Heavy metal contamination level in selected fishes of the Balu river in Bangladesh: Health risk assessments

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Abstract

Metal contamination in water bodies poses serious environmental and health risks due to bioaccumulation in aquatic organisms, particularly fish. This study aimed to assess heavy metal contamination in three fish species-*Systomus sarana* (SS), *Pethia ticto* (PT), and *Mastacembelus armatus* (MA)-from Fakirkhali Bazar, Beraid Bridge, and Isapur Bazar in the Balu River, a site influenced by industrial, agricultural, and residential activities. Muscle samples were analyzed for Pb, Cd, Cr, Cu, As, and Ni concentrations using atomic absorption spectrophotometry (AAS). Principal component analysis (PCA) and cluster analysis were employed to identify pollution sources. Human health risks were evaluated using estimated daily intake (EDI), target hazard quotient (THQ), hazard index (HI), and target cancer risk (TR). Concentrations of Pb, Cd, Cr, and As in fish muscles (Pb: 1.99±0.07–6.26±1.98 mg/kg; Cd: 0.04±0.009–0.49±0.023 mg/kg; Cr: 0.43±0.07–4.29±0.32 mg/kg; As: 0.15±0.09–5.48±1.29 mg/kg) exceeded FAO/WHO and MOFL guideline values (Pb: 0.30, Cd: 0.05, Cr: 1.00, As: 1.00 mg/kg). However, Cd in *Mastacembelus armatus* readings at sites 1 and 2 were at or close to the allowable threshold. PCA and cluster analyses indicated that heavy metal pollution primarily originated from anthropogenic sources, including industrial effluents, agricultural runoff, and residential wastewater. Health risk assessments suggested that long-term exposure to elevated Pb, Cr, and As could pose non-carcinogenic risks, while Cd, Cr, As, and Ni may increase cancer risk for local populations consuming contaminated fish. The findings emphasize the need for regular monitoring and coordinated efforts to reduce heavy metal pollution, protect public health, and preserve the Balu River ecosystem.

Keywords: Heavy metals; River pollution; Target hazard quotient; Hazard index; Target cancer risk

Introduction

Water is essential for the survival of all life on Earth. According to the UN Water Report (2021), over 2 billion people live in countries facing water scarcity (UN Water, 2021). Water pollution has become a critical global issue, impacting ecosystems, wildlife, and human health (Yadav, 2024). Human activities have put immense pressure on the planet, leading to various environmental changes that threaten the availability and safety of water. These changes, affecting both the quantity and quality of water, are contributing to environmental disasters and challenges in river basins around the world. Among the various pollutants such as organic pollutants, inorganic pollutants, pathogens, suspended solids, nutrients and agriculture pollutants, thermal, radioactive, and other pollutants (Wasewar *et al*. 2020), heavy metals are particularly concerning due to their toxicity, long atmospheric lifespan, and potential for bioaccumulation in the human body (Niampradit *et al*. 2024). Metals such as cadmium, copper, chromium, iron, mercury, lead, nickel, manganese, and zinc are commonly used in industrial and agricultural processes, and their use continues to rise with the growing global population (Masindi and Muedi, 2018; Mitra *et al*. 2022). This increased reliance on heavy metals has led to greater contamination of the environment, posing a serious ecological and public health threat (Kinuthia *et al*. 2020).

Heavy metals are highly soluble in aquatic environments, making it easier for living organisms to absorb them. Their presence in surface waters can result in toxic effects on aquatic life, with severe consequences for both the affected organisms and human health (Niampradit *et al*. 2024).

Nowadays, heavy metal contamination in river water has become a pressing concern in rapidly growing cities, driven by population expansion, urbanization (Suchi *et al*. 2024), and insufficient water quality management. (Ahmad *et al*. 2010). The substantial release of toxic heavy metals stems from both human activities (Gao *et al*. 2010; Nduka and Orisakwe, 2011) and natural processes, contributing to metal pollution in aquatic environments (Grigoratos *et al*. 2014; Khan *et al*. 2008; Martín *et al*. 2015; Sekabira *et al*. 2010; Zhang *et al*. 2011). Metals from natural sources are generated through geological processes, including the weathering of metal-bearing rocks (Singh *et al*. 2022). Manmade sources are the greatest conclusive for releasing huge amounts of pollutants, particularly heavy metals, that are immensely deleterious to living organisms (Zhang *et al*. 2019). Human activities, such as industrial emissions, the use of metal-containing fertilizers, agricultural runoff from pesticides, herbicides, and fertilizers, along with wastewater discharge from factories and urban areas, are major contributors to heavy metal pollution (Hoang *et al*. 2020). Because of toxicity, abundance, persistence, and subsequent accumulation in the environment, heavy metal pollution has caused great anxiety (Dong *et al*. 2010).

Bangladesh is a riverine country that has a huge number of internal water bodies dispersed throughout the nation (Joadder *et al*. 2015). Fish provide approximately 60% of the animal protein consumed in Bangladesh, underscoring their critical role in nutrition, employment, foreign exchange, and socioeconomic development. The fishing industry contributes 24.41% GDP and 3.61% to the overall GDP (DoF, 2017). Over the past four decades, production has surged sixfold, reaching an estimated 4.6 million tons by 2020–2021 (FRSS, 2017). However, fish are susceptible to toxin accumulation through sediment, water, and ingestion via gills and skin (Soltani *et al*. 2019). Heavy metals, which persist in fish tissues, particularly muscle, are transferred to humans through consumption (Castro-González and Méndez-Armenta, 2008). These non-biodegradable toxins exhibit long-term persistence and bioaccumulation, causing significant cellular and organ damage in humans (Sharma *et al*. 2007; Rahman *et al*. 2013). Thus, freshwater fish consumption poses a serious public health risk due to heavy metal exposure.

Heavy metal accumulation in various important human organs, including the bones, kidneys, and liver, has several negative health effects, including carcinogenic and neurotoxic ones (Sapkota *et al*. 2008; Liang *et al*. 2011). Heavy metals interfere with the functioning of cellular organelles and mechanisms, including the cell membrane, mitochondria, lysosomes, endoplasmic reticulum, nuclei, and enzymes responsible for metabolism, detoxification, and repair. Additionally, they can bind to DNA and proteins, causing structural damage and alterations that disrupt the cell cycle and may result in carcinogenesis or apoptosis. (Tchounwou *et al*. 2012). Heavy metals such as arsenic, cadmium, chromium, copper, nickel, zinc, and lead present serious health hazards to humans. Exposure to these metals can lead to conditions such as arrhythmia, anaemia, neurological damage, memory impairment, respiratory issues, kidney and liver dysfunction, pregnancy complications, including miscarriage, and a heightened risk of cancer, along with various other forms of toxicity (Jaishankar *et al*. 2014). For instance, lead is a neurotoxin that impairs behaviour, survival, growth, and learning in vertebrates, while in humans, it is carcinogenic and disrupts the nervous system and blood formation, whereas cadmium and chromium are associated with cancer and ulcerative conditions (Rakib *et al*. 2021). Consuming too much copper can cause problems with the liver and kidneys (Tuzen, 2009; Mishra *et al*. 2019). Arsenic is so toxic that it has been linked to a variety of health problems, such as cancer, skin injury, and major circulatory system irregularities (Gothandam *et al*. 2020). Lastly, nickel is recognized to be the cause of several pulmonary disorders (Forti *et al*. 2011). Heavy metals not only pose significant risks to human health but also have detrimental effects on aquatic ecosystems. In these ecosystems, fine particles capture heavy metals, leading to their accumulation in sediments, which later re-enter the water (Maceda-Veiga *et al*. 2013; Arulkumar *et al*. 2017; Matouke *et al*. 2020). The presence of heavy metals in both water and sediments has caused substantial ecological damage, particularly endangering hydrophytes and fish species, which are especially susceptible to heavy metal contamination (Islam *et al*. 2014). These metals, which accumulate in fish tissues, particularly in the muscles, are then transferred to humans through consumption (Castro-González and Méndez-Armenta, 2008). Due to their non-biodegradable nature, heavy metals persist in the environment, bioaccumulate in organisms, and cause long-term cellular and organ damage in humans (Sharma *et al*. 2007; Rahman *et al*. 2013). As a result, consuming freshwater fish contaminated with heavy metals presents a significant public health risk.

The Balu river, located in an industrial area with unplanned development, faces severe surface water contamination due to untreated industrial effluents. In the Tejgaon metropolitan

area, over 300 industrial units discharge approximately 12,000 m³ of untreated waste daily, including residues from soap, dyeing, pharmaceuticals, and metal industries. These effluents are directly released into the Begunbari and Narai canals, which flow into the Balu river, threatening the water quality of the Shitalakhya river, a vital source for the Saydabad water treatment plant (Arefin and Rahman, 2019; Sultana *et al*. 2019). As a riverine country with numerous internal water bodies (Joadder *et al*. 2015), Bangladesh heavily relies on fish, which provide about 60% of the animal protein consumed. The fishing industry plays a crucial role in the nation's nutrition, employment, foreign exchange, and socioeconomic development, contributing 24.41% to agricultural GDP and 3.61% to overall GDP (DoF, 2017). Over the last four decades, fish production has increased sixfold, reaching an estimated 4.6 million tons by 2020–2021 (FRSS, 2017). However, fish in these water bodies accumulate toxins through sediment, water, and ingestion via their gills and skin (Soltani *et al*. 2019). These heavy metals, which persist in fish tissues, particularly in muscles, are transferred to humans through consumption (Castro-González and Méndez-Armenta, 2008). As non-biodegradable toxins, they accumulate over time, causing significant cellular and organ damage in humans (Sharma *et al*. 2007; Rahman *et al*. 2013). Heavy metal contamination in Bangladesh's food chain, especially through fish consumption, is a growing concern. Recent studies show that food products, including fish, exceed the heavy metal limits set by the FAO and WHO. Groundwater and river water also contribute significantly to this pollution (Sarker *et al*. 2022). Fish, often used as indicators of heavy metal pollution in water bodies, contain common contaminants such as Cr, Mn, Cd, Cu, As, and Pb (Arulkumar *et al*. 2017; Rahman *et al*. 2019; Hasan *et al*. 2022; Hasan *et al*. 2023).

Previous research has explored heavy metal contamination in fish from various rivers in Bangladesh, including the Buriganga (Ahmad *et al.* 2010; Begum *et al.* 2013; Kawser Ahmed *et al*. 2016), Dhaleswari (Ahmed *et al*. 2009; Ahsan *et al*. 2018; Wahiduzzaman *et al*. 2022), Bangshi (Rahman *et al*. 2012; Rehnuma *et al*. 2016), Karnaphuli (Ali *et al*. 2020; Khatun *et al*. 2021), Shitalakhya (Ahmed M. K. *et al*. 2010; Irin *et al*. 2016; Islam *et al*. 2014), Meghna (Ahmed *et al*. 2019; Bhuyan *et al*. 2016; Sarker *et al*. 2020), and Brahmaputra (Shorna *et al*. 2021; Zakir *et al*. 2019) rivers. However, a thorough investigation into the heavy metal contamination and associated risk assessment in fish species from the highly polluted Balu river, particularly focusing on commonly consumed species such as *Systomus sarana, Pethia ticto,* and *Mastacembelus armatus,* has not been conducted.

In Bangladesh, fish are a primary source of animal protein and a crucial component of the economy. However, increasing pollution in rivers and water bodies presents a significant public health and environmental challenge. With millions relying on fish as a dietary staple, the growing contamination of freshwater resources raises urgent concerns regarding the effects of heavy metal pollution on both aquatic life and human health. This study aims to address this gap by evaluating the bioaccumulation of heavy metals specifically Pb, Cd, Cr, Cu, As, and Ni in the muscle tissues of three prevalent fish species from the Balu river. This research represents the first comprehensive assessment of heavy metal contamination in commonly consumed fish from this river, providing valuable region-specific data. The findings will not only help determine the extent of heavy metal pollution in the Balu river but also offer insights into the broader implications for public health and ecosystem sustainability. By filling a significant knowledge gap regarding contamination levels in native fish species, this study will contribute crucial information to inform effective mitigation strategies. These efforts will be vital in reducing pollution and safeguarding both public health and the environment.

Materials and methods

Dataset description and parameters

For this study, in Bangladesh's Dhaka region, the three fish species mentioned above were taken from three separate locations along the Balu river due to their widespread consumption and abundance in local markets, *Systomus sarana* and *Pethia ticto* are significant from the standpoint of human exposure. A helpful bioindicator of sediment-associated contamination, *Mastacembelus armatus* is a benthic species that lives in bottom sediments, which are known to be heavy metal sinks (Afrin *et al*. 2015). Balu river is situated on the east side of Dhaka city, known as the most polluted area, which is responsible for contaminating Shitalakshya. The Balu river connects to the Shitalakshya via the Suti River near Kapasia, as well as the Turag via the Tongi canal. Several industries are located on the banks of the Balu river. As a result, industrial effluents and other human activities contaminate the river water. We collected the sample from three different sites known as Fakirkhali bazar, Beraid bridge and Isapur bazar in the Balu river. The selected three fish species *Systomus sarana* (SS), *Pethia ticto* (PT) and *Mastacembelus armatus* (MA) were collected from different sites (Fakirkhali bazar, Beraid bridge and Isapur bazar) in the Balu river from February 2022 to June 2022 the Bangladesh Council of Scientific and Industrial Research (BCSIR) to evaluate heavy metal levels such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), arsenic (As),

and nickel (Ni) at the Bangladesh Council of Scientific and Industrial Research (BCSIR). Total 18 samples (2 from each species of each site) were collected.

Sample processing and preparation

Fresh water was used to carefully rinse three fish samples as soon as they were taken, making sure that no silt or other foreign objects were left behind. After that, the fish were put in an inert polythene bag and kept in an icebox as a carrier. To prevent degradation after being transported to the laboratory, the samples were kept in the freezer at a temperature of -20°C. Within a short time (24 hours) of the samples being stored, the analysis process was started.

The fish's muscles were separated and sliced into tiny pieces in the lab using stainless steel scissors that had been previously cleaned with acetone. To ensure complete cleansing, the samples were then repeatedly washed in deionized water to get rid of impurities. The cleaned samples were then dried in a hot-air oven for an entire night at 60°C to eliminate any last traces of moisture. After drying, an agate mortar was used to grind the samples into a powder. To preserve its integrity, the powder was kept in a vacuum desiccator in airtight plastic vials.

The dried powder of each fish sample was then subjected to applying a microwave digestion system (Speed wave, Berghof, Germany). For powder fish samples that had the highest temperature (200°C), highest pressure (35 bar), and highest power (90%), the best three-step procedure was used. We utilized 5 mL of 65% HNO_3 acid (Merck, Germany) and 2 mL of 30% H_2O_2 for digestion (Merck, Germany) procedures. The digesting reagent was applied to 0.3 g of the samples in a Teflon vessel. After the digestion was finished, we transferred the solution to a volumetric flask, and the volume up to 25 mL with Milli-Q water (Millipore, USA). Lastly, we used a PTFE syringe filter (0.45 μm) to filtrate the mixture. Finally, a plastic tube with a screw cover was used to store the entire mixture.

Sample analysis

The heavy metals were examined using an atomic absorption spectrophotometer (iCE-3000, Thermo-Scientific, USA). The certain spectral lines for Pb, Cd, Cr, Cu, As, and Ni were 217.35, 228.67, 357.65, 324.57, 193.7, and 232.0 nm, respectively. For every metal, we prepared four standard solutions (0.01, 0.1, 1.0, and 5.0 ppm). The lowest detection limits for Pb, Cd, Cr, Cu, As, and Ni were 0.05, 0.01, 0.06, 0.03, 0.01 and 0.03 mg/kg, respectively.

Quality control

A standard quality assurance/quality control (QA/QC) system was used to prepare and evaluate the samples to guarantee appropriate and correct research findings. Deionized water was used to clean the equipment and sample containers before use, and 100% acetone was utilized for disinfection. Each analysis session involved the careful preparation of new batches of acid reagents, and the precision of the device was calibrated using standard metal solutions. Four points of calibration variance were successfully attained, and the R^2 value was more than 0.9995. Three replications were performed to ensure equipment reliability. To confirm the precision and accuracy of the analysis, a repeat analysis (RSD < 5%) was also employed. In repeat analysis, three replications were done. Analyses of blank samples were used for adjusting the trace metal amounts (Samad *et al.* 2023). Verifying the precision and dependability of the analytical procedure, the recovery percentages derived from the examination of these established standards fell within the permissible range of 84% to 106%. Each metal was measured three times, and the mean value in mk/kg is provided. The analytical accuracy was further validated using certified reference materials. The certified concentrations, measured concentrations, and calculated recovery percentages for each metal are presented in Table I. The recovery percentages obtained for the analyzed metals ranged from 92.5% to 104.2%, which falls within the acceptable range of 84–106%, confirming the

Table I. Certified values, measured values, and recovery percentages for heavy metal analysis

Metal	Certified value (mg/kg)	Measured value (mg/kg)	Recovery (%)
Pb	1.5	1.46 ± 0.04	97.3
Cd	0.5	0.48 ± 0.01	96
Cr	1.2	1.25 ± 0.03	104.2
Cu	2	1.92 ± 0.05	96
As	0.8	0.74 ± 0.02	92.5
Ni	1	0.95 ± 0.02	95

reliability and accuracy of the analytical procedure. Limit of detection (LOD) and Limit of quantification (LOQ) for metal (Pb, Cd, Cr, Cu, As and Ni) were 0.05, 0.01, 0.06, 0.03, 0.01 and 0.03 mg/kg respectively; 0.17, 0.03, 0.20, 0.10, 0.03 and 0.10 mg/kg respectively. Each metal was measured three times, and the mean value in mg/kg is provided.

Estimated daily intake (EDI)

Estimated Daily Intake (EDI) is widely utilized as it helps bridge the gap between the detected levels of contaminants in food or environmental samples and their potential impact on human health. To determine EDI, factors such as the average daily fish consumption, the average body weight of fish consumers, and the concentration of metals in the fish are taken into account. In this study, the EDI for each examined element (expressed in μg/kg body weight/day) was calculated using Formula-1 (USEPA, 1989a; USEPA, 1989b):

$$EDI = (CM \times FIR) / ABW \ldots\ldots\ldots(1)$$

where the amount of metal in the fish muscle that can be eaten is represented by CM (μg/g wet weight), the typical adult consumption rate of fish is known as FIR: For coastal and riverine areas people which is 77 g/person/day and 49.5 g/person/day, respectively (BBS, 2015; Raknuzzaman *et al.* 2016). The average body weight is illustrated by ABW, which is 60 kg for adults (USEPA, 2011). Fish EDIs for metals (Pb, Cd, Cr, Cu, As, and Ni) were measured using the oral reference dose (RfD) based on 3.5, 1, 3, 40, 0.3, and 20 μg/kg-bw/day (USEPA, 2008; DEA, 2010; USEPA, 2016; Suchi *et al.* 2024).

Target hazard quotient (THQ)

The target hazard quotient (THQ) is a widely used and straightforward approach to assess whether exposure to an individual contaminant poses a potential health risk. It is calculated as the ratio between the estimated exposure level and the established reference dose (RfD), providing insight into whether the exposure remains within safe limits. A THQ value equal to or greater than 1 indicates a potential health risk for exposed individuals, suggesting the need for precautionary measures to be taken (USEPA, 2011). The USEPA (2011) provided the following formula (2) to determine THQ:

$$THQ = (EF \times ED \times FIR \times CM \times 0.001) / (RfD \times ABW \times ATn) \ldots\ldots(2)$$

From the above equation, the exposure frequency is indicated by EF (365 days/year) (USEPA, 2011), ED stands for exposure duration (30 years for non-carcinogenic risk) (USEPA, 2011), The average fish ingestion rate is known as FIR: For people in coastal and riverine areas which are 77 g/person/day and 49.5 g/person/day, respectively (BBS, 2015; Raknuzzaman *et al.* 2016), the metal concentration is denoted by CM (mg/kg w w.), RfD illustrates the reference dose (mg/kg/day), the average adult body weight is known as ABW (60 kg), and ATn represents the average contact time for non-carcinogens (EF × ED) (USEPA, 2011).

Hazard index (HI)

For studies assessing exposure to multiple pollutants, the hazard index (HI) is a crucial metric as it accounts for the combined effects of various contaminants. By offering an integrated view of potential health risks, HI serves as a comprehensive tool for evaluating the overall impact of cumulative pollutant exposure. To quantify and assess the risk that certain metals cause to human health, the sum of the THQ of each metal is referred to as the hazard index, which is followed by the USEPA recommendation (USEPA, 2022a) and used to assess non-carcinogenic risks from different heavy metals (Hossain *et al.* 2018). Below is the equation (3) for the HI (USEPA, 2022b):

$$HI = THQ (Metal 1) + THQ (Metal 2) + \ldots\ldots + THQ (Metal n) \ldots\ldots(3)$$

Target cancer risk (TR)

The TR refers to carcinogenicity. TR is calculated using the formula (4) found in the USEPA (United States Environmental Protection Agency) Region III Risk-Based Concentration Table (USEPA, 2011).

The equation that was used to compute TR is given below:

$$TR = (EF \times ED \times FIR \times CM \times CPSo \times 0.001) / (ABW \times ATc) \ldots\ldots(4)$$

In this equation, previously, EF, FIR, CM, ABW, and ATc were clarified. The length of contact is ED (70 years for carcinogenic risk) (USEPA, 2011), CPSo $(mg/kg/day)^{-1}$ is the carcinogenic potency slope (USEPA, 2012). Pb, Cd, Cr, As, and Ni consumption alone had TR values established due to the potential for cancer from these metals. CPSo values $(mg/kg/day)^{-1}$ for Pb, Cd, Cr, As, and Ni are 0.0085, 6.3, 0.5, 1.5, and 0.84 (USEPA, 2012; USEPA, 2000; Suchi *et al.* 2024).

Statistical analysis

We showed the mean and standard deviations (SD) of the concentration of potentially hazardous components in fish muscle. The conventional one-way ANOVA for differences among sample sites was calculated using GraphPad Prism 8. and Tukey's multiple comparisons test for pair-wise comparison of sample sites and MPL. Using a Pearson correlation, the associations between the metals in fish were found. To identify the probable sources of heavy metals in the fish, principal component analysis (PCA) was performed. For PCA, components with eigenvalues greater than 1 were retained, and Varimax rotation with Kaiser normalization was applied to simplify the factor structure and improve interpretability. Kaiser normalization scales the component loadings by the variance of each variable before rotation, ensuring that variables with higher variance do not dominate the rotated solution. Furthermore, to assess a comprehensive understanding of the distribution of potentially harmful substances in the fish, a dendrogram was constructed using hierarchical cluster analysis (HCA) with Ward's linkage method. All Pearson correlation, PCA, and HCA analyses were conducted using SPSS (v26.0). A statistically significant level of probability was indicated as ∗ for $p < 0.05$, ∗∗ for $p < 0.01$, ∗∗∗∗ for $p < 0.0001$, and ns for nonsignificant.

Results and discussion

Concentration levels of heavy metals

The average concentrations and standard deviations of heavy metals (Pb, Cd, Cr, Cu, As, and Ni, As) in the three fish species at three stations are represented in Fig. 1 and Table II. The concentrations of Cu and Ni among the six metals under analysis were below permitted limits, but those of Pb, Cd, Cr, and As exceeded their respective MPLs (Table II). The ranges of heavy metal concentrations found in fish are as follows: Pb 1.99±0.07 to 6.26; Cd 0.04±0.009 to 0.49±0.023; Cr 0.43±0.07 to 4.29±0.32; Cu 6.74±0.97 to 12.64±1.69; As 0.15±0.09 to 5.48±1.29 and Ni 1.08±0.56 to 3.73±1.32 mg/kg, respectively.

According to the findings of this study, the maximum Pb concentration was found in *Mastacembelus armatus* (MA) in sampling sites 1 and 3, which were 6.26±1.98 and 5.64±1.74 mg/kg. But *Pethia ticto* (PT) contained a higher amount of Pb in sampling site 2. However, at three sampling sites, *Systomus sarana* (SS) contained a lower

amount of Pb (3.28±0.08, 2.98±0.07, and 1.99±0.07 mg/kg). Every station exhibited significant Pb levels that exceeded the recommended acceptable limits (Table II). The contents of Pb suggested a high concentration of lead in the water, which was deposited in the fish tissues via bioaccumulation. In the Balu river, Banu *et al.* (2023) found that the concentration of Pb was 0.652 mg/kg in the dry season. Which was lower than the present study. A combination of temporal pollution escalation, regional heterogeneity, species-related bioaccumulation variances, and methodological variations is probably responsible for the higher Pb amounts found in this study. On the other hand, in the Shitalakshya river, *Systomus sarana*, *Pethia ticto* and *Mastacembelus armatus* fish had 0.001, 0.003 and 0.005 mg/kg lead content (Tolkou *et al.* 2023). Lead (Pb) is a hazardous heavy metal that leads to cancer in humans (Yap and Al-Mutairi, 2022). Lead is widely used in paints and pigments, batteries, metal goods, electronics, and fuel additives that prevent knocking. (Sharma *et al.* 2014; Carocci *et al.* 2016). Fish that are continuously exposed to such harmful metals experience morphological, behavioral, physiological, and reproductive problems (Wang *et al.* 2014; Reynolds *et al.* 2018). Chronic exposure to lead (Pb) is closely linked to cardiovascular consequences, anemia, renal impairment, and neurotoxicity, especially in children (WHO, 2021; USEPA, 2023).

The Cd had the lowest concentration of any other metal in the three species of fish that were examined in this analysis. The pattern of Cd accumulation in fish muscle in this entire study was PT > SS > MA. The concentration of Cd in PT, SA and MA varies from 0.39±0.078 to 0.49±0.023, 0.29±0.003 to 0.38±0.05 and 0.04±0.009 to 0.09±0.023 mg/kg in three stations (Table II). All locations had results that were significantly greater than MPL, except MA in locations 1 and 2. The current study's results are consistent with those of the earlier investigation (Banu *et al.* 2023). Tolkou *et al.* (2023) reported studied, the concentration of Cd was 0.001 mg/kg in three fishes (*Systomus sarana*, *Pethia ticto* and *Mastacembelus armatus*) at the Shitalakshya river. The main sources of cadmium include industrial processes, sewage wastes, and fertilizers (containing cadmium-phosphorus) (Sharma *et al.* 2014). It is primarily found in freshwater environments as divalent cations (Cd^{2+}), which increase its bioavailability to living things (Dutton and Fisher, 2011). Cd has a deleterious impact on various organs, including kidney, lungs, bones, placenta, brain, and central nervous system (Castro-González and

Méndez-Armenta, 2008). Cd exposure during pregnancy raises the risk of premature death and decreases birth weight (Suchi *et al.* 2024).

At sampling sites 1 and 2, the Cr concentration showed the following order: SS > PT > MA but PT > SS > MA represents sampling site 3. Station 1 and 2, SS and PT fish contained Cr, which were 4.29±0.32 and 2.96±0.19 mg/kg; 3.24±0.075 and 2.28±0.098 mg/kg, whereas MA 0.73±0.03 and 0.58±0.05 mg/kg. On the other hand, sampling site 3, SS, PT and MA fish Cr concentrations were 3.39±1.08, 3.87±0.29 and 0.43±0.07 mg/kg, respectively. SS and PT fish of all sampling sites, Cr loads that are exceed the MPL value but MA is less than the MPL (Table-I). The values of Cr in the current study are higher than Banu *et al.* (2023), which was 0.603 mg/kg. At Shitalakshya river, Dhaka, Bangladesh, *Systomus sarana*, *Pethia ticto,* and *Mastacembelus armatus* fish contain low Cr values (0.004, 0.003, 0.001 mg/kg respectively) (Tolkou *et al.* 2023). Many industrial processes along the Balu River, such as industrial welding, chrome plating, dyeing, and wood preservation, have been linked to the presence of Cr in water as well as in fish. Furthermore, the release of industrial waste into the river exacerbates the contamination. Chromium (Cr) is a significant pollutant and carcinogen that can lead to a variety of lung health issues, including tumours, fibrosis, emphysema, and lung inflammation (Forti *et al.* 2011; Hasan *et al.* 2023).

Arsenic (As) content in fish muscle decreased in the following manner at the three sampling sites: MA > PT > SS. The results of SS and PT fish in all monitoring locations (1, 2, and 3) were considerably lower than MPL, but MA was higher than MPL, which was 5.48±1.29, 4.78±2.25, and 5.31±1.46 mg/kg, respectively as shown in Table II. This study is the first time to investigate arsenic contamination in fish from the Balu river, Bangladesh. Other studies have shown that As in river water comes from industry, fertilizer, and pesticide use, as well as metal refining, supporting the origins of As in water and can be harmful to the human liver and cardiovascular systems (Lee *et al.* 2003). Tolkou *et al.* (2023) reported, that *Systomus sarana*, *Pethia ticto,* and *Mastacembelus armatus* fish collected from the Shitalakshya River, Bangladesh had lower values of As (*Systomus sarana* and *Pethia ticto*: 0.001 mg/kg; *Mastacembelus armatus*: 0.004 mg/kg). Exposure to arsenic (As) is linked to skin lesions, heart illness, and a higher risk of bladder, lung, and skin malignancies (IARC, 2012; WHO, 2018).
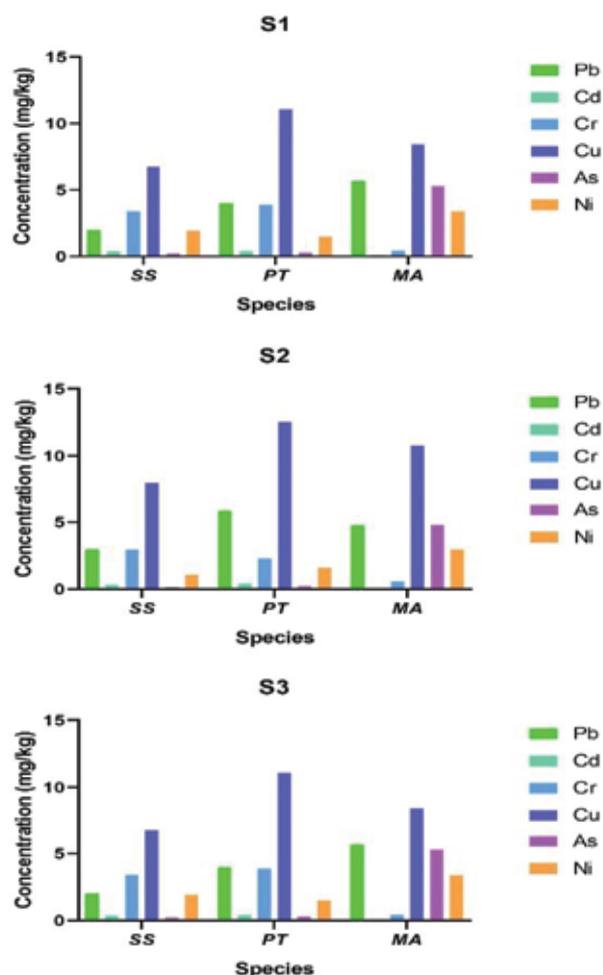

Fig. 1. Heavy metal content of different fishes and sampling site

This study revealed that the concentration pattern of Cu was PT > MA > SS in sampling sites 2 and 3, but in site 1, it was MA > PT > SS. On the other side, Ni was MA > PT > SS in locations 1 and 2 but MA > SS > PT in location 3 is shown in Table II. The remaining concentrations of Cu and Ni in river stations were well below the recommended levels (MPL values 30.0 and 80.0 mg/kg), which was reported by Bristy *et al.* 2021. On the other hand, metal concentration (Pb, Cd, Cr, and As) of fish in Bangladesh (Dhaka), China (Zhejiang), South Korea ware 0.4-2.1, 0.021-0.082, 0.05-0.74 mg/kg respectively; NA, 0.002-0.040, LOD-0.13 mg/kg respectively; 0.09-0.4, 0.016-0.173, 0.09-1.32 mg/kg respectively; 0.4-1.3, 0.315-3.175, 1.23-44.54 mg/kg respectively (Han *et al.* 2021).

Table II. Concentrations (mg/kg) of heavy metals in fishes caught from Balu river

Sampling site	Fish name	Common name	Organ	Pb	Cd	Cr	Cu	As	Ni
	Systomus sarana (SS)	Olive barb		3.28±0.08	0.29±0.003	4.29 ±0.32	7.62±1.20	0.17±0.08	1.29±0.78
Sampling site-1	*Pethia ticto (PT)*	Ticto barb	Muscle	5.32±1.13	0.49±0.023	3.24±0.075	10.87±2.39	0.28±0.09	1.46±0.98
	Mastacembelus armatus (MA)	Tire-track Spinyeel		6.26±1.98	0.04±0.009	0.73±0.03	12.64±1.69	5.48±1.29	3.73±1.32
	Systomus sarana (SS)	Olive barb		2.98±0.07	0.32±0.008	2.96±0.19	8.02±0.09	0.15±0.09	1.08±0.56
Sampling site-2	*Pethia ticto (PT)*	Ticto barb	Muscle	5.86±1.21	0.39±0.078	2.28±0.098	12.56±2.53	0.22±0.06	1.59±0.88
	Mastacembelus armatus (MA)	Tire-track Spinyeel		4.76±1.08	0.05±0.002	0.58±0.05	10.78±2.18	4.78±2.25	2.98±0.88
	Systomus sarana (SS)	Olive barb		1.99±0.07	0.38±0.05	3.39±1.08	6.74±0.97	0.23±0.07	1.92±0.87
Sampling site-3	*Pethia ticto (PT)*	Ticto barb	Muscle	3.97±1.04	0.39±0.051	3.87±0.29	11.09±2.23	0.29±0.05	1.49±0.29
	Mastacembelus armatus (MA)	Tire-track Spinyeel		5.64±1.74	0.09±0.023	0.43±0.07	8.45±1.97	5.31±1.46	3.37±1.07
Recommended maximum permissible limit (MPL) (mg/kg wet weight)				0.30	0.05	1.0	30.0	1.0	80.0
References				Bristy *et al.* 2021					

Table III. Correlation study between the metals found in fish samples from various places

Correlation	Pb	Cd	Cr	Cu	As	Ni
Pb	1					
Cd	-0.386	1				
Cr	-0.658	.830**	1			
Cu	.802**	-0.127	-0.366	1		
As	0.584	-.934**	-.923**	0.273	1	
Ni	0.570	-.873**	-.890**	0.290	.968**	1

** Correlation is significant at the 0.01 level (2-tailed).

In the global comparison of contamination levels of metals in the fish, we can say that all metals showed higher concentration in the present study except As. Metal concentration in fish could also be caused by metal-contaminated feed from effluent released into rivers from various industries nearby the river, as well as other anthropological sources. According to this study, the Balu River has a very high frequency of Pb, Cd, Cr, and As contamination, and if this metal pollution continues unabated, the river may become uninhabitable for marine organisms.

Correlation, ANOVA test, principal component analysis and hierarchical cluster analysis

An investigation of Pearson's correlation was carried out between the metals found in fish, as demonstrated in Table III. The results display that Pb and Cu, Cd and Cr, As and Ni are significantly and positively correlated (r =0.802, r =0.830, r =0.968; $p < 0.01$, $p < 0.01$, $p < 0.01$). On the other hand, Cd and As, Cd and Ni, Cr and As, Cr and Ni are significantly and negatively correlated (r = -0.934, r = -0.873, r = -0.923, r = -0.890; $p < 0.01$, $p < 0.01$, $p < 0.01$, $p < 0.01$). For the Pb-As and Pb-Ni

couples, a moderately positive association has been found (r = 0.584 and r = 0.570). But Pb-Cd, Pb-Cr and Cr-Cu show a moderate and negative correlation (r = -0.386, r = -0.658, and r = -0.366). Both positive and negative correlations were observed in the study. The metal concentrations in fish tissues suggest a common origin, likely associated with anthropogenic activities around the river. Additionally, both endogenous and exogenous factors may have influenced the bioaccumulation of these metals (Jabeen and Chaudhry, 2010). In contrast, the negative correlations indicate that some metals may have originated from different sources, indicating distinct contamination pathways (Hossain *et al.* 2022).

An essential tool for researchers studying several experimental groups and one or more control groups is the Analysis of Variance (ANOVA) test. ANOVA and Tukey's multiple comparison test were carried out between the metals in the sampling site and MPL in fish, as provided in Fig. 2 and 3. In the ANOVA test, the correlation between sampling sites S1 to S2, S2 to S3 and S1 to S3 are nonsignificant for all metals (Pb, Cd, Cr, Cu,
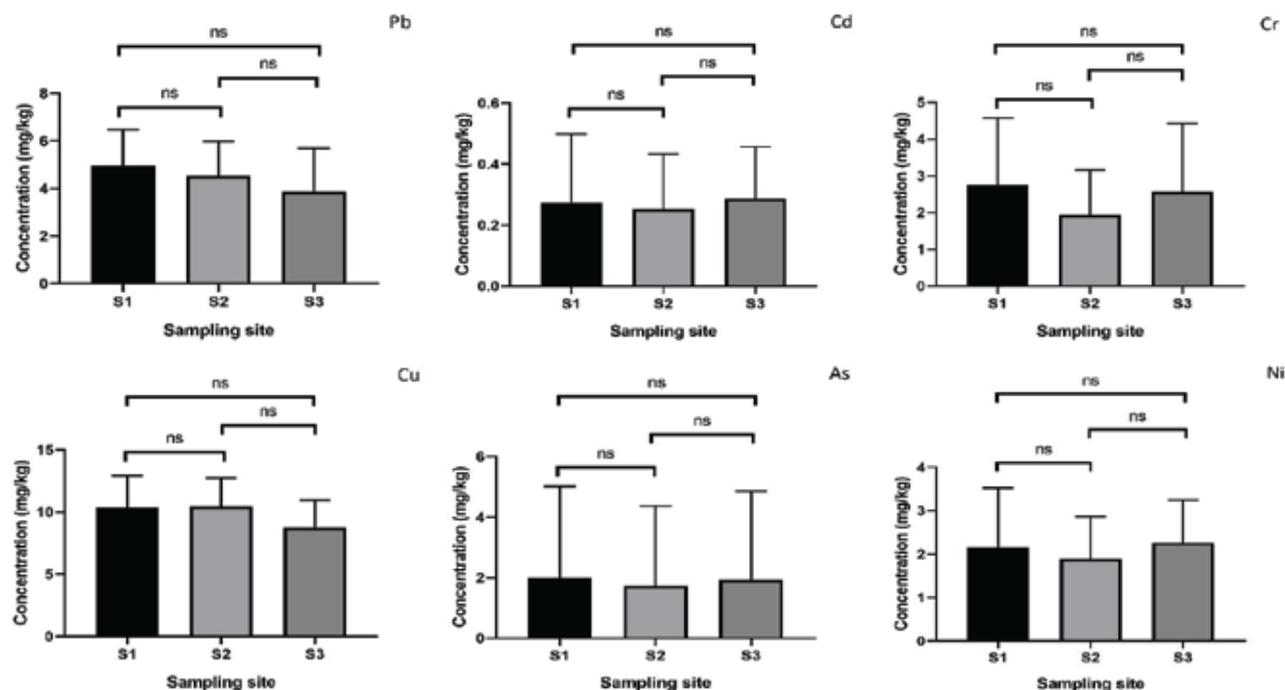

Fig 2. ANOVA test for multiple metals of sampling site and the Tukey's multiple comparisons test for pair-wise comparison of different sampling sites. A statistically nonsignificant level of probability was defined as ns
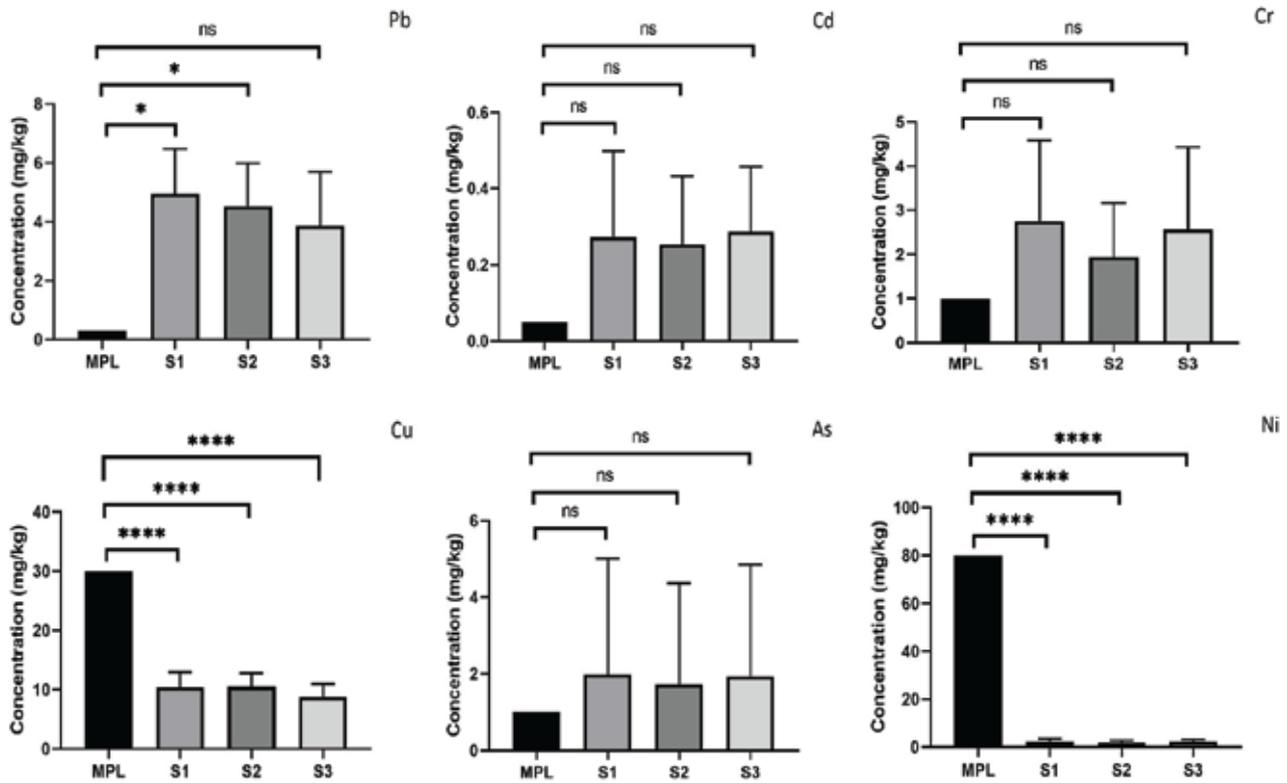
Fig. 3. ANOVA test for multiple metals of sampling site and the Tukey's multiple comparisons test for pair-wise comparison of MPL (Recommended Maximum Permissible Limit) with different sampling sites. A statistically significant level of probability was defined as * $p < 0.05$, **** $p < 0.0001$ and ns nonsignificant
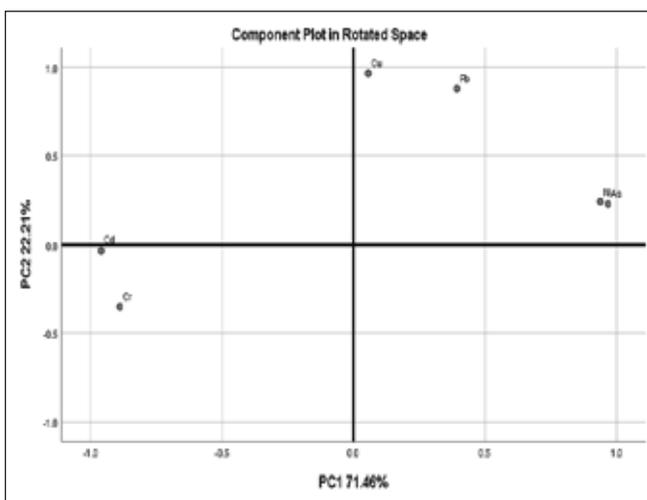

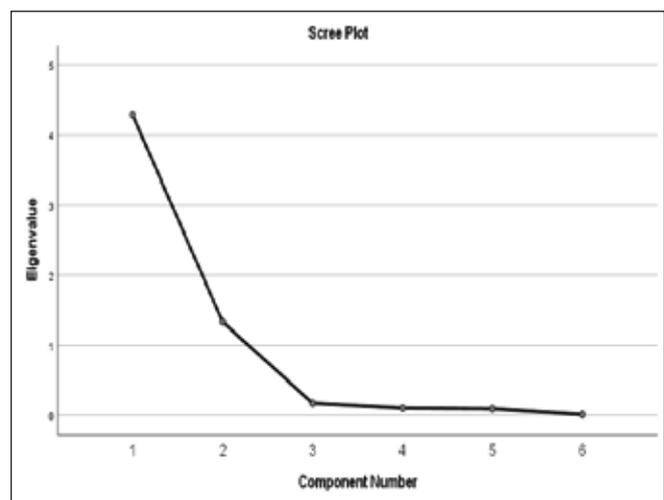**Fig. 4. Principal component analysis loading plots for the two components**

Fig. 5. Scree plot of principal components for metals in Balu river fish

As, and Ni) shown in Fig. 2. On the other hand, the correlation between MPL to sampling site S1, MPL to S2, are significant ($p < 0.05$) whereas MPL to S3 is insufficient for Pb (Fig. 3). In addition, for Cu and Ni, the correlation between MPL-S1, MPL-S2 and MPL-S3 are significant ($p < 0.0001$) but MPL-S1, MPL-S2 and MPL-S3 are insignificant for Cd, Cr, and As (Fig. 3).

The most commonly used technique to locate the origins of potentially hazardous materials is principal component analysis (PCA) (Proshad *et al.* 2019). In the present study (Fig. 4 and Table IV) PCA was employed to examine the patterns of metal contamination in fish from the Balu River. According to Kaiser's criterion, principal components with eigenvalues greater than 1 were retained, resulting in two components both before and after Varimax rotation. The first principal component (PC1) included Pb, Cu, As, and Ni, while the second principal component (PC2) consisted of Pb, Cd, and Cu, accounting for 71.46% and 22.21% of the total variance, respectively. The scree plot (Fig. 5) also indicated a clear inflection after the second component, further supporting the retention of these two components. Varimax rotation with Kaiser normalization simplified the component structure and improved interpretability, highlighting potential source groupings of metals. The PCA results suggest that the observed metal contamination in fish may originate from multiple anthropogenic sources, including industrial effluents and agricultural practices. Overall, PCA condensed the dataset into two principal components, which together explained 93.67% of the total variance, providing a robust and interpretable understanding of metal distribution patterns in the Balu River fish.

Multivariate hierarchical cluster analysis (HCA) was used to examine the degree of similarity or dissimilarity

Table IV. Total variance explained and component matrices for the potentially toxic elements in fish

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.288	71.460	71.460	4.288	71.460	71.460	3.686	61.428	61.428
2	1.333	22.212	93.672	1.333	22.212	93.672	1.935	32.244	93.672
3	0.173	2.881	96.553						
4	0.103	1.716	98.269						
5	0.093	1.545	99.814						
6	0.011	0.186	100.000						

Elements	Component matrix			Rotated component matrix	
	PC1	PC2		PC1	PC2
Pb	0.747	0.606		0.393	0.878
Cd	-0.872	0.403		-0.960	-0.034
Cr	-0.951	0.089		-0.889	-0.349
Cu	0.485	0.836		0.056	0.965
As	0.966	-0.233		0.968	0.228
Ni	0.946	-0.208		0.938	0.242

Extraction method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization.

between the study locations, as seen in Fig. 6. Two clusters that were determined to be statistically significant and unique were produced by the analysis. Two sub-clusters, designated as (a) and (b), were further separated from the original cluster. Sub-cluster (a) included location and sample S1 (SS), S2 (SS), and S3 (SS), whereas sub-cluster (b) contained location and sample S1 (PT), S3 (PT), and S2 (PT). The other cluster, denoted as subclass (c), consisted of S2 (MA), S3 (MA), and S1 (MA). As seen in Fig. 6, these clusters were determined by comparing the sources of contamination. The research may have identified a particular clustering of these stations due to the considerable pollution load resulting from industrial processes and human activity. Degradation of the ecosystem in these places is caused by pollution stress from numerous sectors, including the chemical industries, paper industries, cement industries, fertilizer industries, pharmaceutical companies, dyeing industries, and textile industries. There may be differences in the sources of pollution in Clusters 1 and 2 (Mohiuddin *et al.* 2010).
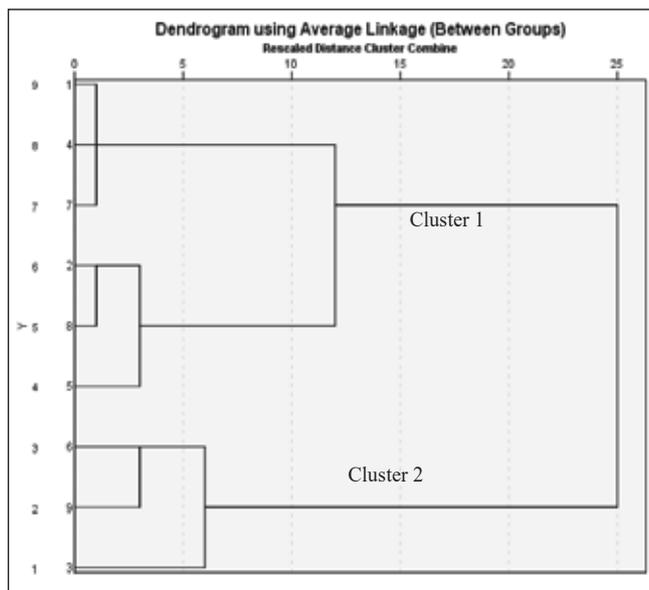

Fig. 6. Multivariate hierarchical cluster analysis among studied locations by Ward linkage

Cluster analysis was shown to elucidate the correlations between the potentially harmful substances examined and their likely sources. This analysis yielded a dendrogram illustrating the diverse clustering patterns of the toxic elements, as depicted in the accompanying Fig. 7. The

metals grouped within the same cluster were assumed to share similar characteristics. There are two distinct clusters: the first cluster subdivision is mainly made up of As, Ni, Cd, and Cr, along with Pb, and the second cluster is composed solely of Cu, which likely resulted from anthropogenic and natural sources. Compared to cluster 2, cluster 1 would be more hazardous, according to this examination of the metals. Similarly, Shaheen *et al.* (2024) also identified a cluster containing As, Ni, Pb, Cr, and Cd, attributing it to a mix of human activities. Consequently, it can be inferred that the presence of these heavy metals in fish is attributable to emissions from chemical industries, batteries and electrical equipment, fertilizers, textiles, and fuel sources (Rakib *et al.* 2021).
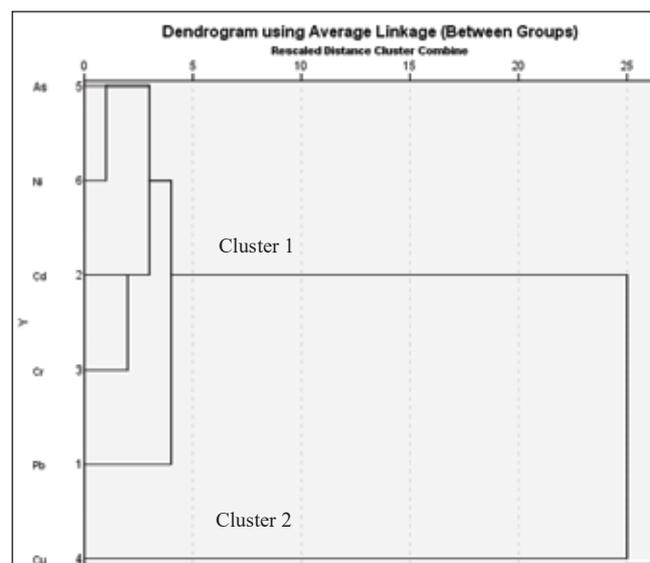

Fig. 7. A hierarchical cluster analysis among metals following the Ward linkage method

Estimated daily intake (EDI)

The EDIs of specific heavy metals obtained from eating fish are shown in Fig. 8 for river and coastal area people. Except for Pb, Cr, and As, the results show that all metals' EDI values (Cd, Cu and Ni) are within the acceptable daily intake limit (RfD). The RfD value was used to evaluate the EDIs because low EDI values relative to RfD suggest less lifetime risk to health from any harmful consequences (DOH, 2007). The Pb EDI value that was highest was found in MA fish in S1 and S3 both river and coastal area people (5.16, 8.03 and 4.65, 7.24 μ g/kg body weight/day).
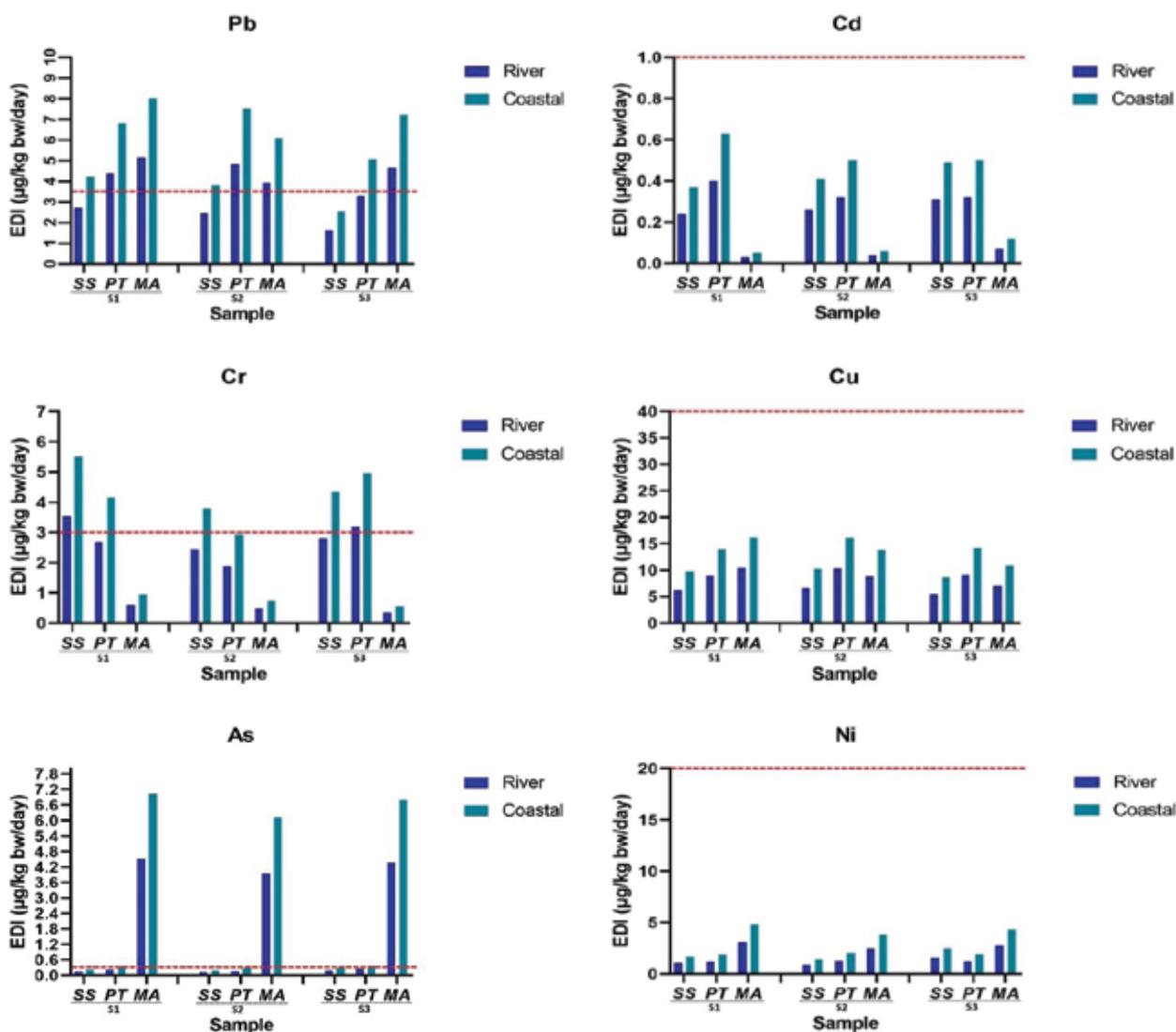
Fig. 8. Bar graph showing Estimated Daily Intake (EDI) of selected metals from fish at different site of riverine and coastal areas people, in comparison with oral reference dose (RfD)

In sampling site S2, PT fish had a higher EDI value (4.83 and 7.52 µg/kg body weight/day for both river and coastal area people). Elevated EDI of Pb was also found in PT (4.39 and 6.83 µg/kg body weight/day) and MA (3.93 and 6.11 µg/kg body weight/day) from S1 and S2 for river and coastal area people. In addition, sampling sites S1, S2, and S3 of SS, SS, and PT fish also had EDI values (4.21, 3.82 and 5.09 µg/kg body weight/day) only for coastal people. Secondly, the highest values of EDI for Cr were found in SS and PT fish from S1 and S3 (river and coastal), which were 3.54, 5.51 and 3.19, 4.97 µg/kg body weight/day, respectively. Furthermore, for coastal people EDI values of Cr were 4.16, 3.80,

4.35 µg/kg body weight/day, respectively (PT, SS and SS) from S1, S2 and S3 locations. Finally, MA fish was giving EDI value both river and coastal side people from S1, S2 and S3 (4.52, 7.03; 3.94, 6.13; 4.38, 6.81 µg/kg body weight/day, respectively). These fish may pose a serious health risk to customers at the polluted stations because their EDI values of Pb, Cr and As surpassed the RfD value. Furthermore, the metals' EDIs (Pb, Cr and As) in fish in the coastal areas were higher than those in the river areas, because of the average value of FIR (fish ingestion rate) which, was 49.5 and 77 g/person/day for people in the riverine and coastal areas, respectively.

Human health risk assessment

There are two categories of health hazards associated with fish chemical presence: carcinogenic and non-carcinogenic. Human health may be adversely affected by the aforementioned hazards.

Non-carcinogenic risk: Target hazard quotient (THQ) and Hazard index (HI)

The non-carcinogenic health hazards to river and coastal side consumers from fish have been that evaluated using THQ and HI, as demonstrated in Tables V and VI. The THQ is a ratio compares a pollutant's measured dosage to a reference dose level. The risk level resulting from the pollutant exposure is shown by the THQ method assessment, even if it does not offer a quantitative estimate of the likelihood that an exposed population will experience a reverse health consequence. In reference to single elements, THQ and HI more than 1 indicate potential adverse health effects (Enyoh, and Isiuku, 2020). The THQ values of Pb in MA (S1, S2 and S3) and PT (S1 and S2) of the river and coastal people show that THQ > 1 but SS is more than 1 for coastal people from S1 and S2. On the other hand, for Cr, SS and PT (S1 and S3) both river and coastal people illustrate that THQ is greater than 1. Finally, the value of THQ, As in MA (S1, S2 and S3) of the river and coastal people displays that, THQ more than 1. However, the values of Cd, Cu and Ni are below 1. This finding implies that consuming fish from these locations would expose people to considerable non-carcinogenic health concerns because of Pb, Cr and As intake. Hypertension, heart disease, neurological system dysfunction, kidney failure, even

Table V. Target Hazard Quotient (THQ) for different metals from fish consumption at different stations of river and coastal area people

Sampling site	Fish Name	Target Hazard Quotient (THQ)											
		Pb		Cd		Cr		Cu		As		Ni	
		River	Coastal	River	Coastal	River	Coastal	River	Coastal	River	Coastal	River	Coastal
Sampling site-1	SS	0.77314	1.20267	0.23925	0.37217	1.17975	1.83517	0.15716	0.24448	0.46750	0.72722	0.05321	0.08278
	PT	1.25400	1.95067	0.40425	0.62883	0.89100	1.38600	0.22419	0.34875	0.77000	1.19778	0.06023	0.09368
	MA	1.47557	2.29533	0.03300	0.05133	0.20075	0.31228	0.26070	0.40553	15.07000	23.44222	0.15386	0.23934
Sampling site-2	SS	0.70243	1.09267	0.26400	0.41067	0.81400	1.26622	0.16541	0.25731	0.41250	0.64167	0.04455	0.06930
	PT	1.38129	2.14867	0.32175	0.50050	0.62700	0.97533	0.25905	0.40297	0.60500	0.94111	0.06559	0.10203
	MA	1.12200	1.74533	0.04125	0.06417	0.15950	0.24811	0.22234	0.34586	13.14500	20.44778	0.12293	0.19122
Sampling site-3	SS	0.46907	0.72967	0.31350	0.48767	0.93225	1.45017	0.13901	0.21624	0.63250	0.98389	0.07920	0.12320
	PT	0.93579	1.45567	0.32175	0.50050	1.06425	1.65550	0.22873	0.35580	0.79750	1.24056	0.06146	0.09561
	MA	1.32943	2.06800	0.07425	0.11550	0.11825	0.18394	0.17428	0.27110	14.60250	22.71500	0.13901	0.21624

Table VI. Hazard Index (HI) from fish consumption at different stations of river and coastal area people

Sampling site	Fish Name	Hazard Index (HI)	
		River	Coastal
Sampling site-1	SS	2.87002	4.46447
	PT	3.60367	5.60571
	MA	17.19388	26.74604
Sampling site-2	SS	2.40289	3.73783
	PT	3.25967	5.07060
	MA	14.81301	23.04246
Sampling site-3	SS	2.56553	3.99083
	PT	3.40948	5.30363
	MA	16.43772	25.56979

genotoxicity, allergic reactions, anemia, burns, and sores especially in the stomach and small intestine, gastrointestinal tract problems, respiratory tract problems are all brought on by lead, chromium, and arsenic poisoning in humans (Mandal and Suzuki, 2002; Lanphear *et al.* 2018; Tamele and V´azquez Loureiro, 2020; Hossini *et al.* 2022). Fish tissues in Nigeria have been shown to contain high levels of metals like lead, cadmium, and arsenic, with Target Hazard Quotient (THQ) values greater than 1, suggesting possible non-carcinogenic health hazards for consumers due to industrial discharge and urban runoff in developing regions (Adegbola *et al.* 2021).
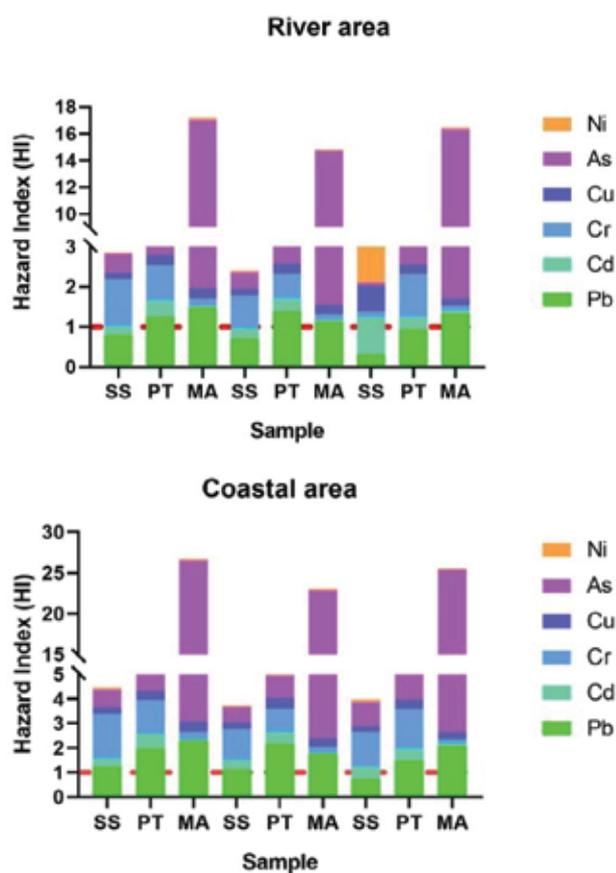

Fig. 9. Composition of Hazard Index (HI) for metals intake from fish at different stations of river and coastal area

The total impact of all the metals taken into account was greater than 1 (HI > 1) in all fish samples for S1 S2 and S3 (Fig. 9). As a result, eating fish that was exposed to a combination of the six metals that were investigated in these locations could be harmful to one's health. The main risk sponsors in this study are As (69.87%), Pb (14.19%) and Cr

(8.99%). Similar to THQ, HI is unable to establish the dose–response relationship, so it is unable to quantify risk directly (USEPA, 1989a). The high value of THQ and HI are responsible for all metals concentration. Many factors, including fast urbanization, industrialization, and insufficient waste management systems, which are responsible for the high concentrations of heavy metals in particular riverine regions.

Carcinogenic risk: Target cancer risk (TR)

Some substances can cause cancer when exposed to them over time. The IARC classified As, Pb, Cd, Ni, Cr, and Ni as carcinogenic (IARC, 2011; Zhang *et al.* 2015; Haque *et al.* 2022; Ali et al. 2022; Kubra *et al.* 2022). Fig. 10 displays the spatial distribution of metals at different sites according to their median levels. The TR values for Pb intake through all fish (SS, PT and MA) for three sampling site varies from 1.40 x 10-5 to 4.39 x 10-5 and 2.17 x 10-5 to 6.82 x 10-5 respectively, for river and coastal area people. On the other hand, TR values of fishes for Cd, Cr, As and Ni range from 4.95 x 10-4 to 6.06 x 10-3 and 7.70 x 10-4 to 9.43 x 10-3; 1.77 x 10-4 to 1.77 x 10-3 and 2.76 x 10-4 to 2.75 x 10-3; 1.86 x 10-4 to 6.78 x 10-3 and 2.89 x 10-4 to 1.02 x 10-2; 1.51 x 10-3 to 5.23 x 10-3 and 2.36 x 10-3 to 8.14 10-3 respectively, for all locations (S1, S2 and S3) both river and coastal people. Between 1 x 10-6 to 1 x 10-4 is the range of acceptable cancer risk, whereas lower 1 x 10-6 and above 1 x 10-4 are considered harmless and insufferable (USEPA, 1989b, 2010).

The TR values for Pb in this investigation indicate that all values are within the acceptable range. All fish from S1, S2, and S2 for river and coastal people to eat exhibit a carcinogenic risk for Cd, Cr, As, and Ni exposure because the values are above the TR permissible limits. It's caused genomic instability, oxidative stress-related DNA damage, and block DNA repair mechanisms (Suchi *et al.* 2024). Consequently, eating fish species that have been exposed to Cd, Cr, As, and Ni puts residents of Bangladesh's river and coastal areas at risk for cancer for the rest of their lives.

The discovery of heavy metal pollution in Balu River fish raises serious issues for the ecosystem and public health. Implementing these findings effectively can aid in the development of focused plans for sustainable management and environmental preservation in the area. The key findings of this study are presence of hazardous metals like lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As), in fish tissues indicates industrial, agricultural, and municipal pollution sources. Costal peoples are among the vulnerable groups that are more at risk due to bioaccumulation effects. Heavy metal contamination has reduced the Balu river's capacity to support sustainable fisheries and ecosystem
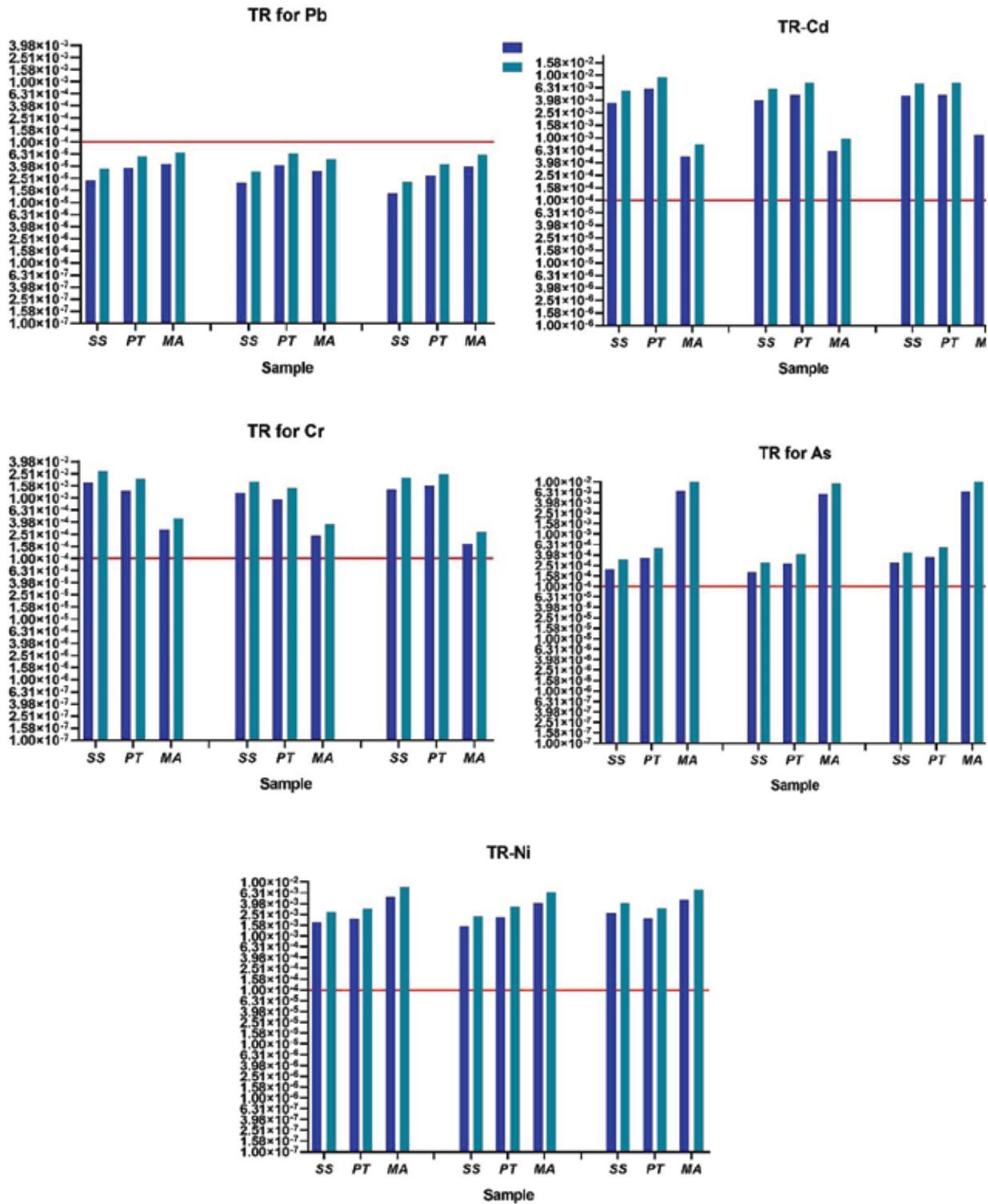
Fig. 10. Target cancer risk (TR) for metals intake from fish at different stations of river and coastal area

services, negatively affecting aquatic biodiversity (Oros, 2025). Metals can cause biomagnification as they move from plankton and benthic creatures to higher trophic levels like fish, which may have an impact on predators like people and birds (Naz *et al.* 2025). To address this, a comprehensive, site-specific strategy is essential. First, enforce regulations requiring all industrial effluents to be treated to acceptable standards before discharge, and promote organic farming to minimize the use of chemical fertilizers and pesticides. Second, establish a real-time monitoring system to track heavy metal levels in fish, water, and sediments. Finally, implement awareness programs to educate local communities about the risks of river pollution and practical steps to mitigate its impact.

This study provides one of the few integrated assessments of heavy metal accumulation, human exposure, and associated health risks linked to fish consumption from the Balu river. Multiple complementary approaches were employed, including concentration analysis, multivariate statiical techniques (correlation, PCA, and HCA), and health risk assessment indices (EDI, THQ, HI, and TR), enabling a comprehensive evaluation of ecological and public health implications. In addition, rigorous quality assurance and quality control procedures, validated analytical methods, and replicated measurements enhance the reliability and accuracy of the generated data. However, several limitations should be acknowledged. First, metal concentrations were measured only in fish muscle tissue, without concurrent measurements in water or sediment, so the multivariate analyses reflect association patterns rather than definitive source identification. Second, the small sample size limits the statistical robustness and generalizability of PCA and cluster analysis; therefore, interpretations regarding potential anthropogenic influences are preliminary and exploratory. Third, the cross-sectional design captures contamination at a single time point and does not account for seasonal variability. Fourth, only muscle tissue was analyzed, while other organs that may accumulate higher metal concentrations were not evaluated. Finally, health risk estimates were based on standard exposure assumptions, which may not fully reflect local consumption patterns or population sensitivity. Despite these limitations, the findings provide important baseline information on heavy metal contamination and human health risks in the study area. Future studies with simultaneous sampling of water, sediment, and multiple fish tissues, larger sample sizes, and seasonal monitoring are needed for more robust source identification and risk assessment.

Conclusion

This study demonstrates that fish from the Balu river are contaminated with heavy metals, with levels varying among species and sampling sites. Mastacembelus armatus exhibited higher Pb, As, and Ni, Pethia ticto showed elevated Cd and Cu, and Systomus sarana contained more Cr, with Sampling Site 1 being the most polluted. Health risk assessments (EDI, THQ, HI, and TR) indicate that long-term consumption of these fish poses both non-carcinogenic and carcinogenic risks to local communities. The findings highlight the urgent need to identify pollution sources, expand sampling coverage, improve industrial waste management, enforce regulations, and raise public awareness. In order to reduce the amount of metal released into nearby water bodies, authorities should stress the need of boosting wastewater treatment systems in industrial zones and encouraging cleaner production practices. Continuous monitoring and further research are essential to reduce contamination, enhance risk assessment accuracy, and protect both human health and aquatic ecosystems. The approaches and findings of this study provide a replicable framework for managing heavy metal pollution in other aquatic habitats globally.

Acknowledgment

References

Adegbola IP, Aborisade BA and Adetutu A (2021), Health risk assessment and heavy metal accumulation in fish species (*Clarias gariepinus* and *Sarotherodon melanotheron*) from industrially polluted Ogun and Eleyele Rivers, *Nigeria. Toxicol Rep.* **14**(8): 1445-1460. doi: 10.1016/j.toxrep.2021.07.007

Afrin R, Mia MY, Ahsan MA and Akbor A (2015). Concentration of Heavy Metals in Available Fish Species (Bain, *Mastacembelus armatus*; Taki, Channa punctatus and Bele, Glossogobius giuris) in the Turag River, Bangladesh: Heavy Metal Concentration in Bangladesh Fish, *Biological Sciences - PJSIR* **58**(2): 104–110. https://doi.org/10. 52763/PJSIR. BIOL.SCI. 58.2.2015.104.110

Ahmed ASS, Rahman M, Sultana S, Babu SMOF and Sarker MSI (2019), Bioaccumulation and heavy metal

concentration in tissues of some commercial fishes from the Meghna River Estuary in Bangladesh and human health implications, *Marine Pollution Bulletin* **145:** 436-447. https://doi.org/ 10.1016/j.marpolbul.2 019.06.035

Ahmed MK, Ahamed S, Rahman S, Haque MR and Islam MM (2009), Heavy metals concentration in water, sediments and their bioaccumulations in some freshwater fishes and mussel in Dhaleshwari River, Bangladesh, *Terr Aquat Environ Toxicol* **3**(1): 33-41.

Ahmad MK, Islam S, Rahman MS, Haque MR and Islam MM (2010), Heavy metals in water, sediment and some fishes of Buriganga River, Bangladesh, *International Journal of Environmental Research* **4**(2): 321-332, doi: 10.22059/ijer.2010.24

Ahmed MK, Bhowmik AC, Rahman S and Haque MR (2010), Heavy metal concentration in water, sediments, freshwater mussels and fishes of the river shitalakhya, Bangladesh. *Asian Journal of Water, Environment and Pollution* **7**(1): 77-90. http://dx.doi.org/10.3233/ AJW-2010-7_1_11

Ahsan MA, Siddique MAB, Munni MA, Akbor MA, Bithi UH and Mia MY (2018), Analysis of major heavy metals in the available fish species of the Dhaleshwari River, Tangail, Bangladesh, *Int J Fish Aquat Stud* **6**(4): 349-354.

Ali MM, Ali ML, Proshad R, Islam S, Rahman Z, Tusher TR, Kormoker T and Al MA (2020), Heavy metal concentrations in commercially valuable fishes with health hazard inference from Karnaphuli river, Bangladesh, *Human and Ecological Risk Assessment: An International Journal* **26**(10): 2646-2662. https://doi.org/10.1080/10807039.2019.1676635

Ali MM, Rahman S, Islam MS, Rakib MRJ, Hossen S, Rahman MZ, Kormoker T, Idris AM and Phoungthong K (2022), Distribution of heavy metals in water and sediment of an urban river in a developing country: a probabilistic risk assessment, *Int J Sediment Res* **37**(2): 173-187.

Arefin MT and Rahman MM (2019), Contamination Status of Surface Water from the Balu River for Irrigation Usage in Bangladesh, *J. Environ. Sci. Nat. Resour* **12**(1-2): 57-65. https://doi.org/10.3329/jesnr.v12i1-2.51986

Arulkumar A, Paramasivam S and Rajaram R (2017), Toxic heavy metals in commercially important food fishes collected from Palk Bay, Southeastern India, *Mar Pollut Bull* **119**(1): 454-459. doi: 10.1016/j. marpolbul.2017.03.045

Banu MR, Jahan B, Mondal MN and Hossain MA (2023), Toxicity Effects of Metals Bioaccumulation in Water and Fishes of the Balu River, Bangladesh, *Egyptian Journal of Aquatic Biology and Fisheries* **27**(3): 271-294

BBS (2015), Statistical pocket book of Bangladesh *In:* Bangladesh Bureau of Statistics MoP, Dhaka Ed., Government of the People's Republic Bangladesh.

Begum A, Muafa AI, Amin MN, Chowdhury TR, Quraishi SB and Banu N (2013), Levels of heavy metals in tissues of shingi fish (*Heteropneustes* fossilis) from Buriganga River, Bangladesh, *Environmental Monitoring and Assessment* **185:** 5461-5469. https:// doi.org/ 10.1007/s10661-012-2959-4

Bhuyan MS, Bakar MA, Akhtar A and Islam MS (2016), Heavy metals status in some commercially important fishes of Meghna River adjacent to Narsingdi District, Bangladesh: health risk assessment, *American Journal of Life Sciences* **13**(6): 60-70. http://dx.doi. org/10.11648/j.ajls.20160402.17

Bristy MS, Sarker KK, Baki MA, Quraishi SB, Hossain MM, Islam A and Khan MF (2021), Health risk estimation of metals bioaccumulated in commercial fish from coastal areas and rivers in Bangladesh, *Environmental Toxicology and Pharmacology* **86:** 103666. https://doi.org/10.1016/j.etap.2021.103666

Castro-González MI and Méndez-Armenta M (2008), Heavy metals: Implications associated to fish consumption, *Environ Toxicol Pharmacol* **26**(3): 263-271. doi: 10.1016/j.etap.2008.06.001

Carocci A, Catalano A, Lauria G, Sinicropi MS and Genchi G (2016), Lead toxicity, antioxidant defense and environment, *Rev Environ Contam Toxicol*, pp 45-67.

DEA (2010), *In:* The Framework for the Management of Contaminated Land, South Africa, Affairs DoE Ed., DEA, South Africa.

DoF (2017), Annual Report 2017 Dhaka. Department of Fisheries, Ministry of Fisheries and Livestock, Government of Bangladesh .

DOH N (2007), Hopewell Precision Area Contamination: Appendix C-NYS DOH, Procedure for Evaluating Potential Health Risks for Contaminants of Concern. The US Department of Health Human Services, New York.

Dong X, Li C, Li J, Wang J, Liu S and Ye B (2010), A novel approach for soil contamination assessment from heavy metal pollution: A linkage between discharge and adsorption, *J Hazard Mater* **175:** 1022-1030. doi: 10.1016/j.jhazmat.2009.10.112

Dutton J and Fisher NS (2011), Salinity effects on the bioavailability of aqueous metals for the estuarine killifish Fundulus heteroclitus, *Environ Toxicol Chem* **30:** 2107-2114. doi: https://doi.org/10.1002/etc.600

Enyoh CE and Isiuku BO (2020), Determination and human health risk assessment of heavy metals in floodbasin soils in Owerri, Southeastern Nigeria, *Chem Afr* **3:** 1059-1071 https:// doi.org/ 10.1007/ s42250-020-00171-2

Forti E, Salovaara S, Cetin Y, Bulgheroni A, Tessadri R, Jennings P, Pfaller W and Prieto P (2011), *In vitro* evaluation of the toxicity induced by nickel soluble and particulate forms in human airway epithelial cells, *Toxicol In Vitro.* **25:** 454-461. doi:10.1016/j.tiv.2010.11.013

FRSS (2017), Fisheries Resources Survey System (FRSS), Fisheries Statistical Report of Bangladesh, Department of Fisheries **34:** 129.

Gao X, Chen CTA, Wang G, Xue Q, Tang C and Chen S (2010), Environmental status of Daya Bay surface sediments inferred from a sequential extraction technique, *Estuarine, Coastal and Shelf Science* **86**(3): 369-378. https://doi.org/10.1016/j.ecss.2009.10.012

Grigoratos T, Samara C, Voutsa D, Manoli E and Kouras A (2014), Chemical composition and mass closure of ambient coarse particles at traffic and urban-background sites in Thessaloniki, Greece, *Environmental Science and Pollution Research* **21:** 7708-7722. https:// doi.org/ 10.1007/ s11356-014-2732-z

Gothandam KM, Ranjan S, Dasgupta N and Lichtfouse E (2020), Environmental Biotechnology, *Springer International Publishing* **2:** doi: 10.1007/ 978-3-030-38196-7

Haque MR, Ali MM, Ahmed W and Rahman MM (2022), Assessment of metal (loid) s pollution in water and sediment from an urban river in Bangladesh: an ecological and health risk appraisal, *Case Studies in Chemical and Environmental Engineering* **6:** 100272, https://doi.org/10.1016/j. cscee.2022.100272

Hasan GMMA, Das AK, Satter MA and Asif Md (2023), Distribution of Cr, Cd, Cu, Pb and Zn in organs of three selected local fish species of Turag river, Bangladesh and impact assessment on human health, *Emerging Contaminants* **9**(1): 100197. https://doi. org/10.1016/j .emcon.2022.11.002

Hasan GMMA, Satter MA, Das AK and Asif M (2022), Detection of heavy metals in fish muscles of selected local fish varieties of the Shitalakshya River and Probabilistic health risk assessment, *Measurement: Food* **8:** 100065. https://doi.org/10.1016/ j.meafoo. 2022.100065

Han JL, Pan XD, Chen Q and Huang BF (2021), Health risk assessment of heavy metals in marine fsh to the population in Zhejiang, China, *Scientifc Reports* **11:** 11079. https:// doi.org/10.1 038/s41598- 021-90665-x

Hoang HG, Lin C, Tran HT, Chiang CF, Bui XT, Cheruiyot NK, Shern CC and Lee CW (2020), Heavy metal contamination trends in surface water and sediments of a river in a highly-industrialized region, *Environmental Technology and Innovation* **20:** 101043. https://doi. org/10.1016/ j.eti.2020.101043

Hossini H, Shafie B, Niri AD, Nazari M, Esfahlan AJ, Ahmadpour M, Nazmara Z, Ahmadimanesh M, Makhdoumi P, Mirzaei N and Hoseinzadeh E (2022), A comprehensive review on human health effects of chromium: insights on induced toxicity, *Environmental Science and Pollution Research* **29:** 70686-70705. https://doi.org/ 10.1007/s 11356-022-2 2705-6

Hossain MB, Ahmed ASS and Sarker MSI (2018), Human health risks of Hg, As, Mn, and Cr through consumption of fish, Ticto barb (*Puntius ticto*) from a tropical river, Bangladesh, *Environ Sci Pollut Res* **25**(31): 31727-31736. doi: 10.1007/ s1135 6-018- 3158-9.

Hossain MB, Bhuiyan NZ, Kasem A, Hossain MK, Sultana S, Nur AAU, Yu J, Albeshr MF and Arai T (2022), Heavy

metals in four marine fish and shrimp species from a subtropical coastal area: accumulation and consumer health risk assessment, *Biology* **11**(12): 1780. https://doi.org/ 10.3390/ biology11121780

IARC (2011), International Agency for Research on Cancer, Agents Classified by the IARC Monographs, pp 1-102.

IARC (2012), *Monographs on the Evaluation of Carcinogenic Risks to Humans* (Arsenic, Metals, Fibres, and Dusts).

Irin A, Islam MS, Kabir MH and Hoq ME (2016), Heavy metal contamination in water and fishes from the Shitalakhya river at Narayanganj, Bangladesh, *Bangladesh Journal of Zoology* **44**(2): 267-273. https://doi.org/10.3329/bjz.v44i2.32766

Islam MM, Rahman SL, Ahmed SU and Haque MKI (2014), Biochemical characteristics and accumulation of heavy metals in fishes, water and sediments of the river Buriganga and Shitalakhya of Bangladesh, *Journal of Asian Scientific Research* **4**(6): 270. https://archive. aessweb.com/ index.php/5003/ rticle/view/3640

Jabeen F and Chaudhry AS (2010), Environmental impacts of anthropogenic activities on the mineral uptake in Oreochromis mossambicus from Indus River in Pakistan, *Environmental Monitoring and Assessment* **166:** 641-651. https:/ /doi.org/10. 1007/s10661- 009-1029-z

Jaishankar M, Tseten T, Anbalagan N, Mathew BB and Beeregowda KN (2014), Toxicity, mechanism and health effects of some heavy metals, *Interdisciplinary Toxicology* **7**(2): 60-72. https://doi.org/ 10.2478/intox-2014-0009

Joadder MAR, Galib SM, Haque SMM and Chaki N (2015), Fishes of the river Padma, Bangladesh: Current trend and conservation status, *J Fish* **3**(2): 259-266. doi: 10.17017/jfish.v3i2.2015.111

Kawser AM, Baki MA, Kundu GK, Saiful IM, Monirul IM and Muzammel HM (2016), Human health risks from heavy metals in fish of Buriganga river, Bangladesh, *SpringerPlus* **5:** 1-12. https://doi.org/ 10.1186/s 40064-01 6-3357-0

Khatun N, Nayeem J, deb N, Hossain S and Kibria MM (2021), Heavy metals contamination: possible health

risk assessment in highly consumed fish species and water of Karnafuli River Estuary, Bangladesh, *Toxicology and Environmental Health Sciences* **13**(4): 375-388. https://doi .org/ 10.100 7/s 13530-021-00101-w

Khan S, Cao Q, Zheng YM, Huang YZ and Zhu YG (2008), Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China, *Environmental Pollution* **152**(3): 686-692. https://doi.org/ 10.1016/j.envpol.2007.06.056

Kinuthia GK, Ngure V, Beti D, Lugalia R, Wangila A and Kamau L (2020), Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication, *Scientific Reports* **10**(1): 8434. https://doi.org/ 10.1038/ s41598-020-65359-5

Kubra K, Mondol AH, Ali MM, Palash MAU, Islam MS, Ahmed AS, Antara MM, Islam ARMT, Bhuyan MS, Rahman MZ and Rahman MM (2022), Pollution level of trace metals (As, Pb, Cr and Cd) in the sediment of Rupsha River, Bangladesh: assessment of ecological and human health risks, *Front Environ Sci* **10:** 778544. https://doi.org/ 10.3389/ fenvs.2022.778544

Lanphear BP, Rauch S, Auinger P, Allen RW and Hornung RW (2018), Low-level lead exposure and mortality in US adults: a population-based cohort study, *Lancet Public Health* **3:** e177-e184. doi: 10.1016/S2468-266 7(18)30025-2

Lee MY, Jung BI, Chung SM, Bae ON, Lee JY, Park JD, Yang SJ, Lee H and Chung JH (2003), Arsenic-induced dysfunction in relaxation of blood vessels. Environ, *Health Perspect* **111**(4): 513-517. https://doi. org/10.1289/ehp.5916

Liang N, Yang L, Dai J and Pang X (2011), Heavy metal pollution in surface water of Linglong gold mining area, China, *Procedia Environ. Sci* **10:** 914-917. doi: 10.1016/j.proenv.2011.09.146

Maceda-Veiga A, Monroy M, Navarro E, Viscor G and de Sostoa A (2013), Metal concentrations and pathological responses of wild native fish exposed to sewage discharge in a Mediterranean river, *Sci Total Environ* **449:** 9-19. doi: 10.1016/j.s citotenv.2 013.01.012

Martín JAR, De Arana C, Ramos-Miras JJ, Gil C and Boluda R (2015), Impact of 70 years urban growth associated with heavy metal pollution, *Environmental Pollution* **196:** 156-163. https://doi.o rg/10.1016/ j.envpol.20 14.10.014

Masindi V and Muedi KL (2018), Environmental contamination by heavy metals, *Heavy Metals* **10**(4): 115-133. doi: 10.5772/intechopen.76082

Matouke MM and Abdullahi KL (2020), Assessment of heavy metals contamination and human health risk in Clarias gariepinus [Burchell, 1822] collected from Jabi Lake, Abuja, Nigeria. *Sci African* **7:** e00292. doi: 10.1016/j.sciaf.2020.e00292

Mandal BK and Suzuki KT (2002), Arsenic round the world: a review, *Talanta* **58:** 201. doi:10.1016/ S0039-9140(02)00268-0

Mishra S, Bharagava RN, More N, Yadav A, Zainith S, Mani S and Chowdhary P (2019), Heavy Metal Contamination: An Alarming Threat to Environment and Human Health. Environ. Biotechnol. Sustain. Futur., pp 103-125, doi: 10.1007/ 978-981-10-7284-0_5

Mitra S, Chakraborty AJ, Tareq AM, Emran TB, Nainu F, Khusro A, Idris AM, Khandaker MU, Osman H and Alhumaydhi FA (2022), Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity, *Journal of King Saud University-Science* **34**(3): 101865. https://d oi.org/10.1016/j.jksus.2022.101865

Mohiuddin KM, Zakir HM, Otomo K, Sharmin S and Shikazono N (2010), Geochemical distribution of trace metal pollutants in water and sediments of downstream of an urban river, *Int J Environ Sci Technol* **7:** 17-28. https://doi.org/10.1007/ BF03326113

Naz S, Habib SS, Arshad M, Majeed S, Acar Ü, Kesbiç OS, Mohany M, Aragona F and Fazio F (2025), Human health risk of heavy metal biomagnification: Trophic transfer patterns in aquatic ecosystems, *J Trace Elem Med Biol.* **91:** 127704. doi: 10.1016/j.j temb.2025.127704

Nduka JK and Orisakwe OE (2011), Water-quality issues in the Niger Delta of Nigeria: a look at heavy metal levels and some physicochemical properties, *Environmental* *Science and Pollution Research* **18:** 237-246. https:// doi.org/10.1007/s11356-010-0366-3

Niampradit S, Kiangkoo N, Mingkhwan R, Kliengchuay W, Worakhunpiset S, Limpananont Y, Hongsibsong S, Inthorn D and Tantrakarnapa K (2024), Occurrence, distribution, and ecological risk assessment of heavy metals in Chao Phraya River, Thailand, *Scientific Reports* **14**(1): 8366. https://doi.org/ 10.1038/s41 598-024-59133-0

Oros A. (2025), Bioaccumulation and Trophic Transfer of Heavy Metals in Marine Fish: Ecological and Ecosystem-Level Impacts. *J Xenobiot* **15**(2): 59. doi: 10.3390/jox15020059.

Proshad R, Kormoker T and Islam S (2019), Distribution, source identification, ecological and health risks of heavy metals in surface sediments of the Rupsa River, Bangladesh, *Toxin Rev* **40**(1): 77-101. https://doi.org/ 10.1080/15569543.2018.1564143

Rahman MM, Asaduzzaman M and Naidu R (2013), Consumption of arsenic and other elements from vegetables and drinking water from an arsenic-contaminated area of Bangladesh, *J Hazard Mater* **262:** 1056-1063. doi: 10.1016/ j.jhazmat. 2012.06.045

Rahman MS, Hossain MS, Ahmed MK, Akther S, Jolly YN, Akhter S and Kabir MJ (2019), Assessment of heavy metals contamination in selected tropical marine fish species in Bangladesh and their impact on human health, *Environmental Nanotechnology, Monitoring and Management* **11:** 100210. doi: 10.1016/j.e nmm.2019.100210

Rahman MS, Molla AH, Saha N and Rahman A (2012), Study on heavy metals levels and its risk assessment in some edible fishes from Bangshi River, Savar, Dhaka, Bangladesh, *Food Chemistry* **134**(4): 1847-1854. https://doi.org/10.101 6/j.foodchem.201 2.03.099

Rakib MRJ, Jolly YN, Enyoh CE, Khandaker MU, Hossain MB, Akther S, Alsubaie A, Almalki ASA and Bradley DA (2021), Levels and health risk assessment of heavy metals in dried fish consumed in Bangladesh, *Scientific Reports* **11**(1): 14642. https://doi.org/ 10.1038/ s41598-021-93989-w

Raknuzzaman M, Ahmed MK, Islam MS, Habibullah-Al-Mamun M, Tokumura M, Sekine M and Masunaga S (2016), Trace metal contamination in commercial fish and crustaceans collected from coastal area of Bangladesh and health risk assessment, *Environ Sci Pollut Res - Int* **23:** 17298-17310. doi: 10.1007/s11356-016-6918-4

Rehnuma M, Islam MS, Meghla NT and Kabir MH (2016), Heavy metal exploration in water and fish from Bangshi River at Mirzapur area under Tangail district of Bangladesh, *Bangladesh Journal of Environmental Science* **30:** 7-12.

Reynolds EJ, Smith DS, Chowdhury MJ and Hoang TC (2018), Chronic effects of lead exposure on topsmelt fish (Atherinops affinis): influence of salinity, organism age, and relative sensitivity to other marine species, *Environ Toxicol Chem* **37:** 2705-2713. doi: 10.1002/etc.4241

Samad A, Roy D, Hasan MM, Ahmed KS, Sarker S, Hossain MM and Shajahan M (2023), Intake of toxic metals through dietary eggs consumption and its potential health risk assessment on the peoples of the capital city Dhaka, Bangladesh, *Arabian Journal of Chemistry* **16**(10): 105104. doi.org/10.1016/j.arabjc.2023.105104

Sapkota A, Sapkota AR, Kucharski M, Burke J, McKenzie S, Walker P and Lawrence R (2008), Aquaculture practices and potential human health risks: Current knowledge and future priorities, *Environ Int* **34**(8): 1215-1226. doi: 10.1016/j.envint.2008.04.009

Sarker A, Kim JE, Islam ARMT, Bilal M, Rakib MRJ, Nand R, Rahman MM and Islam T (2022), Heavy metals contamination and associated health risks in food webs—a review focuses on food safety and environmental sustainability in Bangladesh, *Environmental Science and Pollution Research* **29:** 3230-3245. doi: 10.1007/s11356-021-17153-7

Sarker MJ, Polash AU, Islam MA, Rima NN and Farhana T (2020), Heavy metals concentration in native edible fish at upper Meghna River and its associated tributaries in Bangladesh: a prospective human health concern, *SN Applied Sciences* **2:** 1-13. https://doi.org/10.1007/s42452-020-03445-z

Sekabira K, Origa HO, Basamba TA, Mutumba G and Kakudidi E (2010), Assessment of heavy metal pollution in the urban stream sediments and its tributaries, *International Journal of Environmental Science and Technology* **7:** 435-446. https://doi.org/10.1007/BF03326153

Shaheen N, Sultana M, Hasan T, Khan IN, Irfan NM and Ahmed MK (2024), Heavy Metals in Common Fishes Consumed in Dhaka, a Megacity of Asia: A Probabilistic Carcinogenic and Non-Carcinogenic Health Hazard, *Biological Trace Element Research,* pp 1-16. doi: 10.1007/s12011-024-04140-5

Sharma B, Singh S and Siddiqi NJ (2014), Biomedical implications of heavy metals induced imbalances in redox systems, *Biomed Res Int.,* p 640754. doi: 10.1155/2014/640754

Sharma RK, Agrawal M and Marshall F (2007), Heavy metal contamination of soil and vegetables in suburban areas of Varanasi, India, *Ecotoxicol Environ Saf* **66**(2): 258-266. 2007, doi: 10.1016/j.ecoenv.2005.11.007

Shorna S, Shawkat S, Hossain A, Quraishi SB, Ullah AKMA, Hosen MM, Hossain MK, Saha B, Paul B and Habibullah-Al-Mamun M (2021), Accumulation of trace metals in indigenous fish species from the Old Brahmaputra River in Bangladesh and human health risk implications, *Biological Trace Element Research* **199:** 3478-3488. https://doi .org/10.10 07/s12011-020-02450-y

Singh A, Sharma A, Verma RK, Chopade RL, Pandit PP, Nagar V, Aseri V, Choudhary SK, Awasthi G and Awasthi, KK (2022), Heavy metal contamination of water and their toxic effect on living organisms. *In The toxicity of environmental pollutants*, *IntechOpen*. doi: 10.5772/intechopen.105075

Soltani N, Moore F, Keshavarzi B, Sorooshian A and Javid R (2019), Potentially toxic elements (PTEs) and polycyclic aromatic hydrocarbons (PAHs) in fish and prawn in the Persian Gulf, Iran, *Ecotoxicology and Environmental Safety* **173:** 251-265. https://doi.org/10.1016/j.ecoenv.2019.02.005.

Sultana MN, Hossain MS and Latifa GA (2019), Water quality assessment of balu river, Dhaka Bangladesh, *Water Conservation and Management* **3**(2): 8-10. DOI: 10.26480/wcm.02.2019.08.10

Suchi PD, Shaikh MAA, Saha B, Moniruzzaman M, Hossain MK, Parvin A and Parvin A (2024), Comprehensive

index analysis approach for ecological and human health risk assessment of a tributary river in Bangladesh, *Heliyon* **10:** e32542. https://d oi.org/10. 1016/j.heliyon.2024.e32542

Tamele IJ and V´azquez Loureiro P (2020), Lead, mercury and cadmium in fish and shellfish from the Indian Ocean and Red Sea (African countries): public health challenges, *J Mar Sci Eng* **8:** 344. https://doi.org/10.3390/jmse8050344

Tchounwou PB, Yedjou CG, Patlolla AK and Sutton DJ (2012), Heavy metal toxicity and the environment. *Molecular, Clinical and Environmental Toxicology* **3:** 133–164. https://doi.o rg/10.100 7/978-3- 7643 -8340-4_6

Tolkou AK, Toubanaki DK and Kyzas GZ (2023), Detection of Arsenic, Chromium, Cadmium, Lead, and Mercury in Fish: Effects on the Suainable and Healthy Development of Aquatic Life and Human Consumers, *Sustainability* **15:** 16242. https://doi.org/ 10.3390/ su152316242

Tuzen M (2009), Toxic and essential trace elemental contents in fish species from the Black Sea, Turkey, *Food Chem Toxicol* **47**(8): 1785-1790. doi: 10.1016 /j.fct.2009.04.029.

UN-Water (2021), Summary progress update 2021: SDG 6 – water and sanitation for all. https:// www.unwater.org/sites/default/files/app/uploads/2021/ 12/SDG-6-Summary-Progress-Update-2021_Version-July-2021a.pdf

USEPA, (1989a), Guidance Manual for Assessing Human Health Risks From Chemically Contaminated, Fish and Shellfish. EPA-503/8-89-002. United States Environmental Protection Agency, Washington DC.

USEPA, (1989b), Guidance Manual for Assessing Human Health Risks From Chemically Contaminated, Fish and Shellfish. EPA-503/8-89- 002. USEPA, Washington DC.

USEPA. 2000, Risk Assessment Guidance for Superfund (RAGS), Volume I: Human Health Evaluation Manual (Part A). United States Environmental Protection Agency, Washington, DC.

USEPA (2010), Risk-based Concentration Table 2010. United States Environmental Protection Agency.

USEPA, (2008), Environmental Protection Agency, Integrate d Risk Information System, CRC. United States Environmental Protection Agency.

USEPA (2011), USEPA regional screening level (RSL) summary table: November. https:// www.epa.gov/risk/regional-screening-levels-rsls-gener ic-tables.

USEPA (2012), EPA Region III Risk-Based Concentration (RBC) Table 2008 Region III, 1650 Arch Street. USEPA, Philadelphia, Pennsylvania.

USEPA, 2016, Reference Dose (RfD): Description and Use in Health Risk Assessment. Background Document 1A, Integrated Risk Information System (IRIS). United States Environmental Protection Agency, Washington DC.

USEPA (2022–2023), *Integrated Risk Information System (IRIS)*.

USEPA (2022a), Ecological Risk Assessment, Combustion, Wastes, USEPA. https://archive. epa.gov/ epawaste/ hazard/tsd/td/web/html/ecorisk.html (accessed Jul. 14, 2022).

USEPA (2022b), Regional Screening Levels (RSLs) - Generic Tables, USEPA. https://www. epa.gov/risk/re gional-screen ing-levels-rsls-gen eric-tables.

Wahiduzzaman M, Islam MM, Sikder AHF and Parveen Z (2022), Bioaccumulation and heavy metal contamination in fish species of the Dhaleswari River of Bangladesh and related human health implications, *Biological Trace Element Research* **200:** 3854-3866. https://doi.org/10.1007/ s12011-021-02963-0

Wang Y, Ferrari MCO, Hoover Z, Yousafzai AM, Chivers DP and Niyogi S (2014), The effects of chronic exposure to environmentally relevant levels of waterborne cadmium on reproductive capacity and behaviour in fathead minnows, *Arch Environ Contam. Toxicol* **67:** 181-191. doi: 10.1007/ s00244-014-0018-6

Wasewar KL, Singh S and Kansal SK (2020), Process intensification of treatment of inorganic water pollutants, *In Inorganic pollutants in water, pp* 245–271. https://doi.org/10.1016/B978-0-12-818965-8.00013-5

WHO (2018), *Arsenic Fact Sheet*.

WHO (2021), *Lead Poisoning and Health Fact Sheet*.

Yadav SC (2024), Water Pollution: The Problems and Solutions. Science Insights **44**(2): 1245-1251. doi: 10.15354/si.24.re905

Yap CK and Al-Mutairi KA (2022), Copper and Zinc Levels in Commercial Marine Fish from Setiu, *East Coast of Peninsular Malaysia. Toxics* **10**(2): 52. doi: 10.3390/toxics10020052

Zakir HM, Eti MSA, Quadir QF and Mallick S (2019), Health risk assessment of heavy metal intake of common fishes available in the Brahmaputra river of Bangladesh, *Arch Curr Res Int*, **19**(2): 1-15. https://doi.org/10.9734/acri/2019/v19i230153

Zhang C, Qiao Q, Piper JDA and Huang B (2011), Assessment of heavy metal pollution from a Fe-smelting plant in urban river sediments using environmental magnetic and geochemical methods, *Environmental Pollution* **159**(10): 3057-3070. https://doi.org/10.1016/j.envpol.2011.04.006

Zhang L, Mo Z, Qin J, Li Q, Wei Y, Ma S, Xiong Y, Liang G, Qing L and Chen Z (2015), Change of water sources reduces health risks from heavy metals via ingestion of water, soil, and rice in a riverine area, south China, *Sci Total Environ* **15**: 530-170. https://doi.org/10.1016/j.scitotenv.2015.05.100

Zhang Y, Xu B, Guo Z, Han J, Li H, Jin L, Chen F and Xiong Y (2019), Human health risk assessment of groundwater arsenic contamination in Jinghui irrigation district, China, *J Environ Manage* **237**: 163-169. doi: 10.1016/j.jenvman.2019.02.067