Bioaccumulation and Human Health Risk Assessment of Multi-Metal Pollution in Selected Fishes from River Niger in Lokoja, Kogi State, Nigeria

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Direct Research Journal of Biology and Biotechnology

Direct RESEARCH JOURNALS

Vol. 11(1), Pp. 68-77, December 2025,

https://journals.directresearchpublisher.org/index.php/drjbb; https://www.ajol.info/index.php/djbb

Research Article
ISSN: 2734-2158

Received 5 September 2025, Accepted 10 November 2025, Published 13 December 2025

ABSTRACT

River Niger in Lokoja is a major freshwater resource supporting fisheries and domestic use, yet increasing anthropogenic pressures raise concerns about heavy-metal contamination. This study aimed to assess multi-metal pollution, bioaccumulation, and human health risks associated with consuming three commonly eaten fish species from River Niger. Water, sediment, and biological samples of Clarias gariepinus, Tilapia zilli, and Alestes baremoze were systematically collected during the dry season and analyzed for Pb, Cd, Hg, As, Cr, Ni, Cu, and Zn using Flame Atomic Absorption Spectrophotometer (FAAS) and hydride generation–atomic absorption spectrophotometry (HG–AAS). Data were evaluated with ANOVA and Tukey HSD at $p < 0.05$*. Results showed that all water metals exceeded WHO/FAO (2017) limits, while sediments exhibited high enrichment of Zn, Pb, Cu, and Cr. Heavy-metal concentrations were highest in C. gariepinus, followed by T. zilli and A. baremoze, with Zn showing the strongest bioaccumulation. Estimated Daily Intake (EDI) values were consistently higher in children, and several Target Hazard Quotients (THQ) exceeded 1, resulting in Hazard Index (HI) values > 1 for all species, indicating potential non-carcinogenic health risks. This study has shown that consumption of fish from the River Niger may pose long-term health concerns, especially for children. Strengthened pollution control, routine environmental monitoring, and community-based risk-reduction strategies are recommended.*

Keywords: *Alestes baremoze; Bioaccumulation; Heavy metals; River Niger*

Direct Research Journal of Biology and Biotechnology
ISSN: 2734-2158
Direct RESEARCH JOURNALS

Citation: Ojiego B. O., Obioh G. I.B., Ibrahim M., Madu J., and Ogu G.I (2025). Bioaccumulation and Human Health Risk Assessment of Multi-Metal Pollution in Selected Fishes from River Niger in Lokoja, Kogi State, Nigeria. *Direct Research Journal of Biology and Biotechnology. Vol. 11(1), Pp. 68-77*
https://doi.org/10.26765/DRJBB58986574

INTRODUCTION

Freshwater rivers are vital natural resources that support biodiversity, provide drinking water, and sustain fishing, agriculture, transportation, and recreation. In Nigeria, the River Niger remains one of the most important waters bodies, playing a major ecological and socio-economic role across several states. Lokoja, located at the point where the Niger and Benue Rivers meet, is especially significant. It is a growing urban centre whose economy depends heavily on fishing, small-scale agriculture, and tourism (Olode, 2014; Ebiloma, 2019). The river provides an accessible and affordable source of fish, which serves as a major source of protein for many households. Despite its importance, River Niger and other Nigerian freshwater systems are increasingly exposed to pollution. Rapid population growth, unregulated waste disposal, agricultural runoff, industrial emissions, and urban expansion have contributed to a rise in contaminants, including heavy metals. Recent studies report deteriorating water quality and elevated metal concentrations in rivers, lakes, and reservoirs across Nigeria (Adejuwon and Akinola, 2025; Jolaosho et al., 2025; Olowojuni et al., 2025). Similar patterns have been documented in Ikere Gorge Dam, Asejire Reservoir, the Esinmirin River, Ogbor Hill River, and the Niger Delta, indicating widespread anthropogenic pressure on aquatic environments (Anyanwu et al., 2023; Okey-Wokeh et al., 2023; Olabamiji et al., 2025). Heavy metals are of particular concern because they do not break down in the environment. They persist in water, sediments, and aquatic organisms, where they can bioaccumulate and biomagnify along the food chain. Fish are especially vulnerable, absorbing metals through contaminated water and sediment. Over time, these metals accumulate in fish tissues, creating a direct exposure pathway for humans who consume them (Mustapha et al., 2021; Ehiemere et al., 2022; Amoo et al., 2024). High levels of metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) have been reported in several Nigerian fish species, including Clarias gariepinus and Oreochromis niloticus, which are commonly eaten across the country (Ogbuene et al., 2024; Akpobi et al., 2025; Yusuf et al., 2025). This trend is not limited to Nigeria. Studies across Africa and Asia show similar contamination, raising global concern about the safety of fish from polluted freshwater systems (Lipy et al., 2024; Okouyi et al., 2024; Khedr and Ghannam, 2025). Heavy metals are known to cause neurological damage, kidney dysfunction, developmental problems, immune suppression, and cancer, especially when exposure occurs over long periods (Joseph et al., 2022; Riad et al., 2025; Roy et al., 2025). Children and pregnant women are particularly vulnerable.

Although the River Niger in Lokoja is widely used for fishing and domestic purposes, scientific monitoring of heavy metal contamination in fish consumed by the local population remains limited. Increasing human activities along the riverbank; including refuse dumping, motor-boat operations, open defecation, artisanal workshops, agricultural activities, and runoff from nearby settlements, may introduce harmful metals into the water (Adesiyan et al., 2018; Iwunze and Tobin-West, 2024; Akpotayire et al., 2025). Without proper assessment, communities may unknowingly consume fish containing harmful levels of toxic metals. Previous studies in other regions of Nigeria have already shown that bioaccumulated metals in edible fish can exceed recommended safety limits and pose measurable health risks (Matouke and Abdullahi, 2020; Adebiyi et al., 2024; Nzekwe et al., 2025; Taiwo et al., 2025). Yet, despite the heavy reliance on River Niger fish in Lokoja, there is still limited scientific data on metal concentrations, bioaccumulation patterns, and the associated human health risks in this specific area. By assessing both bioaccumulation and the potential non-carcinogenic health risks, this study provides evidence that can support public health decision-making, environmental regulation, and food safety standards. It also contributes to the growing body of research on freshwater metal pollution in Nigeria, helping to identify areas requiring urgent management and remediation. The aim of this study was to quantify selected heavy metals in fish from River Niger in Lokoja, analyse their bioaccumulation, and associated human health risks.

MATERIALS AND METHODS

Study Area

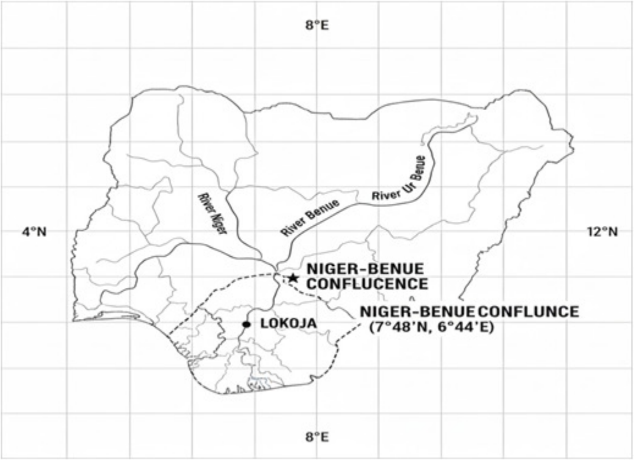

Figure 1: Location map of Nigeria, showing Niger-Benue Confluence in Lokoja, Kogi State

The study was carried out at the River Niger in Lokoja, the capital of Kogi State in North-Central Nigeria, a location renowned for its geographical, ecological, and socio-economic importance (Olode, 2014). The River Niger represents the meeting point of the two largest rivers in West Africa: River Niger and River Benue, situated approximately at latitude 7°47'42" N and longitude 6°44'28" E (Ebiloma, 2019) (Figure 1). Lokoja lies within the Tropical Wet-and-Dry (Aw) climatic zone, characterized by a marked wet season (April–October) and dry season (November–March), with mean annual temperatures between 25–35°C, and a vegetation profile dominated by the Guinea Savannah transitional belt (Olode, 2014; Ebiloma, 2019). The River Niger supports extensive fisheries, domestic water supply, irrigation, transportation, and diverse livelihood systems for millions of rural and urban dwellers in the region (Ebiloma, 2019). However, intense anthropogenic pressures have increased pollutant inputs into the waterbody, elevating concerns over the bioaccumulation of heavy metals in aquatic organisms, particularly fish consumed by local populations.

Collection of water and sediment samples

A systematic sampling strategy was employed in which triplicate samples (n = 3) were collected for each environmental compartment (water and sediment). Sampling was conducted during the peak dry season (December–February, 2025), a period characterized by reduced river discharge and a higher likelihood of contaminant concentration, thereby providing a conservative estimate of pollutant levels in the River Niger. Water samples were collected from the main channel at a depth of approximately 15 cm below the surface using pre-acid-washed 500 mL high-density polyethylene (HDPE) bottles; immediately after collection, the samples were preserved by field-acidification with ultrapure nitric acid (HNO_3) to pH < 2 to prevent metal adsorption onto container surfaces or precipitation. Surface sediment samples (0–10 cm depth) were obtained adjacent to each water sampling point using a pre-cleaned plastic scoop or stainless-steel grab sampler, transferred into labeled polyethylene bags, and stored in an insulated cooler to maintain sample integrity prior to laboratory analysis.

Collection of fish samples

Figure 2: Samples of fish used for the study

Three widely consumed and ecologically representative fish species were selected for biological sampling based on their differing trophic levels and feeding habits within the River Niger ecosystem. They included Clarias gariepinus (African catfish), Tilapia zilli (Redbelly tilapia), and Alestes baremoze (Bonga or Silver fish) (Figure 2). These species were deliberately chosen because their contrasting feeding strategies increase the likelihood of capturing differential patterns of metal uptake across the aquatic food web while also reflecting fish commonly consumed by residents in Lokoja. A total of ten (10) mature individuals of each species were obtained directly from artisanal fishers who operate daily within the River Niger zone to ensure that the sampled fish accurately represented the local catch. Immediately after purchase, all fish were placed in ice-packed coolers to slow metabolic activity and prevent biochemical degradation during transport to the laboratory, where they were subsequently processed for heavy metal analysis.

Sample processing, preparation, and heavy metal analysis

In the laboratory, each fish specimen was measured for total length and weight before being dissected using pre-cleaned stainless-steel surgical instruments to avoid metal contamination, after which the muscle, liver, and gills were carefully excised. Tissue samples from ten individuals of the same species were homogenized and pooled to form a single biological replicate, yielding three pooled replicates (n = 3) per tissue type for each species. All HDPE containers, glassware, and dissection tools were subjected to rigorous quality control procedures, including a 24-hour soak in 10% (v/v) HNO_3 followed by thorough rinsing with deionized water, and only analytical-grade reagents were used throughout the experiment to minimize contamination, consistent with established procedures (Ehiemere et al., 2022). Water samples, previously acidified in the field, were prepared for analysis by subjecting a 50 mL aliquot to mild digestion or dilution in 1% HNO_3 to ensure matrix compatibility with flame atomic absorption spectrophotometry (FAAS). Sediment samples (≈1.0 g) and pooled tissue samples (≈0.5 g) were oven-dried, homogenized, accurately weighed, and digested using a modified wet-digestion protocol in which a 5:1 mixture of concentrated HNO_3 and $HClO_4$ was added to each sample in Kjeldahl flasks and heated under a fume hood until a clear digest was obtained, indicating complete breakdown of organic matter. This approach follows digestion procedures commonly used in Nigerian fish-metal studies (Matouke and Abdullahi, 2020). After digestion, the digests were cooled, filtered, and diluted to a final volume of 50 mL with deionized water. Concentrations of eight target heavy metals (Pb, Cd, Hg, As, Cr, Ni, Cu, and Zn) were subsequently quantified using a Flame Atomic Absorption Spectrophotometer (FAAS), calibrated with certified 1000 mg/L stock solutions to generate linear multi-point standard curves. Instrumental parameters were optimized per manufacturer recommendations for each metal, while mercury (Hg) and arsenic (As) were analyzed using Hydride Generation AAS (HGAAS) to enhance detection sensitivity due to their low environmental concentrations and strict regulatory limits. The performance of the quality control samples was satisfactory, as their measurements remained within acceptable limits when compared with acid blanks, and the recovery of heavy metals ranged from 90.4% to 97.5%, indicating reliable analytical efficiency.

Bioaccumulation factor (BAF)

The Bioaccumulation Factor (BAF) was computed to evaluate the tendency of each heavy metal to accumulate in fish tissues relative to its concentration in the surrounding aquatic environment. BAF serves as a key indicator of the efficiency with which fish absorb and retain contaminants from the water column through processes such as gill filtration, dietary uptake, and dermal absorption. It provides insight into the potential for trophic transfer and long-term ecological risk. The BAF for each metal was determined using the ratio of the mean metal concentration measured in whole fish tissue to the corresponding mean metal concentration in water, expressed mathematically as:

$BAF=Cf/Cw$

Where: Cf represents the mean concentration of the metal in fish tissue (mg/kg), and Cw represents the average concentration of the same metal in the water samples (mg/L). Higher BAF values indicate stronger bioaccumulation potential and a greater likelihood of metals entering the food chain

Estimated Daily Intake (EDI) from Fish Consumption

The Estimated Daily Intake (EDI) was calculated to assess the level of human exposure to heavy metals through the consumption of fish muscle tissue, which is the primary edible portion for the local population. EDI provides a quantitative estimate of the amount of a specific metal ingested per kilogram of body weight per day and is essential for evaluating potential non-carcinogenic and carcinogenic health risks. The calculation integrates metal concentration in fish with local dietary habits and lifetime exposure assumptions. The EDI was computed using the standard USEPA exposure model:

$EDI =(Cf \times IR \times EDBW \times ED)/(Bw \times AT)$

Where Cf is the concentration of each heavy metal in the edible fish muscle (mg/kg), and IR is the daily fish ingestion rate, which for this study was set at 24.7 g/day (0.0247 kg/day) for adults and 1.86 g/day (0.0186 kg/day) for children based on local consumption in North Central, Nigera (Matouke and Abdullahi, 2020). The calculation also uses the average body weight (BW) of each population group, defined as 60 kg for adults and 21.6 kg for children, to express intake on a per-kilogram basis (Matouke and Abdullahi, 2020). Exposure frequency (EF) was assumed to be 365 days per year, and the exposure duration (ED) followed standard health-risk assessment practice (USEPA, 2025).

Non-Carcinogenic Risk Assessment (THQ and HI)

The non-carcinogenic health risk associated with consuming contaminated fish was quantified using the Target Hazard Quotient (THQ) for each heavy metal. THQ compares the Estimated Daily Intake (EDI) of a metal to its oral Reference Dose (RfD), which represents the maximum acceptable daily human exposure without appreciable risk of adverse effects. The THQ for each metal was calculated using the expression:

$THQ= EDI/RfD$

For this study, the standard USEPA Reference Dose (RfD) values were applied as follows: Pb (0.0035 mg/kg/day), Cd (0.001 mg/kg/day), Hg as methylmercury (0.0001 mg/kg/day), As (0.0003 mg/kg/day), Cr (0.003 mg/kg/day), Ni (0.02 mg/kg/day), Cu (0.04 mg/kg/day), and Zn (0.3 mg/kg/day). A THQ value below 1 signifies negligible risk, whereas values above 1 indicate potential for adverse health effects from chronic exposure. To evaluate the combined non-carcinogenic risk posed by simultaneous ingestion of multiple metals, the Hazard Index (HI) was calculated as the sum of individual THQs:

$HI = THQ_{Pb}+THQ_{Cd}+THQ_{Hg}+THQ_{As}+THQ_{Cr}+THQ_{Ni}+THQ_{Cu}+THQ_{Zn}$

An HI value less than 1 suggests that the combined exposure to all metals is unlikely to pose significant non-carcinogenic health risks. Conversely, an HI greater than 1 indicates potential cumulative adverse health effects due to additive or synergistic interactions among the metals.

Data Analysis

All data were analyzed using SPSS Version 25. Prior to analysis, datasets were examined for normality and homogeneity of variance. Differences in heavy metal concentrations among sampling media (water, sediment) and among fish species were assessed using one-way Analysis of Variance (ANOVA). When significant variation was detected ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to determine pairwise differences between means. Results are expressed as Mean ± Standard Deviation (SD).

RESULTS AND DISCUSSION

The results of heavy metal concentrations in the water samples, as presented in Table 1, showed a clear pattern of pollution, with all measured metals exceeding WHO/FAO (2017) guideline values. The markedly high levels of Pb (0.142 mg/L), Cd (0.018 mg/L), Hg (0.006 mg/L), As (0.033 mg/L), Cr (0.087 mg/L), and Ni (0.064 mg/L) indicate substantial anthropogenic loading. These elevated values suggest inputs from domestic wastewater discharges, fuel combustion residues, informal metal workshops, and upstream industrial effluents, around the water bodies. These findings are in agreement with Olowojuni et al. (2025), who reported similarly high Pb, Cr, and Ni in Asejire Reservoir and attributed the sources to urban wastewater and increased industrialization. Adejuwon and Akinola (2025) also reported that Cr and Ni in the Esinmirin River were significantly above permissible limits, which supports the findings of the present study.

Similarly, the dominance of Pb, Cr, and Ni in the Lokoja water samples aligns with observations by Jolaosho et al. (2025), who noted that these metals were among the most persistent pollutants in Nigerian lagoon systems. This supports the idea that these metals are characteristic contaminants across many freshwater systems influenced by urban growth. Although Cu and Zn remained below acceptable limits, their moderately elevated concentrations indicate minor contributions from

Table 1: Heavy metal concentrations (mg/L) in water samples collected from River Niger in Lokoja.

Heavy metal	Rep 1	Rep 2	Rep 3	Mean ± SD	WHO/FAO Limit (mg/L)
Pb	0.153	0.139	0.134	0.142 ± 0.011^{a}	0.01
Cd	0.020	0.017	0.016	0.018 ± 0.002^{b}	0.003
Hg	0.007	0.006	0.005	0.006 ± 0.001^{c}	0.001
As	0.037	0.032	0.030	0.033 ± 0.003^{b}	0.01
Cr	0.094	0.083	0.084	0.087 ± 0.007^{a}	0.05
Ni	0.070	0.060	0.062	0.064 ± 0.005^{b}	0.02
Cu	0.123	0.110	0.103	0.112 ± 0.009^{a}	2.0
Zn	0.310	0.270	0.272	0.284 ± 0.024^{a}	3.0

Different superscripts indicate significant differences across metals ($p < 0.05$).

Table 2: Heavy metal concentrations (mg/kg) in sediment samples from River Niger in Lokoja.

Heavy Metal	Rep 1	Rep 2	Rep 3	Mean ± SD	WHO/FAO Sediment Limit (mg/kg)
Pb	46.1	41.2	41.0	42.8 ± 3.40^{a}	35
Cd	3.9	3.4	3.5	3.6 ± 0.31^{c}	0.6
Hg	1.3	1.1	1.2	1.2 ± 0.12^{c}	0.3
As	10.1	9.0	9.2	9.4 ± 0.80^{b}	5.9
Cr	30.4	26.3	27.7	28.1 ± 2.31^{ab}	25
Ni	21.0	18.7	19.1	19.6 ± 1.71^{b}	16
Cu	34.0	30.2	30.1	31.4 ± 2.60^{a}	36
Zn	94.2	83.7	84.0	87.3 ± 6.81^{a}	123

Different superscripts indicate significant differences ($p < 0.05$).

agricultural runoff, corrosionof household plumbing, and natural geological weathering. This interpretation is consistent with Akpotayire et al. (2025), who reported that Cu and Zn in Eleme River were largely influenced by agrochemical residues and background geochemistry rather than industrial discharges. The high levels recorded across all most metals in this study also corroborate earlier findings across Nigeria. Adesiyan et al. (2018) and Okey-Wokeh et al. (2023) both reported that Pb, Cd, and Cr frequently surpass drinking-water limits in Southwestern and Southern Nigeria, respectively, suggesting that heavily populated regions share similar contamination sources. Iwunze and Tobin-West (2024) also reported critically elevated Pb and Cd in oil-producing communities, reinforcing that heavy-metal pollution is a national problem. Globally, these findings agree with the pollution patterns reported by Shanbehzadeh et al. (2014) in Iran and Khedr and Ghannam (2025) in Egypt, where rivers under high human pressure displayed similar heavy-metal enrichment. The results from this study diverged slightly with respect to Cu and Zn, whose concentrations remained comparatively moderate despite the elevated levels of other metals. This contrasts with Olabamiji et al. (2025), who found significantly higher levels in Ikere Gorge Dam. This disagreement may be linked to differences in agricultural intensity or local geology influencing Cu–Zn release.

The sediment results shown in **Table** 2 revealed a different metal distribution pattern compared to the water samples, with Zn (87.3 mg/kg), Pb (42.8 mg/kg), Cu (31.4 mg/kg), and Cr (28.1 mg/kg) being the dominant accumulated metals. The high values reflect the natural ability of sediments to bind metals through adsorption, precipitation, and incorporation into mineral matrices (El-Sharkawy *et al.,* 2025). Additionally, Cd (3.6 mg/kg), Hg (1.2 mg/kg), As (9.4 mg/kg), and Ni (19.6 mg/kg) all exceeded WHO/FAO (2017) sediment limits, suggesting long-term pollution deposition rather than short-term inflow. The accumulation of Zn, Cr, Cu, and Ni shows close agreement with Eyiseh et al. (2022), who reported a similar order (Zn > Cr > Cu > Ni) in River Donga sediments. It also aligns with the findings of Amoo et al. (2024) in Hadejia River, supporting the idea that these metals share similar geochemical affinity for sediment particles across Nigerian freshwater ecosystems. The elevated As and Hg levels recorded in Lokoja correspond with the high ranges reported by Shanbehzadeh et al. (2014) for the Tembi River, indicating that both natural geological sources and human activities contribute to their accumulation. These findings also agree with the reports from the Niger Delta, where Ehiemere et al. (2022) and Anyanwu et al. (2023) observed significant buildup of Cd, Pb, Cr, and Ni in sediments due to continuous industrial discharges, oil spills, and municipal waste loading. The metal retention observed in the Lokoja sediments aligns with findings from the Orashi River, where Ossai et al. (2025) reported similarly elevated sediment-bound metals. They attributed this accumulation to continuous industrial effluent discharge and reduced water flow conditions, both of which enhance the settling and long-term deposition of contaminants. However, the Cu concentration recorded in this study (31.4 mg/kg) was slightly below the WHO/FAO

Table 3: Heavy Metal Concentrations (mg/kg) in Fish Tissues of Selected Species from the River Niger in Lokoja

Heavy Metal	*Clarias gariepinus*	*Tilapia zilli*	*Alestes baremoze*
Pb	2.14 ± 0.18^{a}	1.68 ± 0.14^{ab}	1.21 ± 0.10^{b}
Cd	0.41 ± 0.03^{a}	0.34 ± 0.03^{a}	0.22 ± 0.02^{b}
Hg	0.19 ± 0.02^{a}	0.14 ± 0.01^{b}	0.08 ± 0.01^{c}
As	0.78 ± 0.06^{a}	0.61 ± 0.05^{b}	0.47 ± 0.04^{c}
Cr	1.34 ± 0.11^{a}	1.06 ± 0.08^{b}	0.79 ± 0.06^{c}
Ni	0.97 ± 0.08^{a}	0.82 ± 0.06^{ab}	0.63 ± 0.05^{b}
Cu	2.28 ± 0.19^{a}	1.86 ± 0.15^{b}	1.41 ± 0.12^{c}
Zn	12.40 ± 1.01^{a}	9.71 ± 0.82^{b}	7.60 ± 0.61^{c}

Different superscripts indicate significant differences across samples ($p < 0.05$).

(2017) sediment limit, a trend that is in disagreement with the findings of Olowojuni et al. (2025) in Asejire Reservoir where Cu levels substantially exceeded guideline values. This discrepancy may reflect differences in watershed characteristics, industrial inputs, and catchment land-use intensity, suggesting that Cu contamination is more site-specific compared to other metals that show consistent regional elevation. The sediment concentrations documented here are substantially higher than those reported for Osun River by Anifowose and Oyebode (2019), indicating more intense anthropogenic loading in Lokoja environment. The persistence and magnitude of metal enrichment in the sediments highlight a significant potential for bioaccumulation and food-chain transfer, supporting the concerns expressed by Amoo et al. (2024) regarding long-term ecological exposure.

The results of the heavy metal analysis in the fish tissues shown in Table 3. The results revealed that Clarias gariepinus recorded the highest concentrations of all heavy metals measured, followed by Tilapia zilli and then Alestes baremoze. These patterns are consistent with established ecological and physiological differences among freshwater fish species, particularly with respect to feeding strategy, habitat occupancy, and metabolic pathways for metal uptake (Lipy et al., 2024). As a benthic omnivore, C. gariepinus frequently interacts with contaminated sediments, which serve as major reservoirs for Pb, Cr, and other trace metals, whereas A. baremoze is predominantly pelagic and consequently experiences reduced direct exposure to sediment-bound contaminants (Bawuro et al., 2018; Okouyi et al., 2024). The elevated Pb concentration recorded in C. gariepinus (2.14 mg/kg) corroborates observations by Ehiemere et al. (2022), who similarly reported substantial Pb accumulation in C. gariepinus from Niger Delta, suggesting species-level susceptibility and strong bioaccumulation potential across diverse hydrological environments. Nevertheless, the Pb levels in the present study exceed those reported for River Niger at Agenebode (Wangboje and Ikhuabe, 2015) and are higher than values documented for Oreochromis niloticus in the Lower Niger at Ajaokuta (Yusuf et al., 2025). These discrepancies could reflect variations in anthropogenic inputs, sediment chemistry, and hydrodynamic conditions at the River Niger, and are heavily influenced by urban effluents, surface runoff, artisanal activities, and fluctuating water flow that enhances metal mobilization. A similar trend is observed for Cd and Cr, whose concentrations were greater than those documented in African pike from Alape River (Awugo and Igejongbo, 2024) and in fish from Okwagbe River (Akpobi et al., 2025), indicating heightened geochemical enrichment of these metals within this River Niger zone. On the other hand, the comparatively high Cu and Zn levels, particularly in C. gariepinus (2.28 and 12.40 mg/kg, respectively), agree with broader regional patterns reported across West Africa (Laoye et al., 2025; Mustapha et al., 2021), where essential trace metals are elevated due to combined influences of natural weathering, aquaculture feeds, and agricultural activities.

The gradients observed for Hg and As, though lower in magnitude relative to other metals, remain consistent with accumulation patterns reported in Gabonese freshwater systems, where benthic and piscivorous species show greater biomagnification potential (Okouyi et al., 2024). The variations between the present results and those reported previously, such as the lower heavy-metal burdens observed in Cynoglossus senegalensis from the Qua Iboe River (Joseph et al., 2022) and the markedly reduced levels recorded in colder, less industrialized systems (Bazarsadueva et al., 2023), highlight the roles of watershed industrialization, sediment characteristics, trophic dynamics, and localized pollution pressures. These differences further point to the need for site-specific monitoring frameworks that account for regional environmental conditions and evolving anthropogenic influences.

Bioaccumulation Factor (BAF) results for heavy metals in fish species from the River Niger in Lokoja are presented in Table 4. From the table, Clarias gariepinus showed the highest accumulation of all metals, followed by moderate levels in Tilapia zilli and the lowest values in Alestes baremoze, with zinc recording the highest BAFs across all species and mercury the lowest. These patterns agree with earlier findings in the Lower River Niger, where Clarias gariepinus was also reported to accumulate metals more readily than tilapia species, likely due to differences in feeding habits and habitat use (Yusuf et al., 2025). Similar species-related differences were observed by

Table 4: Bioaccumulation factor (BAF) for heavy metals in fish Species from River Niger in Lokoja

Metal	*Clarias gariepinus*	*Tilapia zilli*	*Alestes baremoze*
Pb	4.86 ± 0.39^{a}	3.72 ± 0.31^{b}	2.41 ± 0.19^{c}
Cd	1.12 ± 0.09^{a}	0.84 ± 0.07^{b}	0.56 ± 0.05^{c}
Hg	0.36 ± 0.03^{a}	0.27 ± 0.02^{b}	0.16 ± 0.01^{c}
As	1.42 ± 0.12^{a}	1.06 ± 0.09^{b}	0.74 ± 0.06^{c}
Cr	2.18 ± 0.17^{a}	1.71 ± 0.14^{b}	1.21 ± 0.10^{c}
Ni	1.64 ± 0.14^{a}	1.28 ± 0.11^{b}	0.93 ± 0.08^{c}
Cu	5.91 ± 0.46^{a}	4.32 ± 0.35^{b}	2.87 ± 0.23^{c}
Zn	21.80 ± 1.71^{a}	16.41 ± 1.30^{b}	11.6 ± 0.91^{c}

Different superscripts indicate significant differences across samples ($p < 0.05$).

Table 5: Estimated daily intake (EDI) of heavy metals (mg/kg/day) for adults and children consuming fish River Niger in Lokoja

Heavy	*Clarias gariepinus*		*Tilapia zilli*		*Alestes baremoze*	
Metal	Adults	Children	Adults	Children	Adults	Children
Pb	0.000881	0.001843	0.000692	0.001447	0.000498	0.001042
Cd	0.000169	0.000353	0.000140	0.000293	0.000091	0.000189
Hg	0.000078	0.000164	0.000058	0.000121	0.000033	0.000069
As	0.000321	0.000672	0.000251	0.000525	0.000193	0.000405
Cr	0.000552	0.001154	0.000436	0.000913	0.000325	0.000680
Ni	0.000399	0.000835	0.000338	0.000706	0.000259	0.000542
Cu	0.000939	0.001963	0.000766	0.001602	0.000580	0.001214
Zn	0.005105	0.010678	0.003997	0.008361	0.003129	0.006544

Table 6: Target hazard quotient (THQ) and hazard index (HI) for adults and children consuming fish from River Niger in Lokoja.

Heavy	*Clarias gariepinus*		*Tilapia zilli*		*Alestes baremoze*	
Metal	Adults	Children	Adults	Children	Adults	Children
Pb	0.252	0.527	0.198	0.413	0.142	0.298
Cd	0.169	0.353	0.140	0.293	0.091	0.189
Hg	0.780	1.640	0.580	1.210	0.330	0.690
As	1.070	2.240	0.837	1.750	0.643	1.350
Cr	0.184	0.385	0.145	0.304	0.108	0.227
Ni	0.020	0.042	0.017	0.035	0.013	0.027
Cu	0.023	0.049	0.019	0.040	0.014	0.030
Zn	0.017	0.036	0.013	0.028	0.010	0.022
HI	2.515	5.271	1.949	4.074	1.353	2.833

Wangboje and Ikhuabe (2015), who found higher metal loads in bottom-feeding fish from the River Niger, supporting the elevated BAFs seen in C. gariepinus. Additionally, the high zinc and copper accumulation aligns with observations from other Nigerian rivers, where essential metals often occur at higher concentrations in fish tissues due to their biological roles and greater environmental availability (Akpobi et al., 2025). On the contrary, the consistently low mercury BAFs reflects trends reported in Gabonese freshwater systems, where mercury accumulation was comparatively minimal in non-predatory species (Okouyi et al., 2024). These similarities indicate that species ecology, metal availability, and feeding behavior are major factors shaping the bioaccumulation patterns observed at the River Niger.

The results for the estimated daily intake (EDI) for adults and children are shown in (Table 5). It was observed that children consistently exhibited higher EDI values than adults for all metals due to their lower body weight and relatively higher fish consumption rate. This pattern agrees with the studies by Roy et al. (2025) and Nzekwe et al. (2025), who also reported significantly higher exposure in children across multiple fish species. The elevated EDI values for metals such as Pb, Cd, and Hg in the present study are comparable to findings by Shams Ul Samad et al. (2025) in the Barandu River, Pakistan, where artisanal activities similarly contributed to elevated bioaccumulation in fish tissues. Similarly, the high EDI values observed is in consonance with the contamination patterns reported by Riad et al. (2025) in coastal Bangladesh, who also documented excessive intake levels relative to U.S. EPA exposure thresholds. Conversely, Bassey and Chukwu (2019) reported relatively lower dietary exposures in lagoon systems in southwestern Nigeria, which may reflect ecological differences and lower upstream anthropogenic impacts compared to the current study area.

The results for the target hazard quotient (THQ) and hazard index (HI) for adults and children are presented in (Table 6). It was observed that several metals exhibited THQ values greater than 1, indicating potential non-carcinogenic health risks. Consistent with global trends, children demonstrated markedly higher THQ values than adults due to their smaller body mass. These findings are in agreement with Taiwo et al. (2025), who recorded THQ > 1 for multiple metals in differently processed Clarias gariepinus from southwestern Nigeria, and with Ogbuene et al. (2024), who reported similarly elevated THQ values in Clarias gariepinus and Oreochromis niloticus from the Anambra River. The cumulative Hazard Index (HI) values in (Table 6) were also greater than 1 for both adults and children, indicating the potential for combined toxic effects from multiple metals. This observation agrees with the findings of Adebiyi et al. (2024), Kortei et al. (2020), and Matouke and Abdullahi (2020), who all reported HI > 1 in fish from Nigeria and Ghana, suggesting additive human health risks under mixed-metal exposure scenarios. The present HI values also corroborate the conclusions of Amqam et al. (2020) in Kao Bay, Indonesia, where mixed contamination of Hg and as produced hazard indices exceeding safe thresholds for nearly all surveyed consumers. Unlike Bassey and Chukwu (2019), who reported HI < 1 for fish from relatively less impacted lagoon systems, the elevated HI values in the present study reflect heavier contamination pressure, similar to the conditions described in mining-impacted waters by Shams Ul Samad et al. (2025) and Kortei et al. (2020). In general, the THQ and HI results from (Table 6) suggest that consumption of the studied fish species poses a significant non-carcinogenic risk, with children constituting the most vulnerable group.

The implications of these findings are significant, especially because both the EDI and HI values suggest possible long-term health risks, with children being the most affected. The elevated levels of metals such as Pb, Cd, Hg, and as found in this study are linked to serious health problems, including damage to the nervous system, kidneys, and overall development, as well as increased cancer risk. This highlights the vulnerability of people who rely on fish from polluted freshwater environments. Similar concerns were reported by Roy et al. (2025) and Shams Ul Samad et al. (2025), who found that eating fish contaminated with heavy metals can pose major health dangers for communities that depend on their local rivers and lakes. Although these findings are based on estimated values and certain assumptions about fish consumption and exposure, they still provide an important warning. Previous studies, such as those by Riad et al. (2025) and Adebiyi et al. (2024), show that even when calculations are based on estimates, they reliably indicate when there is a potential health risk.

Therefore, the high THQ and HI values observed in this study suggest possibility of harm if current conditions do not improve. This makes it necessary to strengthen pollution control, increase regular monitoring of water and fish quality, and educate local communities, as also recommended by Bassey and Chukwu (2019) and Amqam et al. (2020).

Conclusion

This study has shown that fish from the River Niger contain elevated levels of multiple heavy metals, which bioaccumulate differently across species, with Clarias gariepinus showing the highest burdens. The higher Estimated Daily Intake (EDI) and Hazard Index (HI) values recorded in children indicate greater vulnerability and a higher likelihood of chronic health effects. Although the risk estimates are based on standard assumptions for consumption rate and body weight, the patterns observed closely align with findings from similar studies, suggesting that the potential risks are significant. The results, therefore, highlight the need for stricter environmental pollution control measures, continuous monitoring of local water bodies, and public health strategies to reduce exposure among communities that depend heavily on these fish resources for nutrition and livelihood.

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