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Full Length Research Article

Assessment of Heavy Metals Bioccumulation in Wild Fish Species from Argungu River, and Associated Health Risks in Human Consumption

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ABSTRACT

Freshwater pollution by heavy metals has become a critical global environmental concern with significant implications on ecosystem integrity and public health. Argungu River is a historical freshwater ecosystem with valuable socioeconomic and cultural significance in northwestern Nigeria, hosting the famous annual fishing festival. The aim of this study was to evaluate the concentrations of selected heavy metal in five wild fish species and assess the associated human health risks. A maximum of 375 individual fishes were obtained from the fish anglers of the river at fishing hotspot. The samples were oven dried at 65˚C, and analyzed for the presence of heavy metals using Atomic Absorption Spectrophotometry (AA6300). Mean heavy metal concentrations differed significantly at $p < 0.05$, among species. *C. gariepinus* recorded the highest Fe ($8.045 mg \cdot kg^{-1}$) and Cd ($0.750 mg \cdot kg^{-1}$), while *H. bebe* had the lowest Fe ($2.490 mg \cdot kg^{-1}$) and Cd ($0.180 mg \cdot kg^{-1}$) concentration. Cd concentrations in *C. gariepinus* and *T. zilli* exceeded the FAO/WHO permissible limit of $0.05 mg \cdot kg^{-1}$. Estimated Daily Intake (EDI) values were consistently higher in children than adult, indicating greater exposure risk per body weight. The Target Hazard Quotient (THQ) value for Cd surpassed the safe limit ($THQ \leq 1$) in *C. gariepinus* and *T. zilli*, signaling potential non-carcinogenic risks. Furthermore, Cancer Risk (CR) values for Cd exceeded the acceptable limit of 1×10^{-4} in *H. brevis, T.* zilli and *C. gariepinus* for both demographics, with the highest values (3.72×10^{-4}) in *C. gariepinus*. Cr CR value also exceeded the threshold in children consuming *C. gariepinus*, while Pb CR values remained below $0.5 mg \cdot kg^{-1}$.

Non-carcinogenic and carcinogenic risk assessments confirm that children face higher exposure risk from consuming wild fish inhabiting Argungu River with Cd and Cr presenting the major toxicity. Regular monitoring and pollution control measures are urgently needed to protect the ecosystem and public health.

Keywords: Argungu River, fish contamination, heavy metals, carcinogenic risk, non-carcinogenic risk, and public health.

Introduction

Freshwater pollution by heavy metals has become a critical global environmental concern with significant implications on ecosystem integrity and public health. Rapid urbanization, industrial development, and unsustainable agricultural practices contribute to the deterioration of water quality and declining aquatic biodiversity. Management of water quality has become a major challenge in the world as it is being polluted by industrial and urban wastes that serve as the sources of heavy metals contamination with a far-reaching implication to aquatic animals and ecosystem integrity (Ojutiku and Okojevoh, 2017). Heavy metal contamination is a major aquatic health problem, due to uncontrolled pollution driven by industrial growth and increase in traffic (Maigari *et al.,* 2016). Heavy metals such as cadmium (Cd), lead (Pb) and chromium (Cr) are of particular concern because they are: non-biodegradable, bioaccumulative, and persistent with a large atomic mass and a density (5 gcm^{-3}) (Nowicka, 2022). These metals can accumulate in fish tissues and biomagnify up the food chain, posing serious human health risks, especially to the organisms at higher tropic level (Maigari *et al.,* 2016). The inherent bioaccumulation and biomagnification potentials of heavy metals and their persistence in environmental compartments have attracted scientific attention to evaluate and monitor their concentrations in aquatic ecosystem, in order to promote sustainability of aquatic environments (Wang *et al.,* 2014; Renieri *et al.,* 2019). Ingestion of metals through contaminated food sources has severe health consequences, particularly in the vulnerable populations. Consumption of aquatic fauna has been reported to be an important route of human exposure to heavy metal contaminants (Usero *et al.,* 2003).

Of interest is Fish, which is an essential source of high-quality proteins and micronutrients, playing a vital role in global food security (FAO, 2014). The high-quality proteins, omega-3 fatty acids, low levels of saturated fat, high levels of vitamins and other essential micronutrients found in fish has attracted people to eat fish (Arulkumar *et al.,* 2017). However, their exposure to metal polluted environments negatively influence food safety. Several studies reported heavy metal accumulation in fish tissues from contaminated rivers and reservoirs (Arulkumar *et al.,* 2017; Adetutu *et al.,* 2023; Yahaya *et al.,* 2024). Fish, being the top consumers in aquatic ecosystems are being the most affected species with metal toxicity which easily magnify to human body (Gwimbi *et al.,* 2020). Chronic consumption of contaminated fish with heavy metals above safety thresholds is link to neurological, hepatic, renal, mutagenic, teratogenic and

carcinogenic health effects (Ngo *et al.,* 2011; John and Andrew, 2011). Moreover, Renieri *et al.* (2019) reported that exposure to heavy metals causes kidney and skeletal damage, neurological disorders, endocrine disruption, cardiovascular dysfunction, and various carcinogenic health risks. Because of the higher exposure per body weight and developing physiology, children and pregnant women are especially vulnerable to the carcinogens and non-carcinogenic risks of heavy metal (Korte *et al.,* 2020). Moreover, heavy metals can interact with essential biomolecules such as protein and enzymes in humans, leading to the disruption of metabolic processes.

Assessing human exposure is paramount given the stable, non-biodegradable nature of heavy metals and their ability to accumulate in human organs (Shahsavani *et al.,* 2017). Standardized tools for estimating potential non-carcinogenic health risks from chronic exposure include the Target Hazard Quotient (THQ), developed by the United States Environmental Protection Agency (USEPA), and are widely used (Ezemonye *et al.,* 2019). Despite the ecological and cultural significance of Argungu River, limited data exist on species-specific heavy metal accumulation and associated human health risks within this ecosystem. This study therefore aimed to quantify Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe) and Lead (Pb) concentrations in five dominant wild fish species inhabiting Argungu River, and evaluates the resulting non-carcinogenic and carcinogenic health risks associated with their consumption. The findings will support the development of pollution reduction strategies and inform the establishment of local consumption guidelines to protect public health.

Materials and Methods

Study Area

The study was conducted in Argungu Local Government Area of Kebbi State (Figure 1). Kebbi State is blessed with abundant water bodies covering approximately 2.30% of the total land area (Salisu *et al*., 2025), supporting diverse fish species, food security and the livelihoods of local communities. Argungu covers an area of approximately 428 km^2, at an elevation of approximately 241 m above sea level, and situated in the extreme North-western region of Nigeria. River Argungu originated from Funtua area in Katsina State, flows through Gusau in Zamfara State and then joins River Rima in Sokoto before merging with River Niger through Kebbi State (Obaroh *et al.,* 2015; Umar *et al.,* 2024).

Argungu River has socioeconomic, cultural and agricultural significance; it is a major river for: domestic use, recreational activities, fishing, irrigation, tourism, and international fishing festivals (Umar *et al.,* 2024). Kebbi State experienced approximately 800 mm annual rainfall and an average maximum temperature of 40.98°C and 39.62°C in April and March, respectively, making them the hottest months (Salisu *et al.,* 2025; Salisu *et al.,* 2024). The predominant vegetation type is Sudan savannah with abundant grasses, shrubs and few sparse trees. This river supports fishing, irrigation, tourist, educational field trip, and domestic activities,

experience waste disposal, agricultural runoff, blocks cement activities for construction, and vehicular and cloth washing (Bawa *et al.,* 2018).

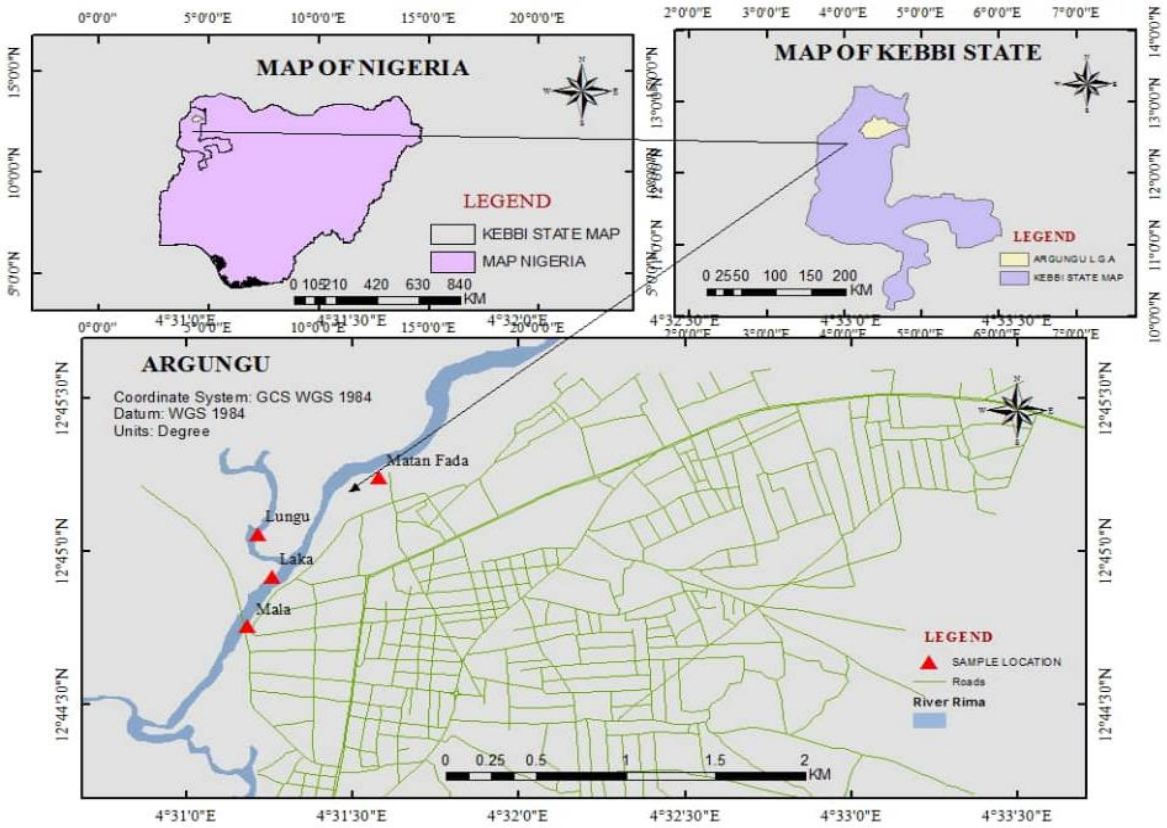


Figure 1: Map of the Study Area Showing the Sampling Locations (Umar *et al.,* 2024).

Fish Sample Collection

Five (5) abundant wild matured fish species inhabiting River Argungu, such as *Clarias gariepinus, Hydrocynus brevis, Alestes baremose, Tilapia zilli* and *Hyperopisus bebe* were collected at three locations of the river (Matan Fada 12˚45'17.32" N | 4˚31'35.93"E, Lungu Lake 12˚45'6.05" N | 4˚31'14.06"E and Laka Lake 12˚45'1.87" N | 40 31'9.51"E) between May and October, 2024. A total of 375 fish samples (75 per species) were obtained, following monthly collections from fishermen, who assisted in collecting the specimens using traditional fishing methods. Samples were obtained between 07:00 to 8:00 am, wrapped in sterile polyethylene bags, placed in insulated iceboxes, and transported to the General Biology Laboratory, Department of Biological Sciences, Federal University Birnin Kebbi for preparation in accordance with United State Environmental Protection Agency (USEPA) Guidelines.

Sample Preparation

Fish samples were placed on a Polytetrafluoroethylene (PTFE) cutting board and were descaled by scrapping from the tail to the head region, using blade edge of a titanium Knife. After descaling, fishes were dissected to remove the digestive tract and the muscle tissues were collected for heavy metal analysis. About 200 g of muscle per fish were oven-dried at 65˚C for 48 hours to constant weight in triplicate.

Sample Digestion and Analyses

Two grams of dried samples were digested in a digestion flask containing 20 mL mixture of 650 mL of concentrated Nitric acid (HNO_3), 80 mL of perchloric acid ($HClO_4$) and 20 mL of conc. Sulfuric acid (H_2SO_4) and analyzed using Absorption Spectrophotometry (AA6300). Quality assurance included the use of blanks, triplicate analyses and calibration against certified standards. For carcinogenic and non-carcinogenic risks assessment, the concentrations of the heavy metal in the dry weight were then converted to the wet weight (the natural moisture content of fish samples) concentrations exactly how the local human populations mostly consuming it. It was converted using the equation I below:

$$C_{wet} = C_{dry} \times (1 - moisture\ fraction)$$

Equation I

From equation I, C_{wet} is metal conc. in the wet samples, while C_{dry} is metal conc. in dry samples.

Estimated Daily Intake of Metal (EDI)

The EDI of each heavy metal per fish consumed was estimated using Equation II (Copat *et al.*, 2013).

$$EDI = \frac{FIR \times C \times EF \times ED}{BW \times AT}$$

Equation II

Where, *FIR* represent fish ingestion rate (0.034 kg/day for adults and 0.027 kg/day for children), *C* is the metal concentration in fish (mg/kg), *EF* represent exposure frequency (365 days/year for daily consumption), *ED* represent exposure duration (70 years for adult and 15 years for children), *AT* represent average time for non-carcinogens ($ED \times 365$) and *BW* is the average body weight of the different age groups (32.7 kg for children and 70 kg for adults).

Non-carcinogenic Risk

The non-carcinogenic health risk was estimated using the Target Hazard Quotient (THQ) equation, which was estimated from equation III (EPA, 2011).

$$THQ = \frac{EF \times ED \times FIR \times C}{RfD \times BW \times TA}$$

Equation III

Where, *RfD* is the oral reference dose of the metal (mg/kg/day). $THQ \leq 1$: Indicating an unlikely cause of adverse non-carcinogenic health effects, while $THQ > 1$: Indicating a potential of a non-carcinogenic risks.

The Hazard Index (HI), define as the sum total of all the Target Hazard Quotients (THQs) for each species and demographic group (HI = ΣTHQ), was used to assess the cumulative non-carcinogenic health risk associated with multi-metal exposure through fish consumption (Cai *et al.,* 2023).

Carcinogenic Risk (CR)

For carcinogens, risks were estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to a potential carcinogen using equation IV (EPA, 2011).

$$CR = \frac{EF \times EDI \times C \times CSFo}{BW \times TA}$$

Equation IV

Where, *CSFo* (cancer slope factor for Pb is 0.009, Cr is 0.5 and Cd is 0.6 mg/kg/day.

Data Analysis

All data were expressed as mean and analyzed using One-way ANOVA at 5% significance level, to assess interspecies variations. Principal component analysis (PCA) was used to identify metals contributing most overall contamination patterns using Minitab Version 17.

Results

Heavy Metal Concentration in Wild Fish Tissues

The mean concentration of heavy metals (mg/kg/wet weight) in the wild fish tissues are presented in Table 1. Fe and Cu concentrations across all analyzed species were found within the WHO/FAO (2022) acceptable limit for fish consumption. The mean concentrations of Cd, Pb and Cr were found above the WHO/FAO (2022) permissible limit in certain species. *C. gariepinus* recorded the highest concentrations of Fe (8.045 $mg \cdot kg^{-1}$) and Cd (0.750 mg/kg), while *T. zilli* and *A. baremose* recorded the lowest concentrations of Fe (2.940 $mg \cdot kg^{-1}$) and Cd (0.180 $mg \cdot kg^{-1}$), respectively (Table 1). The sequence of heavy metals concentrations (in decreasing order) varied among the fish species: Fe > Cu > Pb > Cd > Cr in *H. bebe*, Fe > Cd > Cu > Pb > Cr in both *T. zilli* and *C. gariepinus*, while in *A. baremose*, the metal concentrations follows the pattern of Fe > Cu > Pb > Cr > Cd. Moreover, the metal concentrations in *H. brevis* follows the pattern of Fe > Pb > Cu > Cd > Cr (Table 1). The variation in heavy accumulation among the wild fish species was found statistically significant ($P < 0.05$).

Table 1: Mean Heavy Metal Concentrations, Estimated Daily Intake (EDI), and Target Hazard Quotient (THQ) Values for Adults and Children Consuming Argungu Wild Fish Species

Species	Metal	C_wet ($mg \cdot kg^{-1}$)	EDI Adults ($mg \cdot kg^{-1} \cdot day^{-1}$)	THQ Adults	EDI Children ($mg \cdot kg^{-1} \cdot day^{-1}$)	THQ Children
H. bebe	Cd	0.180	0.00009	0.08743	0.00015	0.14862
	Fe	3.208	0.00156	0.00223	0.00265	0.00378
	Cu	0.458	0.00022	0.00556	0.00038	0.00944
	Pb	0.368	0.00018	0.05100	0.00030	0.08670
	Cr	0.168	0.00008	0.02712	0.00014	0.04610
		HI		**0.17333**		**0.29465**
T. zilli	Cd	0.500	0.00024	0.24286	0.00041	0.41284
	Fe	2.940	0.00143	0.00204	0.00243	0.00347
	Cu	0.418	0.00020	0.00507	0.00035	0.00862
	Pb	0.355	0.00017	0.04927	0.00029	0.08375
	Cr	0.215	0.00010	0.03481	0.00018	0.05917
		HI		**0.33404**		**0.56785**
A. baremose	Cd	0.105	0.00005	0.05100	0.00009	0.08670
	Fe	4.468	0.00217	0.00310	0.00369	0.00527
	Cu	0.688	0.00033	0.00835	0.00057	0.01419
	Pb	0.395	0.00019	0.05482	0.00033	0.09319
	Cr	0.208	0.00010	0.03360	0.00017	0.05711
		HI		**0.15086**		**0.25645**
H. brevis	Cd	0.375	0.00018	0.18214	0.00031	0.30963
	Fe	4.770	0.00232	0.00331	0.00394	0.00563
	Cu	0.605	0.00029	0.00735	0.00050	0.01249
	Pb	0.895	0.00044	0.12420	0.00074	0.21114
	Cr	0.145	0.00007	0.02348	0.00012	0.03991
		HI		**0.34048**		**0.57880**
C. gariepinus	Cd	0.750	0.00036	0.36441	0.00062	0.61947
	Fe	8.045	0.00391	0.00558	0.00664	0.00949
	Cu	0.668	0.00032	0.00811	0.00055	0.01378
	Pb	0.645	0.00031	0.08951	0.00053	0.15216
	Cr	0.285	0.00014	0.04614	0.00024	0.07844
		HI		**0.51375**		**0.87334**

According to FAO/WHO (2022) the permissible limit of the metals employed in this study are Pb (0.50 $mg \cdot kg^{-1}$), Cu (30 $mg \cdot kg^{-1}$), Cd (0.05 $mg \cdot kg^{-1}$), Cr (0.15 $mg \cdot kg^{-1}$) and Fe (100 $mg \cdot kg^{-1}$). HI is the sum total of all heavy metal THQ.

Potential Estimated Daily Intake (EDI) of Heavy Metals

The EDI of the five heavy metals (Cd, Fe, Cr, Cu and Pb) were generally higher in children than in adults (Table 1). Fe consistently recorded the highest EDI values across all the five wild fish species for adults and children. The maximum EDI values for Fe (0.00391 $mg \cdot kg^{-1} \cdot day^{-1}$ for adults and 0.0064 $mg \cdot kg^{-1} \cdot day^{-1}$ for children) was recorded in *C. gariepinus,* followed by *H. brevis* with EDI values (0.00232 $mg \cdot kg^{-1} \cdot day^{-1}$ for adults and 0.00394 $mg \cdot kg^{-1} \cdot day^{-1}$ for children), while the minimum was recorded in *T. zilli* (0.00143 $mg \cdot kg^{-1} \cdot day^{-1}$ for adults and 0.00243 $mg \cdot kg^{-1} \cdot day^{-1}$ for children) (Table 1). The EDI values showed a significant variation ($P < 0.05$) based on the metal intake and species inhabiting Argungu River. The EDI values revealed distinct grouping patterns among the investigated heavy metals and fish species. Fe consistently recorded the highest intake across all species, indicating predominant exposure. Cd and Pb exhibited moderate intake levels, while Cu and Cr showed relatively low intake values among both adults and children. Based on the HI values, *C. gariepinus*, *H. brevis*, and *T. zillii* were identified as high-exposure species, whereas *H. bebe* exhibited moderate exposure. In contrast, *A. baremoze* consistently recorded the lowest HI values, indicating a comparatively lower health risk to consumers.

The PCA biplot of adult EDI values in Figure 2, showed clear species-specific variation in heavy metal dietary exposure. Component 1 was mainly associated with Fe and Cu EDI, while component 2 was strongly influenced by Pb EDI. *C. gariepinus* is closely associated with Fe and Cu exposure, suggesting relatively higher accumulation of these metals than in the other fish species. In contrast, *H. brevis* is more closely associated with Pb, indicating comparatively greater Pb accumulation
(Figure 2). *T. zilli* and *H. bebe* were positioned close to each other on the PCA biplot, indicating similar metal accumulation than the other species. *A. baremose* showed moderate association with the analyzed metals. However, the ordination indicates distinct interspecific differences in heavy metal bioaccumulation and adult exposure risk (Figure 2).

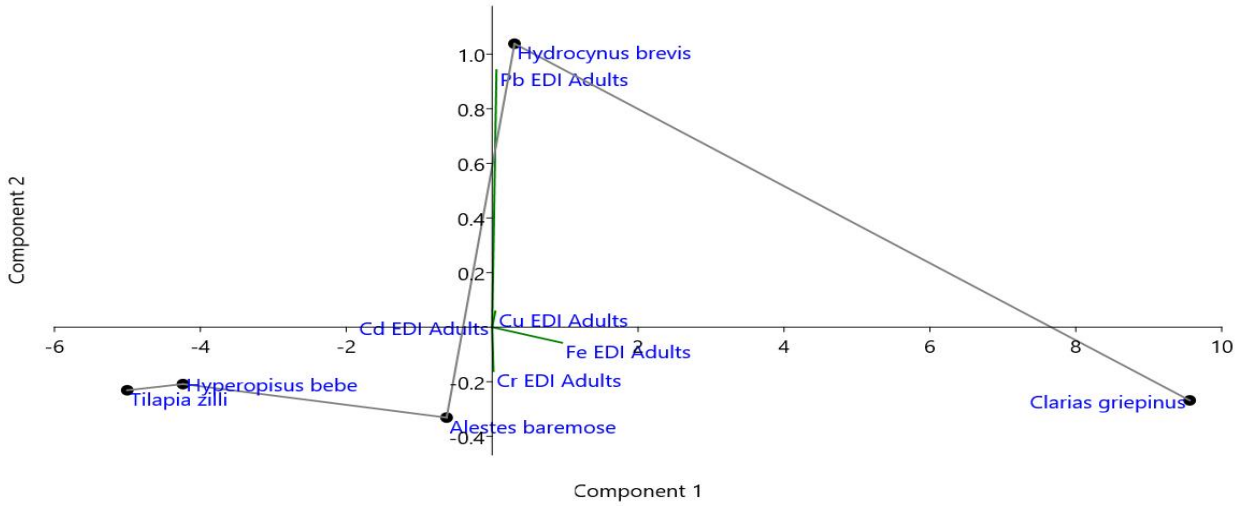


Figure 2: Principal Component Analysis (PCA) of Adults EDI Values

The hierarchical clustering analysis revealed distinct similarities among the fish species based on heavy metal bioaccumulation patterns (Figure 3). *T. zilli* and *H. bebe* were positioned in close proximity on the PCA biplot, indicating similar adult EDI profiles for the analyzed metals. *A. baremose* was located nearby but occupied a distinct position, suggesting an intermediate exposure pattern relative to [illegible]s, while *H. brevis* and *C. gariep*[illegible]d differences in heavy metal bioaccumulation patterns among species (Figure 3). The residual normal probability plot showed slight deviations from the refrence line at the extremes, indicating that the residuals were approximately normally distributed, with only minor deviations and a few potential outlying observations (Figure 4). However, most residuals clustered around the fitted line provided an acceptable fit to the data.

Figure 3

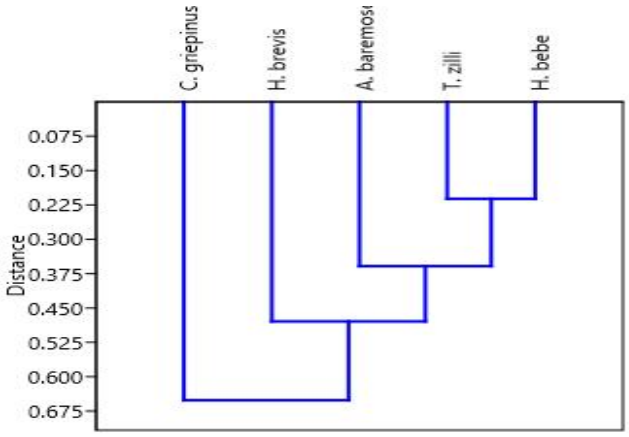


Figure 4

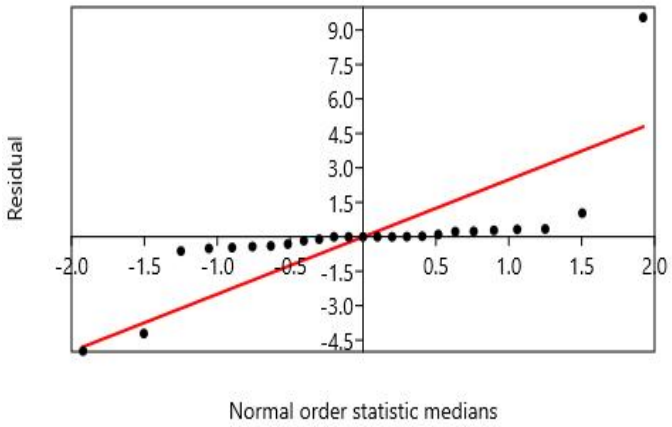


Figure 3 and 4: Dendrogram for Fish Cluster on the Distance of Metals Accumulation and Normal Distribution.

The PCA biplot of children's EDI values in Figure 5 showed a distribution of fish species and metal variables comparable to that observed for (Figure 2). The ordination indicates distinct interspecific differences in metal bioaccumulation and dietary exposure risk among children (Figure 5). *C. gariepinus* was strongly associated with Fe, Cu, and Cr, while *Hydrocynus brevis* showed a closed relationship with Pb. In constrast, *Tilapia zilli* and *Hyperopisus bebe* were more closely associated with Cd and exhibited similar contaminated patterns (Figure 5). *C. gariepinus* was closely associated with Fe, Cu, and Cr EDI values, whereas *H. brevis* was more closely associated with Pb. *T. zilli* and *H. bebe* were positioned nearer the Cd variable, suggesting relatively higher dietary exposure to Cd than the other species, as well as reflecting variations in ecological characteristics and bioaccumulation capacities.

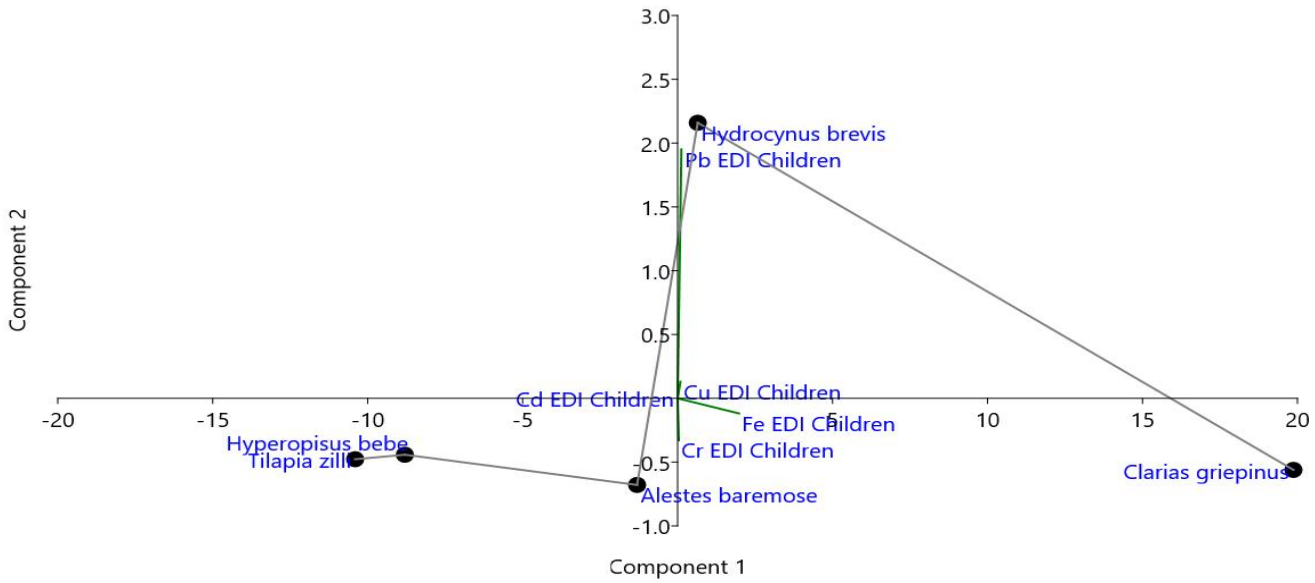


Figure 5: Principal Component Analysis (PCA) of Children EDI Values.

In Figure 6, the dendrogram classified the fish species into groups based on similarities in their heavy metal profiles. *Tilapia zilli* and *Hyperopisus bebe* formed the closest cluster, indicating highly similar contamination characteristics, while *Alestes baremose* showed moderate similarity to this group (Figure 6). Moreover, *Hydrocynus brevis* displayed more distinct profile, whereas *Clarias gripienus* was the most distinct species, reflecting its unique pattern of metal accumulation. In Figure 7, the normal probability plot showed that most residuals were concentrated around the reference line, suggesting an overall acceptable model fit. However, deviations at the distribution tails and the presence of an extreme positive residual indicate departures from normality, likely due to outliers and uneven heavy metal accumulation among fish species (Figure 7). This pattern is typical of environmental contamination data and suggests that the

dataset exhibits some degree of heterogeneity and skewness.

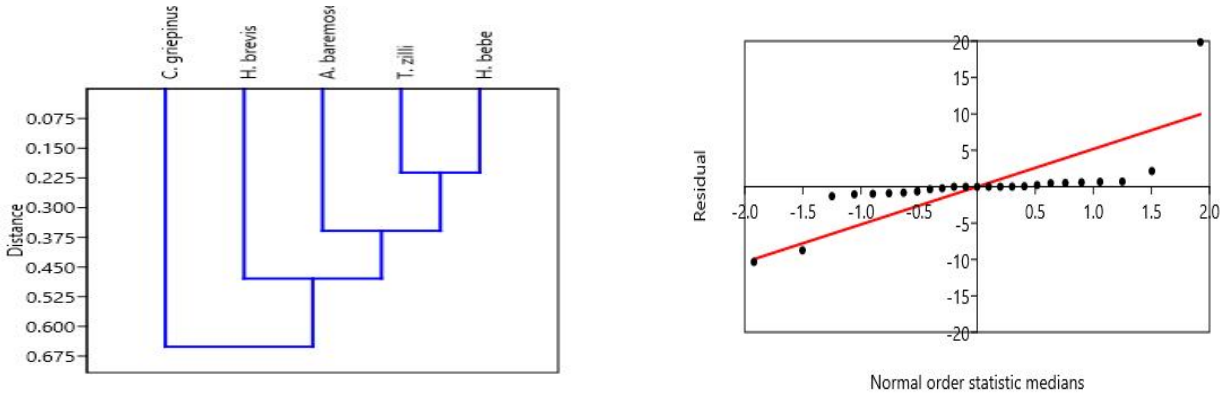


Figure 6 and 7: Dendrogram for Fish Cluster on the Distance of Metals Accumulation and Normal Distribution.

Non-Carcinogenic Health Risks (Target Hazard Quotient, THQ)

The THQ values for individual metals were generally below the safe threshold of THQ < 1.0 for both adult and children across all species. Cd reveals the highest THQ values, particularly in *C. gariepinus* with 0.36441 for adults and 0.61947 for children, and *T. zilli* recorded 0.24286 for adults and 0.41284 for children (Table 1). The maximum THQ values of Pb were found in *A. baremose* with 0.05482 for adults and 0.09319 for children, while Fe recorded the lowest THQ values across all the five wild fish species (Table 1). In this study, the calculated HI values for all species were below the critical threshold (HI < 1), indicating no immediate non-carcinogenic risk. The HI ranged from a minimum of 0.15086 for adults consuming *A. baremose* to a maximum of 0.87334 for children consuming *C. gariepinus* (Table 1).

Carcinogenic Risk (CR) of Consuming Wild Fish Obtained from Argungu River

The potential CR for Cd, Pb and Cr was determined for both adults and children populations (Table 2). The CR values presented in Table 2 revealed that Cd poses the most significant potential for cancer risk among the studied metals. Cd CR values exceeded the acceptable lifetime cancer risk limit of 1×10^{-4} in adults and children consuming *T. zilli* (1.46×10^{-4} for adults and 2.48×10^{-4} for children), *C. gariepinus* (2.19×10^{-4} for adults and 3.72×10^{-4} for children) and *H. brevis* ($1.09\ 10^{-4}$ for adults and 1.86×10^{-4} for children) (Table 2). Furthermore, the Cr CR values of 1.18×10^{-4} exceeded the acceptable limit in children consuming *C. gariepinus*, while the Pb CR values were consistently found below the permissible limit in all species (Table 2).

Table 2: Cancer Risk (CR) Index for Adult and Children Consuming Argungu Wild Fish Species

Fish Species	Cd CR (Adult)	Cd CR (Child)	Pb CR (Adult)	Pb CR (Child)	Cr CR (Adult)	Cr CR (Child)

Hyperopisus bebe	5.24×10^{-5}	8.91×10^{-5}	1.61×10^{-6}	2.72×10^{-6}	4.04×10^{-5}	6.88×10^{-5}
Tilapia zilli	1.46×10^{-4}	2.48×10^{-4}	1.55×10^{-6}	2.68×10^{-6}	5.22×10^{-5}	8.90×10^{-5}
Alestes baremose	3.06×10^{-5}	5.20×10^{-5}	1.73×10^{-6}	2.94×10^{-6}	5.03×10^{-5}	8.56×10^{-5}
Hydrocynus brevis	1.09×10^{-4}	1.86×10^{-4}	3.91×10^{-6}	6.63×10^{-6}	3.50×10^{-5}	5.98×10^{-5}
Clarias gariepinus	2.19×10^{-4}	3.72×10^{-4}	2.81×10^{-6}	4.78×10^{-6}	6.92×10^{-5}	1.18×10^{-4}

Discussion

The observed order of heavy metal accumulation indicates that Fe was the most abundant element in fish species, followed by Cu and Pb, while Cd and Cr occur in lower concentrations. Fe and Cu in all the fish species were found within the WHO/FAO (2022) acceptable limit for fish consumption, but the mean concentrations of Cd and Cr in all the fish were found above the limit. Moreover, Pb concentration were found above the limit in *Clarias gariepinus* and *Hydrocynus brevis*, while in *Tilapia zilli*, *Hyperopisus bebe* and *Alestes baremose* the concentrations were found below the WHO/FAO (2022) acceptable limit. Yu *et al.* (2020) reported that essential elements required for life are more readily available in fish species compared to non-essential elements. Surface contact with water, food chain and respiratory activity are the three major routes of heavy metals exposure through which it enter the fish body and accumulate in the muscles tissues or organs (Ballesteros *et al.,* 2009). However, the heavy metal concentrations found above the threshold in fish muscle inhabiting Argungu River might reveal a potential pollution resulting from human activities like agricultural runoff, vehicular emission, domestic effluent, construction activities, washing of clothes and vehicles. Odjer-Bio *et al.* (2015) reported that excessive concentration of Cd indicates deposition of manures, phosphate fertilizer from farming activities, and sewage sludge. High metals concentrations in aquatic ecosystems caused various morphological, physiological and biochemical changes in aquatic organisms (Santos *et al.,* 2012). Intensified agricultural and human activities like domestic and industrial wastewater raises the heavy metals concentration and its accumulation in aquatic organisms (Kumar and Dwivedi, 2021; Algül and Beyhan, 2020). Moreover, the pattern of accumulation of heavy metals observed in this study is consistent with the findings of Adebiyi *et al.* (2024); Yahaya *et al.* (2024). The high metals concentrations in *Tilapia zilli* and *Clarias gariepinus* might be associated with their bottom-feeding habits and sediments exposure contributes to higher

metal uptake. The variations of metal accumulation across species are influenced by feeding behavior, ecological niche, and lipid content (Jiang *et al.,* 2022). Heavy metals in fish are usually species-dependent and its bioaccumulation is influenced by the aquatic environment and feeding habits of fish species (Jiang *et al.,* 2022; Cai *et al.,* 2023; Wu *et al.,* 2023). The accumulation potential of heavy metal is a complex process primarily regulated by endogenous (feeding habit) and exogenous (bioavailability of metal, alkalinity and environmental temperature) factors (Jabeen and Chaudhry, 2010; Griboff *et al.,* 2016). Furthermore, the species at the top of the food chain or those eating on the benthic organisms have higher accumulation potentials (González *et al.,* 2021). Heavy metals solubility and bioavailability is influenced by pH, temperature and the presence of other dissolved materials that may affects the rate of accumulation in fish tissues (Pinheiro *et al.,* 2021). The findings of this study reveal a relatively lower accumulation of metals in carnivorous fish (*Hydrocynus brevis*) compared to omnivorous fish (*Clarias gariapienus*). The result of the present study is inconsistent with the findings of Jiang *et al.* (2022) who reported that carnivorous fish showed higher accumulation of heavy metal in muscle than other fish species. According to Jezierska and Witeska (2006), the variations of heavy metal concentrations in fish species depends on the exogenous factors like time of exposure, the uptake process, environmental conditions (temperature, pH, dissolved oxygen) and intrinsic factors such as age, feeding habits, and habitat.

The EDI values of Cr, Cd, and Pb analyzed in the tissues of five wild fish species were found above the permissible limit for both adults and children population, while the adults estimated EDI values for Cu and Fe were found below the reference dose in all the species. The consistently higher EDI, THQ and CR values for children in *Tilapia zilli*, *Clarias gariapienus* and *Hydrocynus brevis* highlight the vulnerability of children to heavy metal implications due to lower body mass and underdeveloped detoxification systems, indicating a potential health risk associated to consumption of fish species (Korte *et al.,* 2020). An HI < 1 indicates that adverse health effects are unlikely, whereas values approaching or exceeding 1 suggest increasing potential health concern due to combined toxic effects (Cai *et al.,* 2023). Notably, relatively elevated HI values were observed in children consuming *C. gariepinus*, *H. brevis*, and *T. zilli*, with 0.87334, 0.57880 and 0.56785, respectively. Although these values remain below the safety threshold,

those approaching unity e.g., 0.87334 suggest that cumulative exposure to multiple metals may pose potential health risks over time, particularly for vulnerable group such as children, even when individual THQ values are below 1. Moreover, prolonged exposure of Cd-contaminated fish may lead to renal dysfunction, skeletal damage and carcinogenesis (Lin *et al.,* 2021; Genchi *et al,* 2020). Ezedom *et al* (2020) demonstrated that repeated Cd exposure even at very low concentrations can alter biochemical, genetic and renal parameters. According to Genchi *et al.* (2020), the excessive exposure to Cd may impair liver and kidney functions, and osteoporosis as well as causing various types of cancer, including breast, lung, prostate, nasopharynx, pancreas and kidney cancers. High concentrations of Cd lead to chronic kidney dysfunction, cellular injury and interfering calcium regulation of human biological systems, fish and other aquatic organisms (Ezemonye *et al.,* 2018). In addition, consumption of Pb and Cr concentrations above the threshold limit induce synergistic toxic effects, such as oxidative stress, DNA damage, and endocrine disruption (Silbergeld, 2003; DesMarais and Costa, 2019). This study reported that Cr and Cd CR values exceeded the acceptable lifetime cancer risk limit in adults and children consuming *T. zilli* and *C. grepinus*. Nyarko *et al.,* (2023) reported that for all potential carcinogenic contaminants could not have a potential cancer risk below the CR values of 1×10^{-4}. However, Pb alone may not induce carcinogenesis but can enhance cellular and molecular activities that lead to DNA damage, brain damage, paralysis, digestive complications, oxidative stress and damaging human organs (Silbergeld, 2003; Bassey and Chukwu, 2019). The Cd may exert tumorigenic effects through non-genotoxic events such as epigenetic dysregulation (Lin, 2021). Hexavalent chromium is a known carcinogen (group 1) that causes oxidative stress, chromosome breaks, and DNA-adduct formation (DesMarais and Costa, 2019). Moreover, prolonged exposure to the consumption of fish contaminated with heavy metals (above the safe threshold limit) may result in various health implications.

Conclusion

This study highlights that Argungu River is experiencing heavy metal contamination, with Cd, and Cr concentrations exceeding FAO/WHO safety limits across all the fish species, while Pb found above threshold limit in *Clarias gariepinus* and *Hydrocynus brevis*. The high metals concentrations in *Tilapia zilli*

and *Clarias gariepinus* might be associated with their bottom-feeding habits and sediments exposure contributes to higher metal uptake. The human health risk assessment reveals that regular consumption of fish contaminated with heavy metal may pose health implications, particularly for children revealing their vulnerability to heavy metal exposure, and chronic toxic health implications over time. Non-carcinogenic and carcinogenic risks assessments confirmed that children face higher exposure risks than adults. These findings also indicate a broad environmental challenges that linked both natural and human-driven pollution sources from agricultural runoff, untreated domestic waste and other activities around the river bank that degrade water quality. This situation requires proactive regulatory measures, community engagement in pollution control and awareness programs to protect its ecological integrity, cultural and economic vitality. These actions can enhance a pathway toward a healthier and more sustainable future for the people who depend on it.

Conflict of interest

The authors declare no competing interest.

Authors contributions

N. Salisu: designed the study, coordinated field and laboratory investigations, performed data and risk analyses, interpreted the results, drafted the manuscript, revised and approved the final version of the manuscript.

S. G. Umar: contributed to the conceptualization and supervision of the study, provided methodological guidance, validated the analytical approach, review and edited the manuscript, and approved the fina version.

J. Umar: contributed to study design, supervision, interpretation of findings, manuscript review and editing, and approved the final version of the manuscript.

H. Abubakar: participated in laboratory analyses, data interpretation, manuscript revision, and approved the final copy of this manuscript.

S. Aliyu Abubakar: conducted field sampling and data collection, drafted sections of the manuscript, and approved the final version.

H. M. Mafara: contributed to data collection and interpretation, manuscript review and editing, and approved the final version.

M. Jabir: participated in data collection and interpretation, revised the manuscript and editing the content for intellectual quality, and approved the final version of the manuscript.

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