

Human Health Risk Associated with Heavy Metal Exposure from Consumption of Freshwater Fish in the Dukku River Basin, Nigeria

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DOI: <https://doi.org/10.62154/ajastr.2026.022.01013>

Abstract

Consumption of freshwater fish contaminated with heavy metals is a major pathway for chronic human exposure, particularly in riverine communities where fish constitute a primary source of dietary protein source. This study assessed the concentrations of Mn, Fe, Cu, Zn, Ni, As, Cd, Pb, and Cr in muscle tissues of four trophically diverse species: *Alestes nurse*, *Distichodus affinis*, *Malapterurus electricus*, and *Hyperopisus bebe* from the Dukku River, and evaluated carcinogenic and non-carcinogenic health risks for adults and children's consumers. Across multiple fishing hotspots, a total of 284 specimens were purposely collected and analyzed by atomic absorption spectrophotometer. Ecotoxicological contamination was evaluated using the Metal Pollution Index (MPI), and health risks were characterized through Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), and Cancer (Risk). Mean concentrations of Cd, Fe, Cu, As, Mn, and Cr differed significantly ($p < 0.05$) across species, with *M. electricus* recorded the highest MPI values of 2.19×10^{-6} , driven by elevated arsenic. Fe and Zn dominated the EDI across species, with children consistently exhibited higher exposure than adults. The THQ for As in *M. electricus* is > 1 for children, while $HI > 1$ for children consuming *M. electricus*, *D. affinis* and *H. bebe*, indicating potential non-carcinogenic health risks. As and Cd were the dominant contributors to carcinogenic risk for children consuming these three species. Consumption of certain freshwater fish species from the Dukku River poses significant health risks, particularly to children. Continuous monitoring, trophic-level-based risk characterization, and species-specific consumption advisories are recommended to protect public health.

Keywords: Carcinogenic Risk, Freshwater Fish, Heavy Metals, Health Risk Assessment, Non-Carcinogenic Risk, Nigeria.

Introduction

Fish is one of the primary sources of long-chain omega-3 fatty acids and other micronutrients important to supporting healthy life (Mohanty *et al.*, 2019; Tacon, 2020). A significant portion (approximately 20%) of global animal proteins is supplied to about 3.3 billion human population by fish (FAO, 2020). The growing concern over global environmental pollution and food safety have drawn increasing attention to heavy metal contamination of aquatic ecosystems, which threatens ecosystem function, biodiversity,

and human health (Kumari and Maiti, 2020). Heavy metals are persistent, non-biodegradable, and bioaccumulative contaminants introduced into aquatic ecosystems via industrial discharges, agricultural runoff, and domestic sewage (Kumari and Maiti, 2020). These contaminants enter aquatic systems through natural processes such as soil erosion and atmospheric deposition, as well as anthropogenic activities such as mining, agriculture, transportation, and industrial discharge (Abadi *et al.*, 2015). In aquatic environments, metals do not degrade but accumulate in sediments and biota, biomagnifying through food webs and posing significant risks to aquatic organisms and human health (Taslima *et al.*, 2022). Fish are particularly vulnerable to metal pollution due to their ecological and physiological sensitivity, making them reliable bioindicators of aquatic pollution (Phaenark *et al.*, 2024; Oros, 2025). Freshwater fishes are often more vulnerable to heavy metal pollution because their osmoregulatory mechanisms facilitate ion absorption on gill surfaces, and increasing susceptibility to dissolved contaminants (Phaenark *et al.*, 2024). Contamination of aquatic ecosystems by metals is one of the greatest environmental concerns because of its negative impact on both ecosystem integrity and human health (Ali *et al.*, 2024).

Freshwater fish accumulate heavy metals differently due to the metal bioavailability, feeding behavior, habitat preference, and biological attributes such as age, size, and health status (Anandkumar *et al.*, 2017). The consumption of contaminated fish represents a major exposure pathway for humans, potentially leading to adverse health effects associated with chronic metal intake (Heshmati *et al.*, 2020; Amiri *et al.*, 2021; Su *et al.*, 2021). Some metals, including Cu, Fe, Co, Zn, Mo, Ni, Mn, V, and Se, are essential for physiological functions at trace concentration, but elevated concentrations induce cellular and systemic toxicity (Munir *et al.*, 2021; Ahmed *et al.*, 2021). Excessive intake of essential heavy metals can impair normal metabolic functions and cause gastrointestinal disturbances, liver injury, and broader systemic complications (Obiero *et al.*, 2019; Kwaansa-Ansah *et al.*, 2019). Meanwhile, non-essential metals such as cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), and arsenic (As) are harmful even at trace levels following prolonged exposure, posing significant ecological and public health threats that may include neurological impairments, renal damage and several forms of cancer (Taslima *et al.*, 2022; Ali *et al.*, 2024).

The Dukku River, located in Kebbi State, northwestern Nigeria, is a significant freshwater body supporting the livelihoods and food security of the local communities. Its rich in ichthyofaunal diversity attract local anglers, because fish constitutes a primary dietary protein source and livelihoods for riparian populations. Despite its ecological and economic importance, the Dukku River is subjected to multiple anthropogenic pressures, including sediment re-suspension from sand collection and boating, agricultural runoff, domestic washing activities, and vehicular emissions. These activities raised serious concerns about the potential heavy metal contamination of aquatic biota and associated dietary exposure risks for local communities.

Statement of the Problem

Despite documented anthropogenic pressures on the Dukku River Basin, including agricultural runoff, sand dredging, domestic wastewater disposal, and vehicular emissions, there is a critical gap in the scientific literature regarding species-specific heavy metal bioaccumulation and associated human health risks across trophic levels in this ecosystem. While prior studies have examined heavy metals in various water bodies of Kebbi State (Hassan *et al.*, 2015; Obaroh *et al.*, 2015; Anthony *et al.*, 2019; Yahaya *et al.*, 2021; Zanna *et al.*, 2021; Ibrahim *et al.*, 2023; Ibrahim *et al.*, 2024; Yahaya *et al.*, 2024; Musa *et al.*, 2025; Gwadangaj *et al.*, 2026), none has systematically characterized heavy metal contamination across trophically diverse fish species nor quantified the differential carcinogenic and non-carcinogenic health risks to adult and children consumers of trophic-diverse fish in this basin. Riverine communities in Kebbi State rely on freshwater fish as a primary protein source, yet without species-specific risk data. However, it is impossible to develop evidence-based consumption advisories or target regulatory interventions with trophically diverse data. Furthermore, this study addresses this knowledge gap by quantifying the concentrations of nine heavy metals in the muscle tissues of four freshwater fish species (*Alestes nurse*, *Distichodus affinis*, *Malapterurus electricus*, and *Hyperopisu bebe*) representing distinct trophic levels from the Dukku River Basin, and by conducting a comprehensive human health risk assessment using established USEPA-based indices, thereby generating the evidence base needed to protect public health in this region.

Research Objectives

The specific objectives of this study were to: i) determine the concentrations of nine heavy metals (Mn, Fe, Cu, Zn, Ni, As, Cd, Pb, and Cr) in the muscle tissues of four trophically diverse freshwater fish species from Dukku River Basin, ii) to assess the overall ecotoxicological contamination burden of each fish species using the Metal Pollution Index (MPI), iii) evaluate non-carcinogenic and lifetime carcinogenic risks associated with fish consumption using the USEPA-based indices. The following research questions were established to achieve the above objectives: i) what are the concentrations of selected heavy metals in the muscle tissues of *Alestes nurse*, *Distichodus affinis*, *Malapterurus electricus*, and *Hyperopisu bebe* from the Dukku River Basin? ii) Which species exhibits the highest overall metal pollution burden as assessed by MPI? iii) Do non-carcinogenic (THQ and HI) and carcinogenic risks (CR) exceed acceptable thresholds for adult and children's consumers?

Theoretical and Conceptual Framework

This study is grounded within the United States Environmental Protection Agency (USEPA) Human Health Risk Assessment (HHRA) framework, which provides a systematic four-step paradigm for evaluating the potential for adverse health effects resulting from exposure to environmental contaminants (USEPA, 1989). The four steps include hazard identification, dose-response assessment, exposure assessment, and risk characterization, which

collectively structure the analytical approach adopted in this study. Hazard identification is addressed by characterizing the heavy metal profile of fish muscle tissues through atomic absorption spectrophotometry, quantifying the concentrations of identified metals. Dose-response assessment is incorporated through the use of metal-specific reference dose (RfDs) and cancer slope factors (CSFs) derived from USEPA's integrated Risk information system (IRIS). Exposure assessment is operationalized through Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ) of both adults and children consumers using species-specific consumption data. Risk characterization is achieved through the Hazard Index (HI), which integrates cumulative non-carcinogenic effects across metals, and the Cancer Risk (CR) index, which quantifies the probability of developing cancer over a lifetime exposure. Complementing the USEPA framework, this study draws on bioaccumulation and biomagnification theory, which posits that persistent contaminants accumulate progressively in living organisms and intensify in concentration through successive trophic levels of a food chain or food web (Taslima *et al.*, 2022; Oros, 2025). The selection of four species spanning distinct trophic position; pelagic omnivores (*A. nurse*), benthic detritivores (*D. affinis*), benthic carnivores (*M. electricus*), and piscivorous to predator (*H. nurse*), directly tests the predictive expectations of biomagnification theory within the Dukku River food web. The source-pathway-receptor (SPR) model further contextualizes the study design. Anthropogenic and geochemical sources (agricultural runoff, domestic waste, sand dredging) discharge metals into the aquatic environment (Abadi *et al.*, 2015; Kumari and Maiti, 2020). These metals enter the food web through sediment ingestion, gill uptake, and dietary transfer across trophic levels (pathway). The human receptor population (adults and children) residing in fishing communities along the Dukk River Basin are exposed primarily through the dietary pathway of fish consumption (receptor). Children are identified as a priority vulnerable subgroup due to their lower body weight, higher metabolic rate, and proportionally greater food intake per unit body mass.

Literature Review

Heavy metal Sources and Pathways in Freshwater Ecosystems

Heavy metals enter freshwater ecosystems through both geogenic and anthropogenic pathways. Geogenic sources include natural weathering of metal-bearing rocks, soil erosion, and atmospheric deposition, which establish baseline background concentrations characteristic of a given river catchment (Abadi *et al.*, 2015). Anthropogenic inputs are typically more concentrated and ecologically significant, it includes agricultural runoff carrying pesticide residues and metal-enriched fertilizers, industrial effluents from mining and metallurgical operations (Munir *et al.*, 2021), municipal wastewater discharge, and urban storm-water (Kumari and Maiti, 2020). In West African river systems, including those in Nigeria, the dominant anthropogenic sources identified in recent literature are artisanal mining, irrigated agriculture, sand dredging, and informal domestic waste disposal directly into watercourses (Adebiyi *et al.*, 2024; Yahaya *et al.*, 2024).

In the aquatic environment, metals are subject to complex partitioning between the dissolved phase, suspended particulate matter, and bottom sediments. Sediments acts as both a sink and secondary source: metals can be immobilized under oxidizing conditions and remobilized during physical disturbance events like sand dredging, flooding, or seasonal drawdown (Hedayatzadeh *et al.*, 2024). The bioavailability of sediment-associated metals to benthic organisms depends on pH, redox potential, organic matter content, and the competitive effects of other cations (Anandkumar *et al.*, 2017). This complexity highlights the importance of metal contamination in biota, particularly fish muscle tissue, as a direct indicator of human dietary exposure, rather than relying solely on water or sediments analyses.

Bioaccumulation and Biomagnification across Trophic Levels

The trophic transfer of metals in freshwater food webs is determined by both the physiochemical properties of the metal and feeding ecology of organisms. Metals with high bioaccumulation factor, particularly Cd, Hg, and As tend to accumulate more readily in tissues than essential metals, which are subject to homeostatic regulation (Taslima *et al.*, 2022; Oros, 2025). Biomagnification, the increasing in metal concentration with ascending trophic level, has been empirically documented for metals in numerous freshwater ecosystems (Oros, 2025). Some studies reported that trophic position does not predict metal burdens for all elements, but species-specific feeding behavior, habitat use, and metabolic regulation collectively determine tissues concentrations (Anandkumar *et al.*, 2017). Bottom-feeding and detritivorous species are often disproportionately exposed to sediment-associated metals, explaining the frequently elevated Pb and Cd concentrations reported in benthic taxa compared with pelagic species (Ali *et al.*, 2024; Hedayatzadeh *et al.*, 2024). In Nigerian freshwater ecosystems, comparable multi-species assessment has confirmed interspecific variability in metal accumulation aligned with trophic guild. For instance, Adebisi *et al.* (2024) documented that species occupying higher trophic positions in Nigerian coastal waters showed elevated As and Cd concentrations relative to omnivores, supporting biomagnification pathways for these metals.

Health Risk Assessment frameworks and Regional Evidence

The USEPA human health risk assessment framework has been widely adopted in ecotoxicological studies of dietary metal exposure from fish consumption (Tacon, 2020, Resma *et al.*, 2020). The conventional indices include EDI, THQ, HI, and CR provides a standardized basis for comparing risk levels across studies and populations (Bahreini *et al.*, 2020). However, the validity of these indices is sensitive to the exposure parameters employed, particularly fish ingestion rates and body weight assumptions, which vary substantially between populations. The application of ingestion rate values derived from Mediterranean or East Asian populations to Nigerian communities introduces uncertainty that is frequently acknowledged as a limitation in West Africa studies (Adebisi *et al.*, 2024). Recent health risk assessments from comparable Nigerian and West African freshwater

ecosystems have consistently identified As and Cd as the metals of greatest concern for carcinogenic risk, and Cd as the primary driver of CR exceeds in adults (Adebiyi *et al.*, 2024; Yahaya *et al.*, 2024). Cd concentrations in several Nigerian river fish have been reported above EU maximum permissible level of 0.05 mg/kg wet weight (EU Regulation 1831/2006) and the Codex Alimentarius/WHO maximum level of 0.1 mg/kg, raising food safety concerns that are relevant to present study. Various studies have further reported that children consistently face higher risk quotients than adults due to their lower body weight, with HI > 1 commonly reported for As and Cd in children's consumers (Adebiyi *et al.*, 2024). These regional findings provide direct comparators for the Dukku River Basin results reported herein and contextualize the public health significance of the observed contamination.

Materials and Methods

Study Area

The study was conducted in Birnin Kebbi of Kebbi State, situated between latitude 12° 27' N, and 4° 12' E longitude. 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. The Dukku River is located between latitude 12° 28' N to 12° 35' N and longitude 4° 10' to 4° 15' E. It originates from Sokoto-Rima River in Sokoto State, traverses several villages and towns, and covers a drainage area of approximately 457.92 km² before discharging into the River Bunza. The basin supports intensive agricultural, domestic, and fishing activities, making it an essential location for conducting cross-sectional assessment of the environmental and public health risks associated with dietary heavy metal exposure from freshwater fish consumption.

Study Design and Sample Size

A cross-sectional study design combining purposive species selection and random spatial sampling was employed. Four commonly consumed freshwater fish species representing different trophic levels were selected: pelagic omnivores (*Alestes nurse*), benthic detritivores (*Distichodus affinis*), benthic carnivore (*Malapterurus electricus*), and piscivorous top predators (*Hyperopisu bebe*). The sample size of 284 fish was determined using a Cochran formula for continuous environmental data:

$$n_0 = \frac{Z^2 \sigma^2}{d^2}$$

Where, Z= 1.96 (at 95% confidence level), $\sigma = 0.50$, and $d = 0.05$.

Sample Collection

A total of 284 individual fish specimens (71 per species) were obtained from local fishermen at multiple fishing hotspots along the river between July and August 2023 at two-week intervals. Samples were collected between 07:00 to 8:00am, wrapped in sterile polyethylene bags, placed in insulated iceboxes, and transported to the General Biology

Laboratory, Department of Biological Sciences, Federal University Birnin Kebbi, Nigeria. Only healthy, marketable-sized fish with no visible lesions or spoilage were included. Fish exhibiting deformities, injuries, or signs of deterioration were excluded to ensure dietary relevance.

Sample Preparation

All samples preparation, digestion, and elemental analyses were conducted at the General Biology Laboratory, Department of Biological Sciences, Federal University Birnin Kebbi. Fish specimens were rinsed with distilled water to remove surface debris, and total weight and body length were recorded for each species. To minimize intraspecific variability, 100 g of edible dorsal muscle tissues were dissected from three different individuals of the same species and combined to form composite samples of 300 g per species per sampling occasion. Composite samples were stored at -20°C , oven-dried at 65°C to constant mass and homogenized to a fine powder prior to digestion.

Sample Digestion and Analyses

A 2.0 g aliquot of dried tissue was digested using a 3:1 mixture (v/v) of hydrochloric acid (HCl) and nitric acid (HNO_3) in accordance with the standard digestion protocols described by Ejaz *et al.* (2024) and USEPA Method 3050B. The mixture was heated until its volume reduced to 5.00 mL, and after cooling to room temperature, the digestion was filtered through a $0.45\ \mu\text{m}$ nylon membrane filter to remove undigested residue. The resulting filtrate was then diluted to a final volume of 50 mL with distilled water (Idera *et al.*, 2015). Heavy metal concentrations (Mn, Fe, Cu, Zn, Ni, As, Cd, Pb, and Cr) were determined using a flame atomic absorption spectrophotometer (AAS) at wavelengths specific to each element. Detection limits for each element were as follows: Mn (0.01 mg/kg), Fe (0.05 mg/kg), Cu (0.01 mg/kg), Zn (0.01 mg/kg), Ni (0.01 mg/kg), As (0.005 mg/kg), Cd (0.002 mg/kg), Pb (0.01 mg/kg) and Cr (0.005 mg/kg).

Quality Assurance and Quality Control

Analytical quality control assurance and quality control (QA/QC) measures were implemented throughout the digestion and analysis procedures. Reagent blanks were included in every digestion batch to monitor background contamination. Replicate analyses ($n = 3$ per composite) were conducted to assess precision, relative standard deviation (RSD) values were maintained below 10% for all elements. Standard calibration curves were constructed using certified reference standards at a minimum of five concentration points ($R^2 \geq 0.999$). Recovery rates for certified reference materials (NIST SRM 1566b) were in the range of 90-110% for all elements. Concentrations below the detection limit were recorded as not detected (ND). For the purpose of the Metal Pollution Index calculation, ND was not included (Bazarsadueva *et al.*, 2023; Abdel-Kader and Mourad, 2021).

Ecotoxicological Assessment

Overall metal contamination of fish muscle was evaluated using the Metal Pollution Index (MPI), computed as the n^{th} root of the product of all metal concentrations, providing a composite measure of overall bioaccumulation in each species:

$$C_1 \times C_2 \times C_3 \dots \dots \dots \times C_n / n \quad \text{I}$$

Where C_i , is the concentration of the 1^{st} metal in fish muscle (mg/kg) and (n) is the total number of metals analyzed (Bazarsadueva *et al.*, 2023; Abdel-Kader and Mourad, 2021).

Human Health Risk Assessment

This study employed various conventional health risk indices to evaluate human health risks associated with fish consumption using the EDI (Estimated Daily Intake), THQ (Target Hazard Quotient), HI (Hazard Index) and CR (Cancer Risk) following the USEPA (United State Environmental Protection Agency) guidelines.

Estimated Daily Intake of Metal (EDI):

$$EDI = \frac{FIR \times C}{WB} \quad \text{II}$$

Where, C is the metal concentration (mg/kg) in fish muscle, FIR is the fish ingestion rate (39.03 g/day), and BW is the average body weight (70 kg for adult and 15 kg for children) (Copat *et al.*, 2018).

Target Hazard Quotient (THQ):

$$THQ = \frac{EF \times ED \times FIR \times C}{EF \times BW \times TA} \quad \text{III}$$

Where, FIR is the ingestion rate, EF is the exposure frequency (365 days/year), ED is the exposure duration (67 years representing the estimated average life expectancy in Nigeria per World Bank data, consisted with USEPA guidance to use population-specific lifetime estimates), RfD is the reference dose (mg/kg/day), and AT is the averaging time for non-carcinogens ($EF \times ED$). The THQ value < 1 indicates a negligible risk, whereas a THQ value ≥ 1 indicates a potential non-carcinogenic health concern (Cobbinah *et al.*, 2025).

Hazard Index (HI):

$$HI = \sum THQ \quad \text{IV}$$

An HI < 1 indicates a low risk, whereas an HI > 1 indicates potential adverse health effects from combined metal exposure (Bahreini *et al.*, 2020).

Carcinogenic Risk (CR):

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

Where, CSF is the cancer slope factor (mg/kg/day), with acceptable lifetime cancer risk ranges from 1×10^{-6} to 1×10^{-4} (Resma *et al.*, 2020). CR values $> 10^{-4}$ indicate a potential cancer risk, while $< 10^{-6}$ indicate negligible cancer risk.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics for windows, Version 24.0 (IBM Corp., Armonk, NY, USA, 2016). One-way Analysis of variance (ANOVA) followed by the Least Significant Difference (LSD) post hoc test was applied to determine interspecific differences at $p < 0.05$, and the results are presented as mean $\pm$ SD of the metal concentrations.

Ethical Considerations

Ethical approval was not required because the study did not involve human participants or live experimental animals. Fish samples were obtained from local commercial fishermen under routine market conditions.

Results

Heavy Metal Concentrations and Metal Pollution Index (MPI)

The mean heavy metal concentrations (mg/kg dry weight) and MPI values in the muscle tissues of the four freshwater fish species are presented in Table 1. The maximum mean concentrations of Zn, Mn and Cr were recorded *Alestes nurse*, while the minimum Zn concentration was shared by *Distichodus affinis* and *Malapterurus electricus*, each with 0.45 mg/kg. *M. electricus* exhibited the highest Arsenic (As) concentrations of 0.17 mg/kg, whereas the lowest concentration was recorded in *A. nurse*, with 0.01 mg/kg (Table 1). Cu concentrations ranged from not detected in *M. electricus* and *D. affinis* to a maximum of 0.14 mg/kg in *H. bebe*. Similarly, *H. bebe* recorded the highest Ni concentration of 0.08 mg/kg, followed by 0.07 mg/kg in *A. nurse*, and the lowest concentration of 0.01 mg/kg was found in *D. affinis* (Table 1). Furthermore, *D. affinis* showed maximum concentrations of Cd, Fe, and Pb, and minimum concentrations of Cd and Fe were recorded in *M. electricus* and *H. bebe*. However, Pb was not detected in *A. nurse*, *M. electricus* and *H. bebe* (Table 1). Furthermore, Cobalt (Co) was not detected in any of the four fish species inhabiting the Dukku River. Similarly, Cu was not detected in *D. affinis* and *M. electricus*, likewise Pb was only detected in *D. affinis*, consistent with its benthic detritivorous feeding ecology and associated sediment exposure (Table 1). The mean concentrations of Cd, Fe, Cu, As, Mn, and Cr were significantly different ($p < 0.05$) across the four freshwater fish species, as denoted by different superscript letters in Table 1.

Although *D. affinis* exhibited the total metal load (driven predominantly by Fe), the Metal Pollution Index (MPI) revealed that *M. electricus* with 2.19×10^{-6} MPI value as the most contaminated species because of higher relative contribution of toxic metals, particularly arsenic. This ranking reflects the MPI's weighting of all metals proportionally, such that the elevated toxic metal burden of *M. electricus*, particularly arsenic yielding a higher index value than the predominantly Fe-driven load of *D. affinis* with MPI of 2.70×10^{-7} . This distinction highlights the MPI's utility in providing ecologically relevant assessments of pollution beyond total metal load alone.

Table 1: Mean $\pm$ SD of Heavy Metal Concentrations (mg/kg) and Metal Pollution Index in the Muscles Tissues of Freshwater Fish Species from Dukku River Basin

Metal	<i>Alestes nurse</i>	<i>Distichodus affinis</i>	<i>Malapterurus electricus</i>	<i>Hypropisus bebe</i>
Zn mg/kg	0.84 $\pm$ 0.02 ^a	0.45 $\pm$ 0.01 ^a	0.45 $\pm$ 0.02 ^a	0.46 $\pm$ 0.01 ^a
Cd mg/kg	0.20 $\pm$ 0.10 ^{bc}	0.21 $\pm$ 0.10 ^c	0.19 $\pm$ 0.10 ^{ab}	0.18 $\pm$ 0.10 ^a
Fe mg/kg	9.40 $\pm$ 0.10 ^c	11.65 $\pm$ 0.5 ^d	2.75 $\pm$ 0.5 ^a	4.45 $\pm$ 0.15 ^b
Cu mg/kg	0.11 $\pm$ 0.01 ^b	ND	ND	0.14 $\pm$ 0.01 ^c
Ni mg/kg	0.07 $\pm$ 0.01 ^c	0.01 $\pm$ 0.01 ^a	0.04 $\pm$ 0.01 ^b	0.08 $\pm$ 0.01 ^b
As mg/kg	0.01 $\pm$ 0.00 ^a	0.08 $\pm$ 0.01 ^c	0.17 $\pm$ 0.01 ^d	0.05 $\pm$ 0.01 ^b
Pb mg/kg	ND	0.09 $\pm$ 0.01 ^a	ND	ND
Mn mg/kg	0.19 $\pm$ 0.01 ^d	0.13 $\pm$ 0.01 ^b	0.06 $\pm$ 0.01 ^a	0.17 $\pm$ 0.01 ^c
Cr mg/kg	0.26 $\pm$ 0.02 ^d	0.21 $\pm$ 0.01 ^c	0.16 $\pm$ 0.01 ^a	0.19 $\pm$ 0.01 ^b
MPI	7.51 $\times 10^{-7}$	2.70 $\times 10^{-7}$	2.19 $\times 10^{-6}$	8.33 $\times 10^{-7}$

Legend: Different superscript letters (a–d) within rows denote significant interspecific differences (one-way ANOVA, LSD post hoc test, $p < 0.05$). MPI= Metal Pollution Index; ND= Not Detected.

Estimated Daily Intake (EDI) and Non-carcinogenic Risk

The Estimated Daily Intake (EDI) for both adults and children from the consumption of the four species inhabiting Dukku River are presented in Table 2. Iron (Fe) and zinc (Zn) across all the examined species consistently dominate the EDI profile (Table 2). For adults, the highest Fe EDI of 6.51×10^{-3} mg/kg·day was recorded in *D. affinis* and a lowest value of 1.53×10^{-3} mg/kg·day was recorded in *M. electricus*. *A. nurse* exhibited the maximum Zn EDI of 4.70×10^{-3} mg/kg·day and minimum value of 2.52×10^{-4} was recorded in both *D. affinis* and *M. electricus*. The highest Cd EDI value of 1.18×10^{-4} mg/kg·day was observed in *D. affinis*, followed by *A. nurse* with EDI value of 1.12×10^{-4} mg/kg·day for adult. Similarly, Cr exhibited the highest EDI value of 1.45×10^{-4} mg/kg·day in *A. nurse*, followed by 1.18×10^{-4} mg/kg·day in *D. affinis*. Compared to Fe, Zn, Cd and Cr, arsenic (As) exposure was lower across the species, with an adult maximum EDI value of 9.48×10^{-5} mg/kg·day in *M. electricus*, followed by *D. affinis* with 4.46×10^{-5} mg/kg·day, whereas a minimum As EDI value of 5.58×10^{-6} mg/kg·day was observed in *A. nurse*. Generally, the EDI values estimated for children followed a similar trend to the EDI values observed in adults and were consistently higher in children across all metal and species. Furthermore, Fe, Zn, Cd and Cr contributed notably to the EDI profile of both adult and children populations across all species, but the contribution of As was more prominent in *M. electricus* and *D. affinis*.

Among the metals analyzed, only the THQ for arsenic (As) in *M. electricus* exceeded the threshold value for children, with 1.480 (Table 2), indicating a potential non-carcinogenic health risk. All other metal-species combinations produced THQ values below the threshold of 1.0. The Hazard Index (HI) was consistently higher in children than in adult population across all species. *M. electricus* recorded the highest HI value of 2.133 for children, followed by *D. affinis* with HI value of 1.541 (Table 2). Meanwhile, the minimum HI value of 0.897 was

recorded for children consuming *A. nurse* (Table 2). Similarly, the highest HI values of 0.461 and 0.332 were observed in *M. electricus* and *D. affinis* in adults, respectively. All adults HI values were below 1.0, ranging from minimum of 0.222 in *A. nurse* to a maximum of 0.461 in *M. electricus*, indicating no non-carcinogenic risk concern for adult consumers under the assessed scenario (Table 2). Generally, the THQ values of individual metals were below the safe threshold limit (THQ < 1.0) in adult, and in children only as exceeded the safety limit in *M. electricus* (Table 2). The HI values for children consuming *M. electricus*, *D. affinis* and *H. bebe* were above the safety limit (HI > 1), indicating a potential adverse non-carcinogenic health effect to children consuming these species inhabiting Dukku River (Table 2).

Table 2: Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) for Adults and Children Consuming Freshwater Fish from Dukku River Basin.

Species	Metal	Adults EDI (mg/kg-day)	Adults THQ	Children EDI (mg/kg-day)	Children THQ
<i>Alestes nurse</i>	Zn	4.70×10^{-4}	0.002	2.19×10^{-3}	0.007
	Cd	1.12×10^{-4}	0.112	5.22×10^{-4}	0.522
	Fe	5.24×10^{-3}	0.007	2.45×10^{-2}	0.035
	Cu	6.14×10^{-5}	0.002	2.86×10^{-4}	0.007
	Ni	3.90×10^{-5}	0.002	1.82×10^{-4}	0.009
	As	5.58×10^{-6}	0.048	2.60×10^{-5}	0.087
	Mn	1.06×10^{-4}	0.001	4.94×10^{-4}	0.004
	Cr	1.45×10^{-4}	0.048	6.78×10^{-4}	0.226
HI			0.222		0.897
<i>Distichodus affinis</i>	Zn	2.52×10^{-4}	0.001	1.18×10^{-3}	0.004
	Cd	1.18×10^{-4}	0.118	5.48×10^{-4}	0.548
	Fe	6.51×10^{-3}	0.009	3.04×10^{-2}	0.043
	Ni	5.58×10^{-6}	0.001	2.60×10^{-5}	0.001
	As	4.46×10^{-5}	0.149	2.08×10^{-4}	0.693
	Pb	5.02×10^{-5}	0.014	2.35×10^{-4}	0.067
	Mn	7.25×10^{-5}	<0.001	3.38×10^{-4}	0.002
	Cr	1.18×10^{-4}	0.039	5.48×10^{-4}	0.183
HI			0.332		1.541
<i>Malapterurus electricus</i>	Zn	2.52×10^{-4}	0.001	1.18×10^{-3}	0.004
	Cd	1.06×10^{-4}	0.106	4.94×10^{-4}	0.494
	Fe	1.53×10^{-3}	0.002	7.16×10^{-3}	0.010
	Ni	2.23×10^{-5}	0.001	1.04×10^{-4}	0.005
	As	9.48×10^{-5}	0.320	4.43×10^{-4}	1.480
	Mn	3.35×10^{-5}	<0.001	1.12×10^{-4}	0.001
	Cr	8.93×10^{-5}	0.030	4.17×10^{-4}	0.139
HI			0.461		2.133
<i>Hypropius bebe</i>	Zn	2.58×10^{-4}	0.001	1.20×10^{-3}	0.004
	Cd	1.01×10^{-4}	0.101	4.70×10^{-4}	0.470

Species	Metal	Adults EDI (mg/kg·day)	Adults THQ	Children EDI (mg/kg·day)	Children THQ
	Fe	2.48×10^{-3}	0.004	1.16×10^{-2}	0.017
	Cu	7.81×10^{-5}	0.002	3.64×10^{-4}	0.009
	Ni	4.46×10^{-5}	0.002	2.08×10^{-4}	0.010
	As	2.79×10^{-5}	0.093	1.30×10^{-4}	0.433
	Mn	9.48×10^{-5}	<0.001	4.43×10^{-4}	0.003
	Cr	1.06×10^{-4}	0.035	4.94×10^{-4}	0.165
HI			0.239		1.111

Legend: EDI= Estimated Daily Intake, THQ= Target Hazard Quotient and HI= Hazard Index

Carcinogenic Risk from Consuming of Wild Fish of Dukku River Basin

Carcinogenic Risk (CR) values associated with the lifetime consumption of wild fish inhabiting the Dukku River for arsenic (As), cadmium (Cd), lead (Pb) and chromium (Cr) are presented in Table 3. Children consistently exhibited higher CR values than adults across all species and metals, reflecting greater physiological vulnerability. As and Cd were the dominant contributors to carcinogenic risk for the population consuming *M. electricus*, *D. affinis* and *H. bebe*, especially children's consumers. The CR for Cd in adults exceeded 1×10^{-4} across all four species, ranges from a minimum of 6.36×10^{-4} in *H. bebe* to maximum of 7.43×10^{-4} in *D. affinis* (Table 3). For children, Cd CR values ranged from 2.79×10^{-3} in *M. electricus* to 3.45×10^{-4} in *D. affinis*, indicating extreme risk levels. The CR for As in *M. electricus* also exceeded 1×10^{-4} for both adults and children with 1.42×10^{-4} and 6.64×10^{-4} , respectively. However, Cr and Pb remained within or near acceptable limits for adults across all species, while Cr CR for children was in the moderate risk range. A. nurse exhibited the lowest overall carcinogenic risk profile and *M. electricus* presented the highest.

Table 3: Carcinogenic Risk for Adults and Children Consuming Freshwater Fish from Dukku River Basin

Species	Metal	CR Adult	Risk Status	CR Child	Risk Status
<i>Alestes nurse</i>	As	8.37×10^{-6}	Acceptable	3.90×10^{-5}	Acceptable
	Cd	7.06×10^{-4}	High	3.29×10^{-3}	Very High
	Cr	7.25×10^{-5}	Acceptable	3.39×10^{-4}	High
<i>Malapterurus electricus</i>	As	1.42×10^{-4}	High	6.64×10^{-4}	Very High
	Cd	6.68×10^{-4}	High	2.79×10^{-3}	Extreme
	Cr	4.47×10^{-5}	Acceptable	2.09×10^{-4}	Moderate
<i>Hypropius bebe</i>	As	4.19×10^{-5}	Moderate	1.95×10^{-4}	High
	Cd	6.36×10^{-4}	High	2.96×10^{-3}	Very High
	Cr	5.30×10^{-5}	Acceptable	2.47×10^{-4}	Moderate
<i>Distichodus affinis</i>	As	6.69×10^{-5}	Moderate	3.12×10^{-4}	High
	Cd	7.43×10^{-4}	High	3.45×10^{-3}	Very High
	Pb	4.27×10^{-7}	Acceptable	2.00×10^{-6}	Acceptable
	Cr	5.90×10^{-5}	Acceptable	2.74×10^{-4}	Moderate

Legend: CR= Cancer Risk. Acceptable lifetime cancer risk ranges from 10^{-6} to 10^{-4} .

Discussion

The results of this study show that freshwater fish from the Dukku River accumulated varying levels of heavy metals, reflecting a combination of natural geochemical background and intensified anthropogenic influences within the river basin. This pattern is consistent with global studies, where agricultural runoff, domestic activities, sand dredging and boating contribute significantly to the mobilization and bioavailability of metals in aquatic environments (Rakib *et al.*, 2021; Hedayatzadeh *et al.*, 2024). The dominance of Fe and Zn in the metal profile across all four species is consistent with extensive studies from freshwater ecosystems globally, attributed to their natural abundance in soils and sediments as well as their widespread in agricultural fertilizers and micronutrient supplements (Hedayatzadeh *et al.*, 2024). The predominance of Fe and Zn aligns with Yu *et al.* (2020), who similarly reported high bioavailability of essential elements in fish from Chinese aquatic ecosystems due to their natural abundance and use in agricultural and domestic activities. Although Fe and Zn play essential roles in the fish physiology, chronic exposure to elevated concentrations can exert sub-lethal toxic effects including oxidative stress and metabolic disruptions (Kwaansa-Ansah *et al.*, 2019). Moreover, the detection of non-essential and toxic metals such as Cd, As, Cr and Pb even at low concentrations raises serious ecological and public health concerns. Chronic exposure to non-essential and highly toxic metals, such as Cd, As, Pb, Hg, and Cr even at low concentrations can lead to neurological disorders, kidney damage, and various forms of cancer due to their persistent and bioaccumulative properties (Ali *et al.*, 2024).

The non-detection of cobalt (Co) across the examined species suggests that Co concentrations in the Dukku River are below analytical detection limits and are unlikely to pose significant ecological or public health risks under current conditions. This finding agrees with prior studies indicating that Co typically occurs at trace levels in freshwater ecosystems unless influenced by specific industrial inputs such as mining or metallurgical operations (Munir *et al.*, 2021). In contrast, copper (Cu) was exclusively detected in *A. nurse* and *H. bebe*, indicating species-specific metal uptake and accumulation processes potentially driven by ecological niche, trophic behavior, and metabolic regulation. The non-detection of Cu in *D. affinis* and *M. electricus* may reflect differences in habitat use, limited exposure within their ecological niches, and species-specific homeostatic regulation limiting Cu assimilation. This interspecific variability in metal accumulation is well documented, with feeding habits and trophic level strongly influencing metal burdens in fish tissues (Anandkumar *et al.*, 2017; Kwaansa-Ansah *et al.*, 2019). The detection of lead (Pb) exclusively in *D. affinis* is consistent with its bottom-dwelling feeding ecology: benthic organisms are more directly exposed to sediment-associated contaminants, and benthic species frequently serve as sensitive indicators of localized sediment contamination hotspots (Kumari and Maiti, 2020). In this study, *D. affinis* exhibited the highest total metal concentration, while the Metal Pollution Index (MPI) identified *M. electricus* as the most contaminated species when the relative contributions of toxic metals are weighted. This

distinction highlights the MPI's ecologically relevant capacity to differentiate between species with high essential metal loads and those with high toxic metal burdens.

Human health risk assessment revealed that Fe and Zn contributed most substantially to overall heavy metal EDI by virtue of their high tissue concentrations, while non-essential toxic metals disproportionately influenced individual risk profiles, particularly for children. Children's lower body weight and higher food consumption per unit body mass amplify their vulnerability to metal toxicity, consistently with risk assessments in other Nigeria and West African region (Adebiyi *et al.*, 2024; Yahaya *et al.*, 2024). The Target Hazard Quotient (THQ) for arsenic exposure through consumption of *M. electricus* exceeded the safety threshold (THQ > 1) for children, indicating a potential non-carcinogenic health effect attributable to As. Furthermore, the cumulative HI (Hazard Index) values were also consistently higher for children across all species, reflecting the additive risk posed by simultaneous exposure to multiple metals (Yahaya *et al.*, 2024).

The Carcinogenic Risk (CR) values identified arsenic and Cd as the primary lifetime cancer risk drivers, particularly for children consuming *M. electricus*. The Cd CR values for adults, exceeding 1×10^{-4} across all four species indicate a high carcinogenic risk classification that warrants concern under WHO/USEPA risk guidelines, and are substantially above the Codex Alimentarius safety threshold. In comparison with regional studies, Yahaya *et al.* (2024) reported elevated Cd concentrations and CR values in fish from Bunza River, Kebbi State, consistent with a regional pattern of Cd contamination in northwestern Nigerian freshwater fisheries. Adebiyi *et al.* (2024) similarly documented As-driven non-carcinogenic risks for children consumers in Nigerian coastal species. The convergent of evidence from multiple Nigerian freshwater ecosystems reinforces the public health significance of these findings and the urgent need for species-specific consumption advisories. Nyarko *et al.* (2016) reported that a CR value 1×10^{-4} indicates a negligible potential cancer risk for a contaminant. Chronic dietary intake of As and Cd has been linked to elevated cancer incidence as well as renal and neurological impairment in epidemiological studies (Taslima *et al.*, 2022; Bazarsadueva *et al.*, 2023). The findings of this study highlight the urgent need for continuous environmental monitoring and integrated management strategies to mitigate heavy metal inputs into the Dukku River Basin. Public health interventions, including community education on safe fish consumption, particularly for children and pregnant women, are essential to reduce exposure risks. Additionally, species-specific consumption advisories informed by THQ, HI and CR risk profiles identified here, particularly for *M. electricus*, are vulnerable and directly actionable tools for protecting both human health and the ecological integrity of the Dukku River basin.

Limitations and Future Directions

This study assessed heavy metal exposure through fish consumption but did not account for seasonal variability in metal concentrations, metal speciation, or cumulative exposure from other dietary sources. Additionally, site-specific water and sediment chemistry were not directly correlated with tissue accumulation data. The use of a fish ingestion rate of

39.03 g/day, derived from a Mediterranean study population ([Copat et al., 2018](#)), represent a key methodological limitation, because actual consumption patterns in fishing communities along the Dukku RIVER may differ substantially, and the application of a non-locally determined rate introduces uncertainty into all exposure estimates. Future studies should obtain locally measured fish consumption data from dietary surveys conducted with the study community, incorporate seasonal monitoring, metal speciation analysis, sediment-biota coupling, and probabilistic (Monte Carlo) risk modeling to refine exposure estimates. Integrating biomarkers responses in fish and longitudinal dietary surveys in local communities would further strengthen ecological and public health interpretation of results.

Conclusion

*Freshwater fish from the Dukku River Basin accumulate measurable levels of heavy metal arising from natural processes and anthropogenic activities within the river basin. These contaminations pose significant health risks, particularly for children. The MPI confirmed *Malapterurus electricus* as the most ecotoxicologically contaminated species, driven by elevated arsenic concentrations. Fe and Zn dominated the EDI profile but not-essential toxic metals, particularly As and Cd disproportionately determined the health risk outcomes. In *M. electricus*, As was reported to be the sole metal to the exceeded threshold limit of THQ, and HI > 1.0 for children consuming *M. electricus*, *D. affinis*, and *H. bebe*, indicating meaningful non-carcinogenic risk for this vulnerable population. Additionally, As and Cd were the dominant contributors to carcinogenic risk for both adults and children, with Cd CR exceeded 1×10^{-4} for all adult consumers across all four species, indicating food safety concern relevant to regulatory bodies. These findings highlight the need for the implementation of routine monitoring programs, species-specific consumption advisories, particularly for *M. electricus*, and pollution control strategies to enhance food safety and reduce public health risks associated with consumption of fish from the Dukku River Basin.*

Recommendations

Further research should be conducted locally to validated dietary surveys to determined fish ingestion rates specific to riverine communities along the Dukku River, replacing the generalized value of 39.03 g/day employed in this study. Future studies should also incorporate seasonal monitoring, metal speciation analysis, and probabilistic risk modeling to refine the assessments reported herein. The Kebbi State Ministry of Health and the National Agency for Food and Drug Administration and Control (NAFDAC) should develop and disseminate species-specific consumption advisories targeting *Malapterurus electricus*, for which children face non-carcinogenic risk (THQ > 1 for As) and extreme carcinogenic risk (Cd CR = 0.27×10^{-3}).

Funding

This research was funded by Tertiary Education Trust Fund (TetFund), Nigeria.

Data Availability

The data supporting this research are available from the author(s) on reasonable request.

Authors' Contributions

Naziru Salisu: Conceptualized and designed the study, performed data acquisition, analysis, and interpretation, drafted and critically revised the manuscript, approved the final version and takes full responsibility for integrity of the work.

Kasimu Shehu: Contributed to data acquisition, statistical analysis, and interpretation, critically revised the manuscript, and approved the final version and shares responsibility for the accuracy and integrity of the study.

Conflict of Interest

The authors declare no competing interest.

Acknowledgement

The authors acknowledge the support of the Department of Biological Sciences and the management of Federal University Birnin Kebbi, Kebbi State, Nigeria.

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