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HEAVY METAL BIOACCUMULATION AND HUMAN HEALTH RISK IN *CLARIAS GARIEPINUS* AND *OREOCHROMIS NILOTICUS* FROM KPATA, LOWER RIVER NIGER, NIGERIA

Udechukwu Peace Onyinye[1]*, Adang Kombe Lucas[1], Peace Onas Somdare[2]

[1]*Department of Biology, Faculty of Life Sciences, Federal University Lokoja, PMB 1154, Lokoja, Kogi State, Nigeria*

[2]*Department of Zoology, Federal University Lokoja, PMB 1154, Lokoja, Kogi State, Nigeria*

*Corresponding author: speak2peace.po@gmail.com

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Abstract

Fish from waters contaminated with heavy metals have long been recognised as one of the routes through which humans acquire such metals from their environment, yet information on fish tissue metal burdens, accumulation factors and associated health risk along the River Niger in Nigeria remains scarce. Cadmium, lead, chromium, zinc, mercury, copper and arsenic were quantified in liver tissues of Clarias gariepinus and Oreochromis niloticus caught from the Kpata reach of the Lower River Niger at Lokoja during the dry season (January to March 2025) and the wet season (June to August 2025). Livers were subjected to wet acid digestion in a nitric and perchloric acid mixture before atomic absorption spectrophotometry. Bioaccumulation factors were computed relative to ambient water and sediment, and human health risk was evaluated through the estimated daily intake, target hazard quotient, hazard index and margin of exposure, using a per capita consumption rate of 8.26 grams per person per day. With the sole exception of mercury, all metals exceeded WHO and FAO permissible limits for fish in both species. Clarias gariepinus accumulated higher tissue burdens than Oreochromis niloticus, consistent with its benthic habit, and the bioaccumulation order for both species was Cr > Zn > Cd > Cu > As > Pb > Hg. Individual target hazard quotients were below unity, with chromium the highest (0.271 in C. gariepinus, 0.267 in O. niloticus), and the hazard indices (0.443 and 0.430 respectively) remained below one. The margin of exposure for chromium was nonetheless narrow (36.8 to 37.5), so that higher consumption could raise the chromium hazard quotient toward unity. Periodic tissue monitoring and species targeted consumption advisories are recommended to safeguard chronic consumers along this reach of the River Niger.

Keywords: heavy metal bioaccumulation; *Clarias gariepinus*; *Oreochromis niloticus*; human health risk; River Niger; Nigeria

1. Introduction

Fish supplies high quality protein and essential micronutrients to more than 3.3 billion people worldwide, and it is especially important in low and middle income tropical countries where alternative animal protein is often economically inaccessible (FAO, 2022). In Sub-Saharan Africa, artisanal riverine fisheries underpin food security and livelihoods, and freshwater species such as catfish (*Clarias* spp.) and tilapia (*Oreochromis* spp.) dominate inland dietary fish intake (Lamo et al., 2023). The nutritional value of fish is, however, increasingly offset by the simultaneous ingestion of heavy metals that accumulate in fish tissue from contaminated aquatic environments, a concern most acute in river systems receiving unregulated industrial, agricultural and domestic effluent (Fazio et al., 2020).

Heavy metals are persistent, nonbiodegradable contaminants that partition between water, sediment and biota. Fish absorb metals through gill respiration, dermal contact and dietary ingestion, and accumulate them preferentially in metabolically active organs such as the liver, kidney and gills (Novikova et al., 2019). The liver, as the primary site of metallothionein mediated detoxification, typically carries the highest tissue metal load and is the standard analytical target in fish contamination studies (Bat et al., 2022). Bioaccumulation is species specific: benthic species foraging in direct contact with contaminated sediment accumulate higher metal loads than pelagic or midcolumn feeders (Kassegne et al., 2019). Chronic exposure to cadmium, lead and chromium is associated with nephrotoxicity, neurotoxicity, developmental impairment and carcinogenicity (Tchounwou et al., 2012), while methylmercury exposure is a documented developmental neurotoxin to which pregnant women and developing fetuses are particularly sensitive (Karagas et al., 2012). The standard framework of the United States Environmental Protection Agency, comprising the estimated daily intake, target hazard quotient, hazard index and margin of exposure, translates tissue concentrations into population level risk estimates and supports evidence based public health communication (USEPA, 2011).

The Kpata reach of the Lower River Niger at Lokoja lies at the Niger and Benue confluence and supports an active artisanal fishery serving local and regional markets, while simultaneously receiving industrial effluent, boat fuel handling residues, market waste and agricultural runoff. Despite the dual significance of this reach as both a productive fishery and a contaminated environment, no study has simultaneously characterised heavy metal bioaccumulation in two of the most commercially important species harvested there, the African catfish (*C. gariepinus*) and the Nile tilapia (*O. niloticus*) (Solomon et al., 2012), and applied a comprehensive human health risk framework. This study therefore quantified cadmium, lead, chromium, zinc, mercury, copper and arsenic in liver tissues of *C. gariepinus* and *O. niloticus* from Kpata across two hydrological seasons, computed species specific bioaccumulation factors relative to ambient water and sediment, assessed human health risk through the estimated daily intake, target hazard quotient, hazard index and margin of exposure, and compared the risk profiles of the two species to inform species specific consumption guidance for riverine communities in the Lower Niger basin.

2. Materials and Methods

2.1 Study Area

The study was conducted in the Kpata area of the Lower River Niger at Lokoja, Kogi State, Nigeria, at approximately 7°48′ N and 6°46′ E. Lokoja lies at the confluence of the River Niger and the River Benue and hosts an active artisanal fishery. The site is subject to multiple anthropogenic pollution sources, including industrial effluent, boat fuel handling, rice milling operations and domestic waste discharge. The area experiences a tropical savannah climate with wet (May to October) and dry (November to April) seasons that govern seasonal variation in river discharge, runoff and sediment dynamics (Figure 1).

2.2 Fish Sampling

Sampling was conducted across two hydrological periods, January to March 2025 (dry season) and June to August 2025 (wet season). Forty specimens per species were collected each season, 20 from an upstream location at the New Market waterfront and Galilee axis and 20 from a downstream location near the Jacura Marble Factory, yielding 80 specimens per species across the study. Two commercially important species were targeted, *Clarias gariepinus* (Burchell, 1822) and *Oreochromis niloticus* (Linnaeus, 1758). Specimens were obtained from local artisanal fishermen operating within the study reach, placed in insulated coolers with ice packs at 4 °C, and transported to the laboratory within six hours of collection.

2.3 Tissue Preparation and Laboratory Analysis

Specimens were dissected and their liver tissue excised. Liver samples were washed with deionised water to remove surface contamination and then oven dried to a constant weight at 60 °C. Dried subsamples were digested by the wet acid technique in concentrated nitric and perchloric acids to break down the organic matrix and release the metal ions. Digests were filtered and diluted with deionised water to a known volume. Cadmium, lead, chromium, zinc, mercury, copper and arsenic were determined by atomic absorption spectrophotometry, calibrated with a standardised multielement solution, and analytical accuracy was verified using procedure blanks. Metal concentrations are reported in milligrams per kilogram wet weight.

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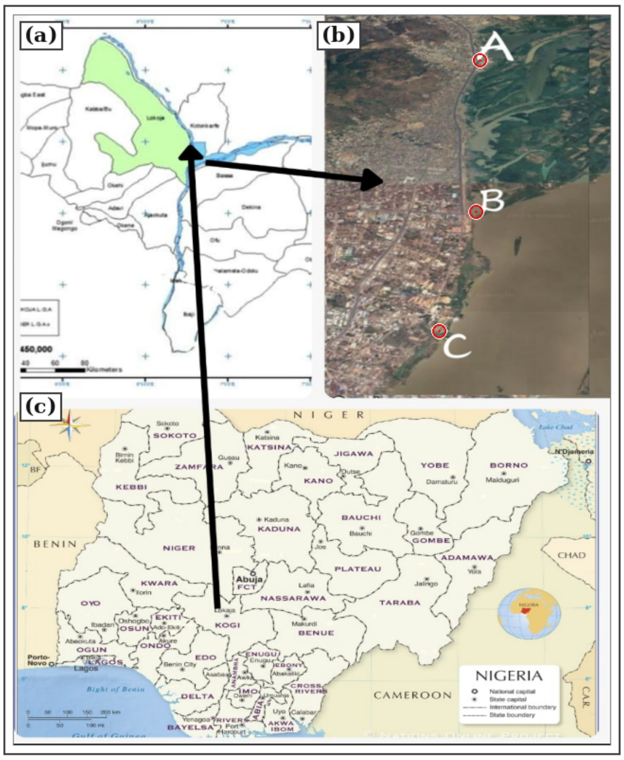

Figure 1. Map of the study area showing (a) Lokoja and environs within Kogi State, (b) a satellite view of the Kpata reach of the Lower River Niger with the sampling zones A, B and C, and (c) the location of Kogi State within Nigeria.

2.4 Bioaccumulation Factor

The bioaccumulation factor was calculated as the ratio of metal concentration in fish liver to that in the ambient water or sediment, following Lau et al. (1998):

$$BCF_{water} = C_{fish}\ (\text{mg kg}^{-1}) / C_{water}\ (\text{mg L}^{-1}) \quad (1)$$

$$BCF_{sediment} = C_{fish}\ (\text{mg kg}^{-1}) / C_{sediment}\ (\text{mg kg}^{-1}) \quad (2)$$

A bioaccumulation factor greater than one indicates net accumulation above the environmental concentration (USEPA, 2000).

2.5 Human Health Risk Assessment

The estimated daily intake represents the daily mass of metal ingested per kilogram of body weight through fish consumption and was calculated following USEPA (2011):

$$EDI = (MC \times FIR \times 10^{-3}) / BW \quad (3)$$

where MC is the mean metal concentration in fish liver (mg kg^{-1} wet weight), FIR is the fish ingestion rate of 8.26 grams per person per day (the Nigerian per capita daily freshwater fish consumption rate; FAOSTAT, 2013), and BW is the adult reference body weight of 70 kg (USEPA, 2011). The target hazard quotient is a dimensionless noncarcinogenic risk estimator (USEPA, 2011):

$$THQ = (EF \times ED \times FIR \times C \times 10^{-3}) / (RfD \times BW \times AT_n) \quad (4)$$

where EF is the exposure frequency (365 days per year), ED is the exposure duration (54.5 years, the Nigerian average life expectancy; WHO, 2017), C is the mean metal concentration in fish, RfD is the oral reference dose (mg kg^{-1} day^{-1}; USEPA, 2011, 2012), and AT_n is the averaging time for noncarcinogens, taken as 365 × ED. A quotient below one indicates no significant noncarcinogenic risk, while a value of one or more indicates potential concern. The hazard index is the sum of the target hazard quotients across all metals for a species:

$$HI = \Sigma\, THQ_i,\ \ i = Cd, Pb, Cr, Zn, Hg, Cu, As \quad (5)$$

A hazard index below one indicates cumulative noncarcinogenic risk within acceptable bounds. Finally, the margin of exposure evaluates the safety margin between the reference dose and the estimated daily exposure (Watanabe et al., 2003):

$$MOE = RfD / EDI \quad (6)$$

A larger margin of exposure indicates a wider safety margin, while lower values warrant greater precautionary concern for sensitive populations.

2.6 Statistical Analysis

Data are expressed as mean ± standard deviation. Independent samples t tests were used to assess differences between the two species, and likewise to compare the upstream and downstream sites within each species, since only two site groups were involved. Differences were considered significant at $p < 0.05$. All analyses were performed in GENSTAT version 11.0. Different superscript letters in the tables denote statistically significant differences between species (t test, $p < 0.05$).

3. Results

3.1 Heavy Metal Concentrations in Fish Liver

Seven heavy metals were detected in the liver tissue of both species across both periods (Table 1). With the exception of mercury, every metal exceeded the WHO and FAO permissible limit for fish intended for human consumption in at least one species and period. *C. gariepinus* recorded higher mean concentrations than *O. niloticus* for all seven metals, with statistically significant differences ($p < 0.05$) for cadmium, lead, zinc and arsenic in both periods and for chromium in the wet season.

In the dry season, chromium was the most abundant metal in both species (1.110 ± 0.08 mg kg^{-1} in *C. gariepinus*; 1.090 ± 0.03 in *O. niloticus*), far exceeding its WHO limit of 0.003 mg kg^{-1}. Copper followed (3.47 ± 0.12 and 3.42 ± 0.11), then zinc (5.07 ± 0.13 and 4.84 ± 0.19). Cadmium, lead, arsenic and mercury occurred at lower absolute levels, though cadmium, lead and arsenic still exceeded their thresholds. Mercury was the only metal below its WHO guideline in both species and periods. Wet season concentrations were marginally higher for most metals: in *C. gariepinus*, cadmium rose to 0.068, chromium to 1.163 and copper to 3.69 mg kg^{-1}, while mercury approached but did not exceed the threshold. The overall concentration hierarchy across both species and periods was Zn > Cu > Cr > Pb ≈ Cd > As > Hg, as shown in Figure 2.

Table 1. Mean (±SD) heavy metal concentrations (mg kg^{-1} wet weight) in liver tissues of *Clarias gariepinus* and *Oreochromis niloticus* from the Kpata area across two sampling periods.

Period	Species	Cd	Pb	Cr	Zn	Hg	Cu	As
Jan–Mar	*C. gariepinus*	0.066±0.01[a]	0.069±0.01[a]	1.110±0.08[a]	5.07±0.13[a]	0.0003[a]	3.47±0.12[a]	0.021±0.01[a]
	O. niloticus	0.058±0.03[b]	0.056±0.01[b]	1.090±0.03[a]	4.84±0.19[b]	0.0003[a]	3.42±0.11[a]	0.007±0.01[b]
	Grand mean	0.062	0.063	1.100	4.955	0.0003	3.445	0.014
Jun–Aug	*C. gariepinus*	0.068±0.01[a]	0.069±0.01[a]	1.163±0.11[a]	5.10±0.17[a]	0.0008[a]	3.69±0.09[a]	0.015±0.00[a]
	O. niloticus	0.059±0.02[b]	0.058±0.03[b]	1.127±0.01[b]	4.85±0.23[b]	0.0003[a]	3.61±0.18[a]	0.012±0.00[b]
	Grand mean	0.064	0.064	1.145	4.975	0.001	3.650	0.014
WHO/FAO limit	—	0.005	0.010	0.003	3.000	0.001	0.020	0.010

Different superscript letters within the same period and column indicate significant differences between species (t test, $p < 0.05$). All values mg kg^{-1} wet weight.

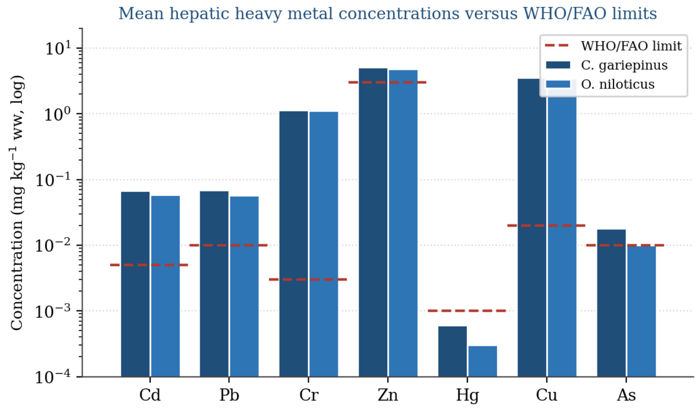

Figure 2. Mean hepatic heavy metal concentrations in both species against WHO and FAO permissible limits (logarithmic scale). All metals except mercury exceed their limits, with chromium and copper the most pronounced.

Except for mercury, the higher wet season concentrations are consistent with greater metal loading during wet periods, when increased surface runoff delivers additional dissolved and particulate metal from anthropogenic activity within the catchment. The seasonal increment was small, generally below 10 percent for most metals.

3.2 Species Specific Bioaccumulation

Metal levels in *C. gariepinus* were significantly higher than in *O. niloticus* during both seasons, with statistical significance for cadmium, lead, zinc and arsenic ($p < 0.05$). Bioaccumulation factors, calculated relative to ambient water and sediment, were below one for all metals and both species (Table 2), indicating that liver concentrations were lower than the environmental matrix concentrations on a mass basis. Nevertheless, the factors are informative about relative bioavailability and accumulation tendency. Chromium recorded the highest water based factor in both species (0.847 in *C. gariepinus* and 0.819 in *O. niloticus*), pointing to its comparatively high bioavailability from the water column, with zinc and cadmium next in order. Mercury recorded the lowest values, consistent with its low tissue concentrations. *C. gariepinus* exceeded *O. niloticus* for every metal, most markedly for arsenic and cadmium. The accumulation order shown in Figure 3 was Cr > Zn > Cd > Cu > As > Pb > Hg.

Table 2. Bioaccumulation factors for heavy metals in *Clarias gariepinus* and *Oreochromis niloticus* relative to ambient water and sediment (averaged across all sites and periods).

Metal	*C. gariepinus* (mg kg^{-1})	*O. niloticus* (mg kg^{-1})	BCF_{water} C.g.	BCF_{water} O.n.	BCF_{sed} C.g.	BCF_{sed} O.n.
Cd	0.067	0.059	4.18×10^{-1}	3.62×10^{-1}	7.31×10^{-2}	6.35×10^{-2}
Pb	0.069	0.057	3.00×10^{-2}	2.50×10^{-2}	1.06×10^{-2}	8.77×10^{-3}
Cr	1.137	1.109	8.47×10^{-1}	8.19×10^{-1}	8.71×10^{-1}	8.49×10^{-1}
Zn	5.085	4.845	4.94×10^{-1}	4.70×10^{-1}	3.99×10^{-1}	3.80×10^{-1}
Hg	0.0006	0.0003	1.29×10^{-2}	4.80×10^{-3}	1.53×10^{-2}	7.69×10^{-3}
Cu	3.580	3.515	3.36×10^{-1}	3.29×10^{-1}	3.38×10^{-1}	3.32×10^{-1}
As	0.018	0.010	2.42×10^{-1}	1.94×10^{-1}	3.19×10^{-1}	1.85×10^{-1}

$BCF_{water} = C_{fish}/C_{water}$; $BCF_{sediment} = C_{fish}/C_{sediment}$. A factor below one indicates tissue concentrations below the environmental matrix (USEPA, 2000). C.g. = C. gariepinus; O.n. = O. niloticus.

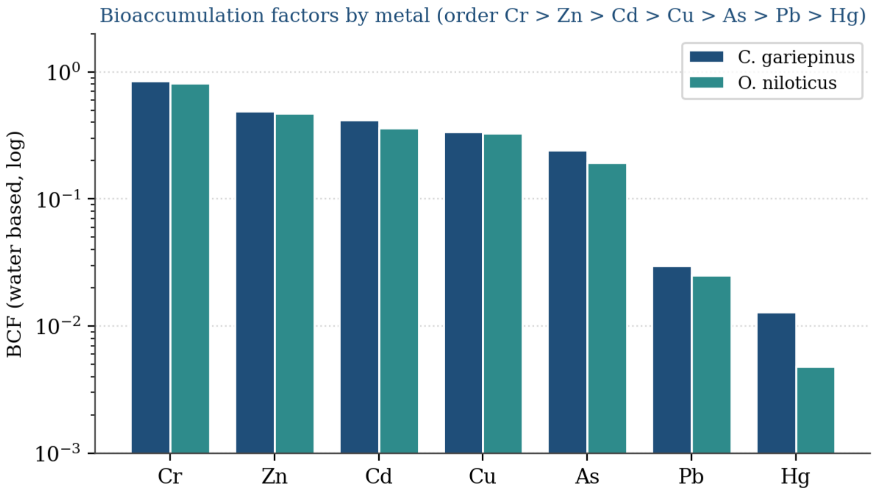

Figure 3. Water based bioaccumulation factors by metal for both species on a logarithmic scale, following the order Cr > Zn > Cd > Cu > As > Pb > Hg.

3.3 Human Health Risk Assessment

Estimated daily intake values were low for both species (Tables 3 and 4). For *C. gariepinus* they ranged from 7.14 × 10^{-7} mg kg^{-1} day^{-1} (mercury) to 3.61 × 10^{-3} (zinc), and for *O. niloticus* from the same mercury value to 3.54 × 10^{-3} (zinc). These modest values reflect both the applied consumption rate and the measured tissue concentrations, with chromium and copper yielding the highest intakes after zinc. Target hazard quotients were below one for every individual metal in both species, indicating that noncarcinogenic risk at the assumed ingestion rate lies within the acceptable range. Chromium showed the highest quotient in both *C. gariepinus* (0.271) and *O. niloticus* (0.267), reflecting the large gap between tissue chromium concentrations and its low oral reference dose. The cumulative hazard index was 0.443 for *C. gariepinus* and 0.430 for *O. niloticus*, both below one, indicating no significant cumulative noncarcinogenic risk at the assumed rate (Figure 4). Margins of exposure varied widely and were smaller in *C. gariepinus* than in *O. niloticus*, owing to its higher tissue burdens; mercury showed the widest margin and chromium the narrowest, at 36.8 in *C. gariepinus* and 37.5 in *O. niloticus* (Figure 6).

Table 3. Estimated daily intake, target hazard quotient, margin of exposure and hazard index for heavy metals in *Clarias gariepinus*.

Metal	Fish conc. (mg kg^{-1})	EDI (mg kg^{-1} d^{-1})	THQ	MOE	Status	Interpretation
Cd	6.60×10^{-2}	4.71×10^{-5}	4.71×10^{-2}	2.12×10^{2}	<1	No immediate risk
Pb	7.10×10^{-2}	5.07×10^{-5}	1.01×10^{-2}	6.90×10^{2}	<1	No immediate risk
Cr	1.14×10^{0}	8.14×10^{-4}	2.71×10^{-1}	3.68×10^{1}	<1	Warrants monitoring
Zn	5.05×10^{0}	3.61×10^{-3}	1.20×10^{-2}	8.32×10^{2}	<1	No immediate risk
Hg	1.00×10^{-3}	7.14×10^{-7}	2.38×10^{-3}	4.20×10^{3}	<1	No immediate risk
Cu	3.64×10^{0}	2.60×10^{-3}	6.50×10^{-2}	1.54×10^{2}	<1	No immediate risk
As	1.50×10^{-2}	1.07×10^{-5}	3.57×10^{-2}	2.80×10^{2}	<1	No immediate risk

Metal	Fish conc. (mg kg^{-1})	EDI (mg kg^{-1} d^{-1})	THQ	MOE	Status	Interpretation
HI (ΣTHQ)	—	—	0.443	—	<1	No cumulative risk

Body weight 70 kg; ingestion rate 8.26 g day^{-1}; reference doses from USEPA (2011).

Table 4. Estimated daily intake, target hazard quotient, margin of exposure and hazard index for heavy metals in *Oreochromis niloticus*. Parameters as in Table 3.

Metal	Fish conc. (mg kg^{-1})	EDI (mg kg^{-1} d^{-1})	THQ	MOE	Status	Interpretation
Cd	6.15×10^{-2}	4.39×10^{-5}	4.39×10^{-2}	2.28×10^{2}	<1	No immediate risk
Pb	5.70×10^{-2}	4.07×10^{-5}	1.02×10^{-2}	8.60×10^{2}	<1	No immediate risk
Cr	1.12×10^{0}	8.00×10^{-4}	2.67×10^{-1}	3.75×10^{1}	<1	Warrants monitoring
Zn	4.96×10^{0}	3.54×10^{-3}	1.18×10^{-2}	8.48×10^{2}	<1	No immediate risk
Hg	1.00×10^{-3}	7.14×10^{-7}	2.38×10^{-3}	4.20×10^{3}	<1	No immediate risk
Cu	3.23×10^{0}	2.31×10^{-3}	5.80×10^{-2}	1.73×10^{2}	<1	No immediate risk
As	1.55×10^{-2}	1.11×10^{-5}	3.71×10^{-2}	2.71×10^{2}	<1	No immediate risk
HI (ΣTHQ)	—	—	0.430	—	<1	No cumulative risk

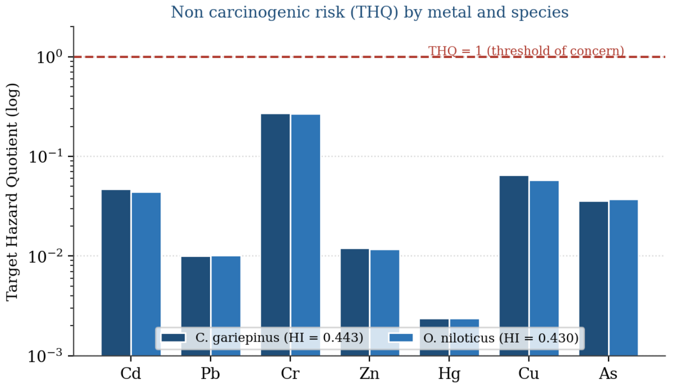

Figure 4. Target hazard quotients by metal and species on a logarithmic scale. All quotients are below the threshold of concern; chromium dominates the cumulative hazard index in both species.

Table 5. Summary comparison of mean concentrations, WHO and FAO exceedance status, bioaccumulation rank and species specific target hazard quotients.

Metal	C.g. (mg kg^{-1})	O.n. (mg kg^{-1})	WHO (mg kg^{-1})	WHO exceedance	BCF rank	THQ C.g.	THQ O.n.
Cd	0.067	0.059	0.005	Yes (both)	3rd	4.71×10^{-2}	4.39×10^{-2}
Pb	0.069	0.057	0.010	Yes (both)	6th	1.01×10^{-2}	1.02×10^{-2}
Cr	1.137	1.109	0.003	Yes (both)	1st	2.71×10^{-1}	2.67×10^{-1}
Zn	5.085	4.845	3.000	Yes (both)	2nd	1.20×10^{-2}	1.18×10^{-2}
Hg	0.0006	0.0003	0.001	No	7th	2.38×10^{-3}	2.38×10^{-3}
Cu	3.580	3.515	0.020	Yes (both)	4th	6.50×10^{-2}	5.80×10^{-2}
As	0.018	0.010	0.010	Yes (C.g. only)	5th	3.57×10^{-2}	3.71×10^{-2}

Bioaccumulation rank based on the water phase factor, where first denotes the highest accumulation. C.g. = C. gariepinus; O.n. = O. niloticus.

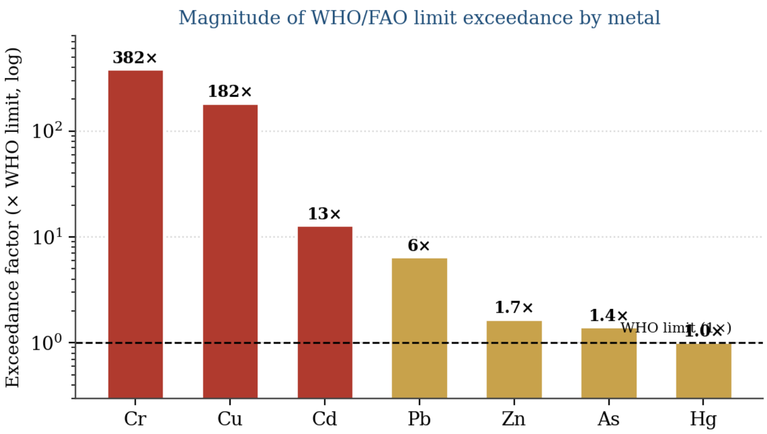

Figure 5. Magnitude of WHO and FAO limit exceedance by metal (grand mean divided by the permissible limit, logarithmic scale). Chromium exceeds its limit by more than two orders of magnitude.

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4. Discussion

The magnitude of the exceedances observed here, with chromium at roughly 380 times its WHO limit, copper at about 180 times, cadmium at some 13 times and lead at nearly 7 times (Figure 5), indicates that contamination of this reach is sufficient to raise fish tissue concentrations to levels of genuine food safety concern. Comparable exceedances of WHO fish tissue limits for cadmium and chromium have been reported from other impacted Nigerian rivers: Ehiemere et al. (2022) recorded cadmium of 0.04 to 0.09 mg kg^{-1} in *C. gariepinus* from Niger Delta fish farms, and Akan et al. (2015) reported lead of 0.04 to 0.10 mg kg^{-1} in freshwater fish from polluted Nigerian environments, both ranges consistent with the present findings. The convergence across geographically distinct Nigerian systems points to multisource anthropogenic contamination as a systemic driver of fish metal accumulation in the country's freshwater fisheries. The absence of significant mercury bioaccumulation most likely reflects the predominance of inorganic mercury in the water column of this site, rather than the organic methylmercury form that is more readily absorbed and biomagnified in fish (Wang et al., 2020), and is consistent with the low mercury profile of nonmining African river environments (Adebayo et al., 2016). Arsenic exceedance was partial, significant in *C. gariepinus* but marginal in *O. niloticus*, consistent with sediment contact being a more important arsenic pathway for benthic feeders.

The consistently higher burdens in *C. gariepinus* correspond to the difference in trophic niche between the two species. *C. gariepinus* is an opportunistic benthic omnivore that feeds directly on the river bottom, ingesting detritus, benthic organisms and particulate matter from the sediment, and such an organism is likely to carry higher metal concentrations than the surrounding water on account of its diet (Chale, 2016). Direct sediment ingestion is regarded as one of the principal metal acquisition pathways in bottom dwelling fish, and such organisms receive larger dietary metal loads than midwater feeders (Novikova et al., 2019). Both arsenic and cadmium show strong affinity for organic particulate matter and tend to concentrate in the sediment organic fractions accessible to benthic feeders (Alloway, 2013). Similar species specific patterns have been documented by Adeniyi et al. (2019) and Ovie et al. (2020) in Nigerian rivers. The near identical mercury factors and tissue concentrations of the two species suggest that mercury uptake at this site occurs predominantly through gill absorption from the water column rather than dietary sediment ingestion, a route that is not species specific and reflects the behaviour of inorganic mercury.

The bioaccumulation order, Cr > Zn > Cd > Cu > As > Pb > Hg, is consistent with patterns reported for comparable freshwater systems across West and Central Africa, where chromium and zinc routinely exhibit higher bioavailability indices than lead and mercury under typical pH and redox conditions (Kassegne et al., 2019; Akoto et al., 2014). The absolute magnitude of the chromium burden (1.09 to 1.163 mg kg^{-1}) is, however, notably higher than values from nonindustrial reaches of comparable West African rivers, where fish liver chromium typically ranges from 0.05 to 0.40 mg kg^{-1} (Duncan et al., 2018). This suggests that the Kpata environment contributes elevated chromium loading, consistent with the industrial effluent and marble processing activities identified among the pollution sources of the study area.

Zinc concentrations in both species (4.84 to 5.10 mg kg^{-1}) exceed the WHO limit of 3.00 mg kg^{-1} yet lie within ranges documented for fish from moderately contaminated agricultural catchments, where fertiliser derived zinc contributes substantially to aquatic zinc loads (Nsofor et al., 2017). Because zinc is an essential micronutrient that fish actively regulate, hepatic zinc accumulation tends to plateau under homeostatic control rather than rising in direct proportion to ambient concentration. This regulatory ceiling helps explain why the measured zinc burden, and its correspondingly low bioaccumulation factor, remained below the ambient concentrations in water and sediment. Copper displayed a comparable pattern, indicating active physiological regulation in both species. Chromium nonetheless accounted for 61.2 percent of the total hazard index in *C. gariepinus* and 62.1 percent in *O. niloticus*, identifying it as the dominant risk determining metal.

These risk estimates must be read against the assumptions inherent in their calculation. The ingestion rate of 8.26 grams per day equals the national per capita average for freshwater fish in Nigeria (FAOSTAT, 2013); yet consumption in artisanal fishing communities living directly on the riverbank, for whom fish is a daily staple rather than an occasional protein source, can be three to five times higher. At a consumption rate of 25 to 40 grams per day, the chromium hazard quotient in *C. gariepinus* approaches or exceeds unity (an estimated 0.82 to 1.30), moving the exposure into the zone of potential noncarcinogenic concern. In addition, chromium in fish occurs mainly in the trivalent form, which is far less toxic than the hexavalent form. In the presence of industry, such as near the Jacura Marble Factory, partial oxidation to the hexavalent form cannot be ruled out, and this would sharply increase the toxicity hazard. Speciation was not assessed here for want of the necessary instrumentation, and it should be a priority for further work.

A further consideration concerns the tissue basis of the exposure estimate. The risk indices reported here derive from liver concentrations, whereas the ingestion rate refers to whole fish consumption. The liver constitutes only a small fraction of the edible mass and is eaten far less frequently than muscle, which forms the bulk of dietary fish and generally carries lower metal burdens than liver. Applying a whole fish consumption rate to organ specific concentrations is therefore a conservative approach that likely overestimates the true dietary dose, so the quotients, indices and margins presented here should be regarded as upper bound estimates. More precise assessment, based on muscle concentrations and organ specific consumption data, is recommended for future studies.

Margins of exposure of 30 to 40 represent thin safety margins, particularly for sensitive subpopulations such as children and pregnant women, who consume more fish per unit body weight, possess less developed detoxification capacity and may carry additional metabolic sensitivity to chromium, all of which would lower their effective margins. This does not warrant a general consumption warning, but it does justify targeted advice on species choice, favouring *O. niloticus* over *C. gariepinus* from this reach, and on consumption frequency for these groups. The comparatively low mercury hazard here stands in contrast to reports from West African artisanal gold mining communities, where fish mercury exceeds 0.5 mg kg^{-1} and the mercury hazard quotient rises above unity (Adebayo et al., 2016). One ecologically meaningful seasonal signal was the rise in mercury in *C. gariepinus* from 0.0003 to 0.0008 mg kg^{-1}, reaching about 80 percent of the WHO guideline during the wet season (Table 1); this indicator warrants close attention in future wet seasons should ambient mercury loading increase.

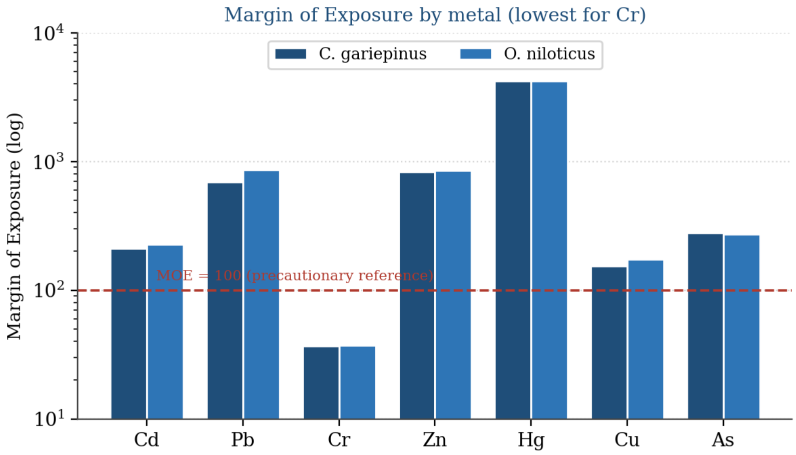

Figure 6. Margins of exposure by metal and species on a logarithmic scale. Chromium presents the narrowest margin in both species, and every margin is narrower in *C. gariepinus* than in *O. niloticus*.

5. Conclusion

This study presented an integrated analysis of heavy metal bioaccumulation and the associated human health risk from consumption of *C. gariepinus* and *O. niloticus* in the Kpata area of the Lower River Niger at Lokoja. Of the seven metals analysed, six, namely cadmium, lead, chromium, zinc, copper and arsenic, exceeded the WHO and FAO permissible limits in the liver tissue of both species, with chromium showing the highest concentration and the greatest risk. *C. gariepinus* accumulated higher burdens than *O. niloticus* in the same environment, reflecting its benthic trophic habit and greater contact with bottom sediment, and the accumulation hierarchy Cr > Zn > Cd > Cu > As > Pb > Hg mirrors the differing bioavailability of these ions in the contaminated system.

All individual target hazard quotients were below one in both species, and the hazard indices, 0.443 for *C. gariepinus* and 0.430 for *O. niloticus*, likewise remained below one, indicating no cumulative noncarcinogenic risk at the national average consumption rate. However, the tight margin of exposure for chromium (36.8 to 37.5) and the sensitivity of the hazard quotient to consumption rate mean that, among riverside populations with higher intake, the chromium quotient in *C. gariepinus* could reach unity. Monitoring of chromium exposure is therefore recommended, and because chromium is the principal risk determining metal, its speciation into trivalent and hexavalent forms should be a focus of future study.

Recommendations

The following management and research measures are recommended: (i) a quarterly fish tissue monitoring programme for both species, focused on chromium, cadmium and copper; (ii) consumption advisories targeted at sensitive subpopulations, especially children and pregnant women, favouring *O. niloticus* over *C. gariepinus* from this reach; (iii) speciation of chromium in environmental and tissue samples to refine risk estimates; (iv) derivation of a community specific fish consumption rate for riverside populations to replace the national average in future assessments; and (v) collaboration with regulatory bodies such as NESREA and the Kogi State Environmental Protection Agency to implement source specific control of industrial chromium loading in the Kpata area. The data reported here may serve as a baseline reference for further food safety investigations in the Lower River Niger.

Declaration of Competing Interest

The authors have no conflict of interest to disclose regarding this work.

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