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ARTICLE

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EVALUATION OF POTENTIALLY TOXIC ELEMENTS IN GANGETIC FISH: AN ENVIRONMENTAL AND HEALTH ASSESSMENT PERSPECTIVES

SHREYA ROY, AYAN BISWAS, SUSMITA JANA, LOKNATH CHAKRABORTY, DHRUBA JYOTI SARKAR, BASANTA KUMAR DAS* AND PRANAYA KUMAR PARIDA

The present study investigates the contamination and bioaccumulation of potentially toxic elements (PTEs) like Cadmium (Cd), Chromium (Cr), Lead (Pb) and Arsenic (As) in surface of the water and economically important fish species along the lower riverine stretch and estuarine zones of the Ganga River, with a focus on their implications for human health. Bioconcentration factors (BCFs) of Mystus bleekeri showing the highest levels of Cd, Pb, and As accumulation. As emerged as the most critical contributor to non-carcinogenic and carcinogenic risks, with certain species exceeding acceptable carcinogenic risk (CR) thresholds. The overall estimated daily intake (EDI), total hazard quotient (THQ), hazard index (HI) and CR for combined PTEs exposure through fish consumption remained within permissible level, site-specific and species-specific analyses unveiled significant localized health risks.

Introduction

The Ganga River constitutes the most significant river system in India. Its perennial water flow has been instrumental in supporting the development of Indian civilization and sustaining economic activities[1]. The Ganga Basin is one of the most densely populated regions globally, with an average population density of approximately 520 individuals/sq. km[2]. Rapid industrialization has led to a significant rise in the discharge of effluents into natural water bodies which is the major contributors to environmental toxicity, posing a threat to aquatic ecosystems and causing the degradation of water quality[3].

Water pollution is characterized by the presence of various contaminants and toxic metals are of particular concern due to their bioaccumulation nature, leading to environmental hazards through the food chain[4,5]. Elevated concentrations of PTEs can form harmful complexes that disrupt biological functions. The riverine ecosystem is polluted by a range of anthropogenic activities, including untreated or partially treated sewage, industrial wastewater discharge, agricultural runoff, mining, smelting, electroplating, vehicular emissions, and antifouling paints used on ship hulls. Additionally, environmental phenomenon such as volcanic activity, weathering of rocks, and soil erosion also contribute to contamination[6].

This study investigated to assess the bioaccumulation of potentially toxic elements (PTEs), including Cadmium (Cd), Chromium (Cr), Lead (Pb), and Arsenic (As), in six commercially significant fish species from the lower (Buxar to Tribeni) and estuarine (Godakhali to Fraserganj) stretch of the River Ganga. Additionally, associated human health risks was evaluated, focusing on health hazards and carcinogenic impacts linked to the consumption of fish contaminated with the PTEs.

Materials and Methods

Study Area: The study area has been selected along the river Ganga comprising of 2 states and 11 stations

ICAR-Central Inland Fisheries Research Institute, Barrackpore, West Bengal
* Corresponding author: basantakumard@gmail.com

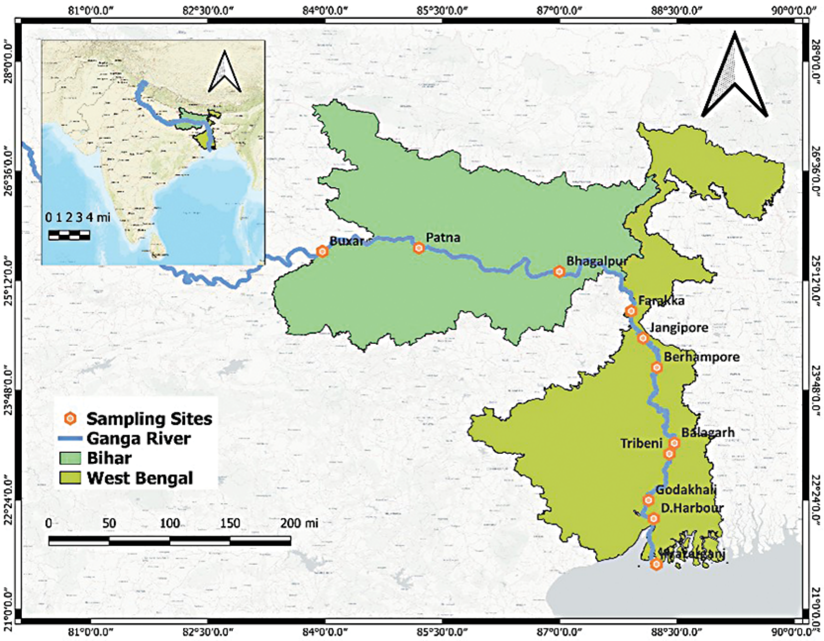

Fig. 1. GIS location of the sampling sites along the river Ganga.

(Fig. 1). Among the 11 stations, the river was divided into 2 parts i.e., lower riverine stretch (Buxar to Tribeni) and estuarine zone (Godakhali to Fraserganj).

Water and Fish Sample Preparation for PTEs Detection: Water samples (100 mL) were digested with concentrated HNO_3 (1 mL) in a sand bath at~250°C. Fish samples were homogenized and dried in hot air oven at 110 ºC. 1 gm dried fish sample (1 gm) was kept in tri-acid mixture (HNO_3:$HCLO_4$:$H2SO_4$::10:4:1) for overnight and digested on sand bath at ~250°C. Milli-Q (18.2 MÙ cm) water was used to dilute the digested samples and filtered through Whatman 42 filter paper. Inductively coupled plasma mass spectrometry (ICP-MS) was used to analyse the PTEs concentrations (Cr, Cd, Pb and As) from water and fish muscles[9].

Ecological Assessment in Water:

Heavy Metal Pollution Index: The heavy metal pollution index (HPI) is a widely used metric for the comprehensive evaluation of water quality, particularly concerning the presence of potentially toxic metals. The HPI is assessed using the following formula:

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}$$

$$W_i = \frac{1}{S_i}$$

$$Q_i = \sum_{i=1}^{n} \frac{|O_i - I_i|}{S_i - I_i} \times 100$$

In this study, the unit weightage factor (W_i) and sub-index (Q_i) of each metal was calculated, where S_i is the highest permissible limit, O_i is the evaluated concentration, and I_i is the maximum desirable limit of the i^{th} metal. Based on the calculated HPI, water quality is classified into five categories[10]: Excellent- HPI < 25, Good- 25 ≤ HPI < 50, Poor- 50 ≤ HPI < 75, Very Poor- 75 ≤ HPI < 100, Unsuitable for Drinking- HPI > 100.

Heavy Metal Evaluation Index: Heavy metal evaluation index (HEI), which is determined by dividing the observed concentration of i^{th} metal (O_i) by the maximum allowable limit of i^{th} metal (S_i) according to Indian regulations, also indicates the water quality regarding metal contamination[11]. Based on the calculated HEI, samples can be categorised

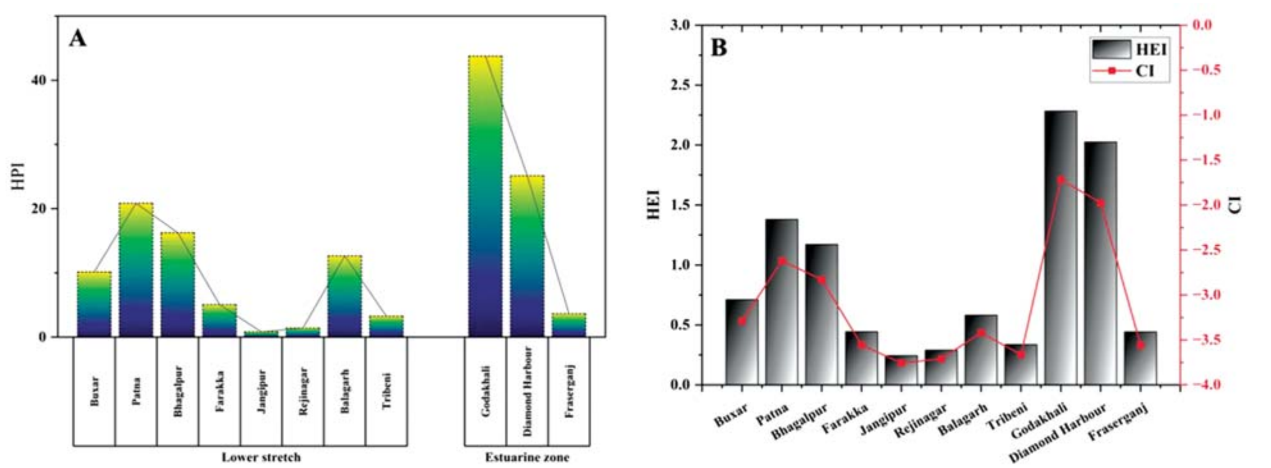

Fig. 2. A. Heavy metal pollution Index (HPI) in the lower riverine stretch and estuarine zone of river Ganga; B. Heavy metal evaluation index (HEI) and contamination index (CI) along the 11 sites of river Ganga.

as low (HEI < 1), medium (1 ≤ HEI < 2), and high (HEI > 2) and equation is as follows.

$$HEI = \sum_{i=1}^{n} \frac{O_i}{S_i}$$

Contamination Index (CI): The contamination index (CI) provides a quantitative measure of the degree of toxic metal contamination in water by integrating the contamination factors of each metal that exceeds the maximum permissible limits set by national standards[12,10]. CI values are classified into three pollution categories[13,10]: Low contamination: CI < 1, Moderate contamination: 1 ≤ CI < 3, High contamination: CI> 3.

$$Cl = \sum\nolimits_{i=1}^{n} C_F^i$$

Where, C_F^i is the contamination factor of the i^{th} trace metal.

PTEs Concentration Assessment in Fish Tissue: **Bioconcentration Factor (BCF):** The Bioconcentration Factor (BCF) is an essential metric in environmental toxicity, representing the uptake of heavy metals by organisms via respiratory and dermal pathways[14].

BCF=Cf/Cw

Where Cf is the concentration of metal in fish in dry weight (dw) and Cw is the concentration of heavy metal in surrounding water.

Human Health Risk Assessment: **Estimated Daily Intake (EDI):** Fish muscle is a fundamental dietary staple globally, with assessments of human health risks from metal exposure often focusing on intake through fish consumption. Consumption of 100–200 g of fish muscle / week for adults, while children should consume 25–40 g / week. The Estimated Daily Intake (EDI) is determined by the following equation[15].

$$EDI = \frac{C \times FIR}{BW} \times 10^{-3}$$

In this equation, 'C' represents the mean concentration of heavy metals in fish muscle (mg/Kg, dw basis). FIR (Food Ingestion Rate) signifies the daily intake of fish per capita (g/day)[16].

Target Hazard Quotient (THQ): The THQ serves as an estimate of the non-carcinogenic risk level attributed to exposure to heavy metals. This THQ is determined by the following equation[17].

$$THQ = \frac{Efr \times ED \times FIR \times C}{Rfd \times BW \times Atn} \times 10^{-3}$$

In this context, Efr= Exposure frequency

RfD= Reference Dose evaluates the health risks linked with fish consumption

ATn denotes the average exposure duration for non-carcinogenic effects.

A Total Hazard Quotient (THQ) below 1 indicates minimal or negligible evidence of significant health risks in the exposed population. In contrast, a THQ exceeding 1 suggests potential adverse health effects may be present.

Hazard Index (HI): The Hazard Index (HI) serves as a tool for assessing the risk to human health from the combined concentrations of various heavy metals[18,19].

HI= ΣTHQ (Cr)+ΣTHQ (Cd)+ΣTHQ (Pb)+ΣTHQ (As)

Carcinogenic Risk (CR): Carcinogenic risk quantifies the increased lifetime probability of developing cancer from daily exposure to potential carcinogens by[19,20] .

CR = CSF × EDI

The carcinogenic risk of PTEs is denoted through analysis a CR value below $10^{"6}$ is considered negligible, while values between $10^{"6}$ and $10^{"4}$ fall within the acceptable range. Any CR value exceeding $10^{"4}$ is unacceptable.

Results and Discussion: **PTEs Contamination in Water:** The mean concentration of potentially toxic elements (PTE)s in surface water samples collected from

Table 1: Heavy metal concentration (µg L^{-1}) in water at selected sites of Ganga River

Sites	Cd (µg L^{-1})	Cr (µg L^{-1})	Pb (µg L^{-1})	As (µg L^{-1})
Buxar	0.23±0.03	6.80±0.56	1.60±0.31	16.93±4.56
Patna	0.23±0.07	9.75±0.43	6.18±0.46	24.52±4.75
Bhagalpur	0.09±0.01	10.69±4.30	5.95±0.76	16.65±5.60
Farakka	BDL	0.87±0.08	2.35±0.34	9.59±0.21
Berhampore	BDL	0.90±0.06	0.34±0.05	9.63±0.25
Jangipore	BDL	0.79±0.06	0.60±0.05	10.73±8.40
Balagarh	0.38±0.09	6.65±0.37	1.41±6.20	8.98±0.46
Tribeni	BDL	4.78±0.64	1.17±0.15	6.23±0.76
Godakhali	1.29±0.27	10.64±2.40	3.20±1.57	66.09±4.60
D. Harbour	0.59±0.10	63.66±7.10	2.55±6.40	15.04±1.64
Fraserganj	BDL	9.93±0.51	1.15±0.43	6.45±0.37

BDL- Below detection level

Ganga River are summarized in Table 1. The results reveal significant environmental and public health concerns at several sites. Cadmium (Cd) was below detection limits (BDL) at most locations, but higher levels at Godakhali (1.29 µg L^{-1}) and Diamond Harbour (0.59 µgL^{-1}) could pose long-term kidney risks. Chromium (Cr) levels were mostly low, except at Diamond Harbour, where it reached 63.66 µg L^{-1} but did not escalade the drinking water quality guideline mentioned by the U.S Environmental Protection Agency[21] (USEPA, 2024). Arsenic (As) was highest at Godakhali (66.09 µg L^{-1}) followed by Patna (24.52 µg L^{-1}), well above the prescribed value of 10 µg L^{-1} posing serious health threats[21] (USEPA, 2024). Significant fluctuations of PTEs concentration in river ecosystems are primarily due to geological factors, input of various natural resources and anthropogenic interferences at different sampling sites. The average PTEs concentration is much higher in estuarine zone than the lower stretch of the river. Both the zones exhibited the metal trend of As>Cr>Pb>As. These findings highlight the need for regular monitoring, detailed metal speciation, and targeted interventions to protect environmental and public health in the affected areas.

Contamination Assessment in Water: The indices related to PTEs for Ganga River water at various sampling sites are shown in Fig. 2A. The highest HPI was recorded at Godakhali and the lowest at Jangipur, with the mean HPI for all samples remaining below the critical threshold of 100 for drinking water[22] (Prasad and Bose, 2001). Across all sites, 18.18% were classified as good and 81.81% as excellent, with HPI values ranging from 0.82 to 43.77. In both the lower riverine stretch and estuarine zones, the HPI was below 50, these areas were recorded as good. HEI values (Fig. 2B) were calculated for each PTE at each sampling station, ranging from 0.24 to 2.28. Based on HEI categorization, 63.63% of sites showed low pollution levels, 18.18% moderate, and 18.18% high. From our study it can be conferred that the HEI value is much higher in the estuarine zone than lower riverine stretch. It might be due to the sediment-transferring systems of River Ganga which carries significant amounts of sediment-attached metals to the Bay of Bengal[23] (Singh et al. 2003). Additionally, domestic and industrial effluents further contribute to its higher concentration. The CI values for each site were all below 0, indicating lower pollution level. The indices revealed generally good water quality across the sites, with most HPI values below critical levels, in the lower riverine stretch and estuarine zones. Overall, these findings suggest stable, acceptable water quality in the assessed areas of the Ganga River.

Bioaccumulation of PTEs in Fish Muscles from the Ganga River : The concentrations of selected PTEs (µg/g) and their corresponding bio-concentration factors (BCF) (Table 2) were assessed from fish muscle tissues collected from the Ganga River. The studied metals are known for their ecological relevance and potential toxicity. The bioconcentration factor index revealed significant habitat-specific differences in metal accumulation among the six selected fish species from the Ganga River.

Freshwater species (*Mystus bleekeri*, *Ailia coila*, *Systomus sarana*) exhibited substantially higher BCF values for cadmium (Cd), lead (Pb), and arsenic (As), indicating higher metal uptake from the environment. *Systomus sarana* and *Mystus bleekeri* showed exceptionally high BCFs for Cd (187.00 and 178.90, respectively). *Mystus bleekeri* also recorded the highest BCF for Pb (133.51) and moderate levels for As (18.83), highlighting its strong bioaccumulative potential. *Ailia coila* had consistently low or undetectable BCFs, suggesting lower exposure. The bioaccumulation of PTEs in aquatic organisms can result in adverse health effects, including damage to the liver and kidneys, cardiovascular disorders, and an increased risk of cancer[24].

In comparison to freshwater species, *Johnius coitor*, *Setipinna phasa*, and *Tenualosa ilisha* showed significantly lower BCF values. *Johnius coitor* had the highest BCF among estuarine fish, but still far below freshwater counterparts- Cd (10.31), Pb (23.65), As (2.11). *Setipinna phasa* and *Tenualosa ilisha* showed low accumulation, with BCF values mostly below 5. The bioaccumulation of PTEs in fish is influenced by various exogenous and endogenous factors. Environmental parameters such as water and sediment quality, temperature, alkalinity, and metal bioavailability are key exogenous factors. In contrast, endogenous factors include species characteristics like age, size (length and weight), sex, feeding habits (herbivorous, carnivorous, omnivorous, or planktivorous), the specific tissues analyzed, habitat preferences, and the physiological condition of the fish[25] .Bioconcentration factor of Cd and Pb were 10-20 times higher in freshwater fish than in estuarine species. Arsenic BCF was moderately higher in freshwater fish, indicating more consistent uptake. Bioconcentration factor for Cr was low across all species, but slightly higher in *M. bleekeri* and *T. ilisha*. These findings suggest that freshwater habitats are more prone to metal bioaccumulation, likely due to stagnant conditions and limited dilution. In contrast, estuarine species exhibit lower accumulation, possibly due to tidal mixing, salinity effects, and reduced metal bioavailability. Overall, *Mystus bleekeri* and *Systomus*

Table 2: Average heavy metal concentration (µg/g-fw) and their bioconcentration factor index of the selected fish muscles collected from Ganga River

Habitat	Scientific name	Family	Common name	Conser-vation status	Average PTEs concentration (µg/g-fw)				BCF			
					Cd	Cr	Pb	As	Cd	Cr	Pb	As
Freshwater	*Mystus bleekeri*	Bagridae	Tengra	LC	0.04186	0.02708	0.32711	0.24313	178.900	5.25482	133.512	18.8352
	Ailia coila	Ailiidae	Kajuli	NT	0.00007	BDL	BDL	0.00090	0.28705	-	-	0.06974
	Systomus sarana	Cyprinidae	Sar puti	LC	0.04376	0.00146	BDL	0.20167	187.002	0.28295	-	15.6233
Estuarine	*Johnius coitor*	Sciaenidae	Bhola	LC	0.00967	0.01180	0.05441	0.06145	10.3080	0.92103	23.6476	2.10502
	Setipinna Phasa	Engraulidae	Phasa	LC	0.00182	0.00151	0.03565	0.03045	1.93970	0.11785	15.4911	1.04308
	Tenualosa ilisha	Dorosomatidae	Hilsa	LC	0.00405	0.01941	BDL	0.08398	4.32124	1.51518	-	2.87697

LC- Least concern; NT- Near Threatened

sarana stand out as indicator species for monitoring heavy metal contamination in freshwater ecosystems.

Human Health Risk Assessments: The health risk assessment based on estimated daily intake (EDI), hazard index (HI), and cancer risk (CR) (Table 3) across different fish species indicates varying levels of exposure to potentially toxic elements. *M. bleekeri* showed the highest EDI and HI values, particularly for arsenic (As), with HI values of 0.4377 for adults and 1.0464 for children, and CR values of 1.7365×10^{-4} and 4.1510×10^{-4}, respectively—both exceeding acceptable limits, indicating significant non-carcinogenic and carcinogenic risks. *S. sarana* also exhibited elevated HI values (0.3207 for adults and 0.7668 for children) and CR values (1.4404×10^{-4} for adults and 3.4432×10^{-4} for children), mainly due to As. *J. coitor* presented moderate health risks, with HI values of 0.1096 for adults and 0.262 for children and CR values slightly above safe limits (0.4389×10^{-4} for adults and 1.0492×10^{-4} for children), again attributed to As. *T. ilisha* showed comparatively lower EDI and HI values (Adults: 0.1425 and Children: 0.34), but CR values (Adults: 0.5999×10^{-4} and 1.4339×10^{-4} for children) still exceeded the acceptable limit, suggesting a potential cancer risk. *S. phasa* exhibited lower risk levels, with HI values of 0.0532 for adults and 0.1274 for children, and CR values (Adults: 0.2175×10^{-4} and Children: 0.5199×10^{-4}) that, while lower, still suggest caution. *A. coila* had the lowest risk among all species, with negligible HI (0.0014 for adults and 0.0034 for children) and CR values (0.0002×10^{-4} for adults and 0.0004×10^{-4} for children), indicating minimal health concern. Overall, arsenic was the most significant contributor to health risks across species, with children consistently facing greater exposure, underscoring the need for targeted consumption guidelines and regular monitoring. The THQ and HI assessments suggested that non-carcinogenic health risks are unlikely from the dietary consumption of fish, whether due to individual or combined PTEs[26], for all studied PTEs across all fish species, the THQ and HI values were found to be less than 1.

Conclusion

The study provides an overview of the current status of PTEs in the River Ganga. PTEs are naturally occurring components of the Earth's crust and are released into the environment through both natural processes and human activities. Industrialization has significantly increased the deposition of elements on the Earth's surface, far surpassing contributions from natural background sources. Within rocks, metals are present in the form of ores, which are extracted as minerals. Acid drainage originates from

Table 3: Table Estimated daily intake (mg kg^{-1} day^{-1}), target hazard quotient, hazard index and carcinogenic risk estimated for adult and children after consuming heavy metal contaminated fish collected from river Ganga

Fish Sp.	PTEs	EDI		THQ		CR		HI	
		Adults	Children	Adults	Children	Adults	Children	Adults	Children
Mystus bleekeri	Cd	0.01993 × 10^{-3}	0.04765 × 10^{-3}	0.00001329	0.0000318	0.099 × 10^{-4}	0.238 × 10^{-4}	0.4377	1.0464
	Cr	0.01290 × 10^{-3}	0.03083 × 10^{-3}	0.01289618	0.0308275	0.049 × 10^{-4}	0.117 × 10^{-4}		
	Pb	0.15576 × 10^{-3}	0.37233 × 10^{-3}	0.03893913	0.0930816	0. × 10^{-4}	0.031 × 10^{-4}		
	As	0.11577 × 10^{-3}	0.27674 × 10^{-3}	0.38589340	0.9224543	0.44 × 10^{-4}	4.15 × 10^{-4}		
Ailia coila	Cd	0.00003 × 10^{-3}	0.00008 × 10^{-3}	0.00000002	0.0000001	0.00015 × 10^{-4}	0.00038228	0.0014	0.0034
	Cr	-	-	-	-	-	-		
	Pb	-	-	-	-	-	-		
	As	0.00043 × 10^{-3}	0.00102 × 10^{-3}	0.00142878	0.0034154	0.0016 × 10^{-4}	0.015 × 10^{-4}		
Systomus sarana	Cd	0.02084 × 10^{-3}	0.04981 × 10^{-3}	0.00001389	0.0000332	0.104 × 10^{-4}	0.245 × 10^{-4}	0.3207	0.7668
	Cr	0.00069 × 10^{-3}	0.00166 × 10^{-3}	0.00069441	0.0016599	0.002 × 10^{-4}	0.006 × 10^{-4}		
	Pb	-	-	-	-	-	-		
	As	0.09603 × 10^{-3}	0.22955 × 10^{-3}	0.32008981	0.7651549	0.364 × 10^{-4}	3.443 × 10^{-4}		
Johnius coitor	Cd	0.00460 × 10^{-3}	0.01101 × 10^{-3}	0.00000307	0.0000073	0.023 × 10^{-4}	0.055 × 10^{-4}	0.1096	0.262
	Cr	0.00562 × 10^{-3}	0.01343 × 10^{-3}	0.00561707	0.0134273	0.021 × 10^{-4}	0.051 × 10^{-4}		
	Pb	0.02591 × 10^{-3}	0.06194 × 10^{-3}	0.00647745	0.0154839	0.098 × 10^{-4}	0.005 × 10^{-4}		
	As	0.02926 × 10^{-3}	0.06994 × 10^{-3}	0.09753426	0.2331496	0.111 × 10^{-4}	1.049 × 10^{-4}		
Setipinna phasa	Cd	0.00087 × 10^{-3}	0.00207 × 10^{-3}	0.00000058	0.0000014	0.004 × 10^{-4}	0.01 × 10^{-4}	0.0532	0.1274
	Cr	0.00072 × 10^{-3}	0.00172 × 10^{-3}	0.00071872	0.0017181	0.002 × 10^{-4}	0.006 × 10^{-4}		
	Pb	0.01697 × 10^{-3}	0.04057 × 10^{-3}	0.00424327	0.0101433	0.064 × 10^{-4}	0.003v		
	As	0.01450 × 10^{-3}	0.03466 × 10^{-3}	0.04833042	0.1155309	0.055 × 10^{-4}	0.519 × 10^{-4}		
Tenualosa ilisha	Cd	0.00193 × 10^{-3}	0.00461 × 10^{-3}	0.00000129	0.0000031	0.009 × 10^{-4}	0.023 × 10^{-4}	0.1425	0.340
	Cr	0.00924 × 10^{-3}	0.02209 × 10^{-3}	0.00924062	0.0220891	0.035 × 10^{-4}	0.083 × 10^{-4}		
	Pb	-	-	-	-	-	-		
	As	0.03999 × 10^{-3}	0.09559 × 10^{-3}	0.13330188	0.3186499	0.151 × 10^{-4}	1.433 × 10^{-4}		

both anthropogenic and natural sources, with mining activities for coal and metal ores being the most prominent contributors. These processes, along with other natural and human-induced factors, lead to contamination of air, water, and soil ecosystems. Numerous studies on PTEs contamination reveal that concentrations of various elements in the water and fish of the River Ganga significantly exceed acceptable limits. The bioaccumulation and biomagnification of PTEs pose a significant threat to human health and well-being. Therefore, it is imperative to implement measures to reduce the discharge of metallurgical effluents into the River Ganga. This research highlights the need for rigorous monitoring of PTEs sources in the Ganga river water and fish, along with efforts to improve environmental conditions by limiting industrial effluents and domestic sewage discharge.

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