, M.A.H., 2018. Sundarbans mangrove forest of Bangladesh: causes of degradation and sustainable management options. Environmental Sustainability, 1, 113–131. https://doi.org/10.1007/s42398-018-0018-y

Joadder, A.R., Hossain, M.D., 2008. Convenient pattern of food and feeding habit of *Liza parsia* (Hamilton) (Mugiliformes: Mugilidae). Journal of Fisheries International, 3, 61–64.

Jolaosho, T.L., Elegbede, I.O., Akintola, S.L., Jimoh, A.A., Ndimele, P.E., Mustapha, A.A., Adukonu, J.D., 2024. Bioaccumulation dynamics, noncarcinogenic and carcinogenic risks of heavy metals in commercially valuable shellfish and finfish species from the world largest floating slum, Makoko, Nigeria. Marine Pollution Bulletin, 207, 116807. https://doi.org/10.1016/j.marpolbul.2024.116807

Kalay, M., Ay, Ö., Canli, M., 1999. Heavy metal concentrations in fish tissues from the Northeast Mediterranean Sea. Bulletin of Environmental Contamination and Toxicology, 63, 673–681. https://doi.org/10.1007/s001289901033

Kumar, S., Karmoker, J., Pal, B.K., Luo, C., Zhao, M., 2019. Trace metals contamination in different compartments of the Sundarbans mangrove: a review. Marine Pollution Bulletin, 148, 47–60. https://doi.org/10.1016/j.marpolbul.2019.07.063

Lin, H., Luo, X., Yu, D. He, C., Cao, W., He, L., Liang, Z., Zhou, J., Fang, G., 2024. Risk assessment of As, Cd, Cr, and Pb via the consumption of seafood in Haikou. Scientific Reports, 14, 19549. https://doi.org/10.1038/s41598-024-70409-3

Lorenzon, S., Francese, M., Smith, V.J., Ferrero, E.A., 2001. Heavy metals affect the circulating haemocyte number in the shrimp Palaemon elegans. Fish & Shellfish Immunology, 11, 459–472. https://doi.org/10.1006/fsim.2000.0321

MacFarlane, G.R., 2002. Leaf biochemical parameters in *Avicennia marina* (Forsk.) Vierh as potential biomarkers of heavy metal stress in estuarine ecosystems. Marine Pollution Bulletin, 44, 244–256. https://doi.org/10.1016/S0025-326X(01)00255-7

MacFarlane, G.R., Burchett, M.D., 2000. Cellular distribution of copper, lead and zinc in the grey mangrove, *Avicennia marina* (Forsk.) Vierh. Aquatic Botany, 68, 45–59. https://doi.org/10.1016/S0304-3770(00)00105-4

Marchand, C., Allenbach, M., Lallier-Vergès, E., 2011. Relationships between heavy metals distribution and organic matter cycling in mangrove sediments (Conception Bay, New Caledonia). Geoderma, 160, 444–456. https://doi.org/10.1016/j.geoderma.2010.10.015

Mitra, A., Ghosh, R., 2014. Bioaccumulation pattern of heavy metals in commercially important fishes in and around Indian Sundarbans. Global Journal of Animal Scientific Research, 2, 33–44.

Mitra, A., Chowdhury, R., Banerjee, K., 2012. Concentrations of some heavy metals in commercially important finfish and shellfish of the River Ganga. Environmental Monitoring and Assessment, 184, 2219–2230. https://doi.org/10.1007/s10661-011-2111-x

Moschetto, F.A., Ribeiro, R.B., De Freitas, D.M., 2021. Urban expansion, regeneration and socioenvironmental vulnerability in a mangrove ecosystem at the southeast coastal of Sao Paulo, Brazil. Ocean & Coastal Management, 200, 105418. https://doi.org/10.1016/j.ocecoaman.2020.105418

Nath, B., Birch, G., Chaudhuri, P., 2014. Trace metal biogeochemistry in mangrove ecosystems: A comparative assessment of acidified (by acid sulfate soils) and non-acidified sites. Science of The Total Environment, 463–464, 667–674. https://doi.org/10.1016/j.scitotenv.2013.06.024

Pandion, K., Khalith, S.B.M., Ravindran, B., Chandrasekaran, M., Rajagopal, R., Alfarhan, A., Chang, S.W., Ayyamperumal, R., Mukherjee, A., Arunachalam, K.D., 2022. Potential health risk caused by heavy metal associated with seafood consumption around coastal area. Environmental Pollution, 294, 118553, https://doi.org/10.1016/j.envpol.2021.118553

Pandiyan, J., Mahboob, S., Govindarajan, M., Al-Ghanim, K.A., Ahmed, Z., Al-Mulhm, N., Jagadheesan, R., Krishnappa, K., 2021. An assessment of level of heavy metals pollution in the water, sediment and aquatic organisms: A perspective of tackling environmental threats for food security. Saudi Journal of Biological Sciences, 28, 1218–1225. https://doi.org/10.1016/j.sjbs.2020.11.072

Peters, E.C., Gassman, N.J., Firman, J.C., Richmond, R.H., Power, E.A., 1997. Ecotoxicology of tropical marine ecosystems. Environmental Toxicology and Chemistry, 16, 12–40. https://doi.org/10.1002/etc.5620160103

Pourang, N., Dennis, J.H., Ghourchian, H., 2004. Tissue distribution and redistribution of trace elements in shrimp species with the emphasis on the roles of metallothionein. Ecotoxicology, 13, 519–533. https://doi.org/10.1023/B:ECTX.0000037189.80775.9c

Praveena, S.M., Aris, A.Z., Radojevic, M., 2010. Heavy metals dynamics and source in intertidal mangrove sediment of Sabah, Borneo Island. Environment Asia, 3, 79–83.

Proshad, R., Rahim, M.A., Rahman, M., Asif, M.R., Dey, H.C., Khurram, D., Al, M.A., Islam, M., Idris, A.M., 2024. Utilizing machine learning to evaluate heavy metal pollution in the world's largest mangrove forest. Science of The Total Environment, 951, 175746. https://doi.org/10.1016/j.scitotenv.2024.175746

Saha, M., Sarkar, S.K., Bhattacharya, B., 2006. Interspecific variation in heavy metal body concentrations in biota of Sunderban mangrove wetland, northeast India. Environment International, 32, 203–207. https://doi.org/10.1016/j.envint.2005.08.012

Samal, A.C., Bhattacharya, P., Banerjee, S., Majumdar, J., Santra, S.C., 2013. Distribution of arsenic in the estuarine ecosystem of Nayachar island, West Bengal, India. Earth Science India, 6, 70–76.

Samanta, S., Hazra, S., Mondal, P.P., Chanda, A., Giri, S., French, J.R., Nicholls, R.J., 2021. Assessment and Attribution of Mangrove Forest Changes in the Indian Sundarbans from 2000 to 2020. Remote Sensing, 13, 4957. https://doi.org/10.3390/rs13244957

Santhosh, K., Kamala, K., Ramasamy, P., Musthafa, M.S., Almujri, S.S., Asdaq, S.M.B., Sivaperumal, P., 2024. Unveiling the silent threat: Heavy metal toxicity devastating impact on aquatic organisms and DNA damage. Marine Pollution Bulletin, 200, 116139. https://doi.org/10.1016/j.marpolbul.2024.116139

Sharma, M., Kant, R., Sharma, A.K., Sharma, A.K., 2025. Exploring the impact of heavy metals toxicity in the aquatic ecosystem. International Journal of Energy and Water Resources, 9, 267–280. https://doi.org/10.1007/s42108-024-00284-1

Su, J., Friess, D.A., Gasparatos, A., 2021. A meta-analysis of the ecological and economic outcomes of mangrove restoration. Nature Communications, 12, 5050. https://doi.org/10.1038/s41467-021-25349-1

Sun, Z., Shao, Y., Yan, K., Yao, T., Liu, L., Sun, F., Wu, J., Huang, Y., 2023. The link between trace metal elements and glucose metabolism: evidence from zinc, copper, iron, and manganese-mediated metabolic regulation. *Metabolites, 13,* 1048. https://doi.org/10.3390/metabo13101048

Tanhan, P., Lansubsakul, N., Phaochoosak, N., Sirinupong, P., Yeesin, P., Imsilp, K., 2023. Human Health Risk Assessment of Heavy Metal Concentration in Seafood Collected from Pattani Bay, Thailand. Toxics, 11, 18. https://doi.org/10.3390/toxics11010018

Traven, L., Marinac-Pupavac, S., Žurga, P., Linšak, Z., Žeželj, S.P., Glad, M., Lušić, D.V., 2023. Assessment of health risks associated with heavy metal concentration in seafood from North-Western Croatia. Scientific Reports, 13, 16414. https://doi.org/10.1038/s41598-023-43365-7

US EPA, 2000. Risk-Based Concentration Table. Philadelphia PA: United States Environmental Protection Agency.

Usese, A.I., Chukwu, L.O., Naidu, R., Islam, S., Rahman, M.M., 2020. Arsenic fractionation in sediments and speciation in muscles of fish, Chrysichthys nigrodigitatus from a contaminated tropical Lagoon, Nigeria. Chemosphere, 256, 127134. https://doi.org/10.1016/j.chemosphere.2020.127134

Usese, A., Chukwu, O.L., Rahman, M.M., Naidu, R., Islam, S. and Oyewo, E.O., 2017. Concentrations of arsenic in water and fish in a tropical open lagoon, Southwest-Nigeria: Health risk assessment. Environmental Technology & Innovation, 8, 164–171. https://doi.org/10.1016/j.eti.2017.06.005

USFDA, 1993. Food and drug administration, Guidance document for nickel in shell fish. DHHS/PHS/FDA/CFSAN/Office of seafood, Washington D.C.

Vu, N.T.T., Jerry, D.R., Edmunds, R.C., Jones, D.B., Zenger, K.R., 2023. Development of a global SNP resource for diversity, provenance, and parentage analyses on the Indo-Pacific giant black tiger shrimp (*Penaeus monodon*). Aquaculture, 563, 738890. https://doi.org/10.1016/j.aquaculture.2022.738890

Waltham, N.J., Connolly, R.M., 2022. Food webs supporting fisheries production in estuaries with expanding coastal urbanization. Food Webs, 33, e00259. https://doi.org/10.1016/j.fooweb.2022.e00259

WHO, 2006. WHO Guidelines for the Safe Use of Wastewater Excreta and Greywater: Volume 4: Excreta and Greywater Use in Agriculture (World Health Organization).

WHO, 1996. Chromium in drinking-water, Guidelines for drinking water quality, World Health Organization, 2nd Edn., Geneva, Switzerland, 2.

Younis, A.M., Hanafy, S., Elkady, E.M., Alluhayb, A.H., Alminderej, F.M., 2024. Assessment of health risks associated with heavy metal contamination in selected fish and crustacean species from Temsah Lake, Suez Canal. Scientific Reports, 14, 18706. https://doi.org/10.1038/s41598-024-69561-7

Zaynab, M., Al-Yahyai, R., Ameen, A., Sharif, Y., Ali, L., Fatima, M., Khan, K.A., Li, S., 2022. Health and environmental effects of heavy metals. Journal of King Saud University - Science, 34, 101653. https://doi.org/10.1016/j.jksus.2021.101653

Publisher's note

The author(s) are solely responsible for the opinions and data presented in this article, and publisher or the editor(s) disclaim responsibility for any injury to people or property caused by any ideas mentioned in this article.