American Journal of Aquaculture and Animal Science (AJAAS)

ISSN: 2835-8945 (ONLINE)

VOLUME 5 ISSUE 2 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Volume 5 Issue 2, Year 2026
ISSN: 2835-8945 (Online)
DOI: https://doi.org/10.54536/ajaas.v5i2.8144
https://journals.e-palli.com/home/index.php/ajaas

American Journal of Aquaculture and Animal Science (AJAAS)

Non-Carcinogenic and Carcinogenic Health Risk Assessment of Heavy Metal Exposure Via Oral and Dermal Pathways in Riparian Communities of Katsina-Ala River, Benue State, Nigeria

Athanasius Aondohemen Aende[1*], Saratu Ibrahim[2], Tersoo Bajah[3], Gabriel Ataguba[1], Orfega. Benjamin Kwaghvihi[1] , Salifu Eyiojotule Daniel[3]

Article Information

Received: May 04, 2026

Accepted: July 07, 2026

Published: September 07, 2026

Keywords

Carcinogenic Risk, Hazard Quotient, Health Risk Assessment, Heavy Metals, Katsina-Ala River

ABSTRACT

Heavy metal contamination of freshwater poses a growing public health concern in sub-Saharan Africa, yet quantitative risk assessments for Nigerian riparian communities relying on unregulated river water remain scarce. This study assessed non-carcinogenic and carcinogenic health risks from six heavy metals which are mercury, arsenic, nickel, cadmium, zinc, and lead in water from Katsina-Ala River at Buruku, Benue State, Nigeria, via oral ingestion and dermal exposure in adults and children during the wet (July–September 2025) and dry (January–March 2026) seasons. Risks were calculated using the USEPA (1989) framework, incorporating measured metal concentrations, exposure parameters, reference doses, and cancer slope factors across three sampling stations. Hazard Index (HI) values for oral ingestion exceeded the safety threshold at all sites and in both seasons, with children facing markedly higher risk (HI up to 70.07) than adults (HI up to 55.06) in the wet season, driven mainly by arsenic and cadmium. Dermal exposure posed moderate risk (HI up to 3.47) in children, primarily from cadmium. Carcinogenic risk remained very low overall, though nickel contributed the highest risk in children (ILCR up to 0.052). These findings indicate unacceptable non-carcinogenic risk from river water ingestion in Buruku, particularly for children, highlighting the urgent need for water treatment interventions and community health risk communication.

INTRODUCTION

Heavy metal contamination of freshwater systems poses a significant and growing threat to human health, particularly in developing countries where inadequately treated or untreated river water serves as the primary source of drinking and domestic water for millions of people (Duruibe *et al.*, 2007; Wongsasuluk *et al.*, 2014). Metals such as arsenic (As), cadmium (Cd), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn) are recognized as priority environmental pollutants by the World Health Organization and the United States Environmental Protection Agency (USEPA) due to their persistence, bioaccumulation potential, and documented associations with a spectrum of adverse health effects ranging from renal toxicity and neurodevelopmental impairment to carcinogenesis (Sharma & Agrawal, 2005; Cobbina *et al.*, 2015; Rafiee *et al.*, 2020).

Human exposure to heavy metals through contaminated water occurs principally via two routes: oral ingestion and dermal absorption during bathing, washing, and recreational contact (Li & Zhang, 2010; Okafor *et al.*, 2025). The relative contribution of each pathway to total exposure depends on the physicochemical properties of individual metals, the concentration in the water matrix, and population-specific exposure factors such as body weight, skin surface area, and duration of contact. Children are recognized as a uniquely vulnerable demographic given their higher ingestion rates relative to body weight, greater dermal permeability, and longer anticipated lifetime of exposure (Lanphear *et al.*, 2005; Mazumdar *et al.*, 2011).

Recent investigations across Nigerian freshwater systems continue to document elevated heavy metal loads and associated health risks, underscoring the persistence of this exposure pathway. Within the Benue River basin specifically, Onoja *et al.* (2022) reported lead and arsenic concentrations in River Enumabia, a Benue State tributary at Orokam, that substantially exceeded WHO guideline values, while Ezechi *et al.* (2026) recently applied an integrated hydrogeochemical and health-risk framework to the Benue River mainstream and reported cumulative Hazard Index values for fish and aquatic-species consumption ranging from 1.98 to 3.12, exceeding the acceptable safety threshold. Comparable evidence from other Nigerian rivers, including the Ala River (Alabi *et al.*, 2025) and the Bunza River (Yahaya *et al.*, 2024), similarly confirms that heavy metal contamination of freshwater used for domestic and dietary purposes remains a widespread and current public health concern in the country.

Katsina-Ala River at Buruku, Benue State, Nigeria, is heavily utilized by riparian communities for drinking, bathing, cooking, irrigation, and artisanal fishing. The river receives effluents from an active abattoir, outboard engine repair workshops, agricultural fields with inorganic fertiliser and pesticide application, sand mining operations, and paint-containing canoe construction activities (Vershima *et al.*, 2015; Soom *et*

[1] Department of Fisheries and Aquaculture, College of Forestry and Fisheries, Joseph Sarwuan Tarka University Makurdi, P. M. B- 2373, Benue State, Nigeria
[2] School of Agriculture and Agricultural Technology, Federal University of Technology Minna, Nigeria
[3] Department of Zoology and Environmental Biology, Faculty of Biological Sciences, University of Nigeria Nsukka. Enugu State, Nigeria
[*] Corresponding author's e-mail: aende.athanasius@uam.edu.ng

al., 2018). Despite documented exceedances of WHO and Nigerian standard guideline values for several heavy metals in this river system, no study has applied the USEPA probabilistic health risk framework to quantify the chronic non-carcinogenic and carcinogenic risks to adults and children in this community. This gap in the evidence base limits the capacity of public health authorities to prioritize interventions and communicate risk to affected populations. The present study addresses this gap by providing a rigorous, pathway-specific, age-stratified health risk assessment for six heavy metals in Katsina-Ala River water across two seasons and three sampling stations, constituting the first such assessment for this ecologically and demographically important river system.

MATERIALS AND METHODS

Study Area and Sampling

The study was conducted on Katsina-Ala River within Buruku town, Benue State, Nigeria (7°26'5"N to 7°28'3"N; 9°12'9"E to 9°12'14"E). Three sampling stations were established representing distinct anthropogenic pressure profiles: Station 1 (upstream), influenced by domestic washing, brick-moulding, and farm runoff; Station 2 (midstream), a ferry-crossing and fish landing site with heavy boat traffic, abattoir effluent, and engine maintenance activities; and Station 3 (downstream), subject to intensive agricultural activities including use of inorganic fertilizers, herbicides, and pesticides. Water samples were collected bimonthly over six months — July to September 2025 (wet season) and January to March 2026 (dry season) yielding n = 24 observations per station per parameter.

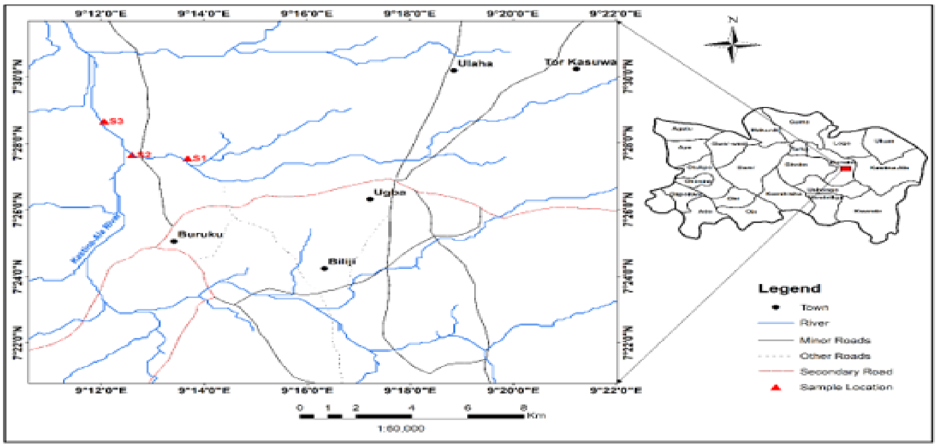

Figure 1: Drainage map showing the study area.
Source: ArcGIS

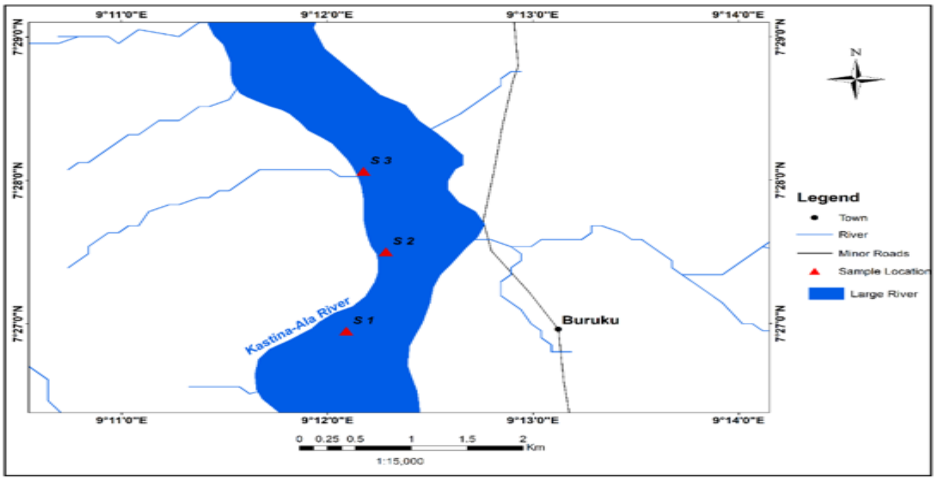

Figure 2: Map of study area showing the sampled sites.
Source: ArcGIS

Sample Collection

Water and sediment samples were collected twice monthly from all three stations across six months, spanning July–September 2025 (wet season) and January–March 2026 (dry season), producing a total of n = 24 samples per site for each parameter. Water samples were drawn from a depth of 30 cm using pre-cleaned 500 mL polypropylene bottles. One bottle was treated with $MnSO_4$ and KI to enable determination of dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5). A second bottle was preserved with 5 mL of concentrated HNO_3 for heavy metal analysis and transported to the laboratory at 4°C within 48 hours of collection. Sediment samples were obtained using an Eckman grab sampler, placed into pre-acid-treated plastic containers, and stored at 4°C until analysis.

Heavy Metal Concentrations

Mean heavy metal concentrations used as inputs for health risk calculations were obtained from analyses of water samples by Atomic Absorption Spectrophotometry (AAS; Unicam® 696 Series) for Hg, Zn, and Pb, and by UV-Visible Spectrophotometry for As, Ni, and Cd. Seasonal mean concentrations by site are presented in Table 1.

Health Risk Assessment Framework

Health risk was assessed following the USEPA (1989) Risk Assessment Guidance for Superfund framework, as applied in comparable studies (Wu *et al.*, 2009; Riaz *et al.*, 2022; Seleem *et al.*, 2021). Two exposure pathways were evaluated: oral ingestion and dermal absorption. Risk was calculated separately for adults and children.

Chronic Daily Intake

The Chronic Daily Intake (CDI) via oral ingestion (CDI_oral, mg/kg/day) was calculated as:

$$CDI\_oral = (Cw \times IR \times EF \times ED) / (BW \times AT) \quad (1)$$

The CDI via dermal absorption (CDI_dermal, mg/kg/day) was calculated as:

$$CDI\_dermal = (Cw \times SA \times Kp \times ET \times EF \times ED \times CF) / (BW \times AT) \quad (2)$$

where Cw = measured metal concentration in water (mg/L); IR = ingestion rate (L/day); EF = exposure frequency (days/year); ED = exposure duration (years); BW = body weight (kg); AT = averaging time (days); SA = skin surface area exposed (cm^2); Kp = dermal permeability coefficient (cm/hr); ET = exposure time per event (hr/event); CF = volumetric conversion factor (0.001 L/cm^3). Exposure parameters are presented in Table 1.

Non-Carcinogenic Risk

Non-carcinogenic risk for each metal was expressed as the Hazard Quotient (HQ):

$$HQ = CDI / RfD \quad (3)$$

where RfD is the pathway-specific reference dose (mg/kg/day). The overall Hazard Index (HI) was computed as the sum of HQ values for all six metals per pathway. HQ or HI > 1 indicates potential unacceptable non-carcinogenic risk; HQ or HI ≤ 1 indicates acceptable risk (USEPA, 1989). Risk classification followed Bortey-Sam *et al.* (2015): negligible (HQ/HI < 0.1), low (0.1–1), medium (1–4), and high (≥ 4).

Carcinogenic Risk

Incremental Lifetime Cancer Risk (ILCR) was estimated for carcinogenic metals (Cd, As, Ni, and Pb) as:

$$ILCR = CDI\_oral \times CSF \quad (4)$$

where CSF is the cancer slope factor $(mg/kg/day)^{-1}$. Carcinogenic risk was classified as: very low ($<10^{-6}$), low (10^{-6} to 10^{-5}), medium (10^{-5} to 10^{-4}), high (10^{-4} to 10^{-3}), and very high ($>10^{-3}$), following Bortey-Sam *et al.* (2015) and Gržetić and Ghariani (2008).

Table 1: Exposure Parameters for Oral Ingestion and Dermal Absorption Pathways

Parameter	Unit	Oral Value	Dermal Value	Reference
IR (Ingestion rate) — Adult	L/day	2.2	—	Karim (2011)
IR (Ingestion rate) — Child	L/day	1.0	—	Karim (2011)
EF (Exposure frequency)	days/yr	365	350	Riaz *et al.* (2022)
ED (Exposure duration) — Adult	years	70	30	Riaz *et al.* (2022)
ED (Exposure duration) — Child	years	10	6	Riaz *et al.* (2022)
ET (Exposure time) — Adult	hr/event	—	0.58	Riaz *et al.* (2022)
ET (Exposure time) — Child	hr/event	—	1.0	Riaz *et al.* (2022)
BW (Body weight) — Adult	kg	70	70	Karim (2011)
BW (Body weight) — Child	kg	25	25	Karim (2011)
AT (Averaging time) — Adult	days	25,550	25,550	Riaz *et al.* (2022)
AT (Averaging time) — Child	days	3,650	3,650	Riaz *et al.* (2022)
SA (Skin surface area) — Adult	cm^2	—	18,000	Riaz *et al.* (2022)
SA (Skin surface area) — Child	cm^2	—	6,600	Riaz *et al.* (2022)
CF (Conversion factor)	L/cm^3	—	0.001	Karim (2011)

Table 2: Reference Doses (RfD) and Cancer Slope Factors (CSF) for Heavy Metals

Metal	RfD oral (mg/kg/day)	RfD dermal (mg/kg/day)	CSF $(mg/kg/day)^{-1}$	Reference
Cd	5.00×10^{-4}	5.00×10^{-6}	0.38	USEPA (2018)
As	3.00×10^{-4}	1.23×10^{-4}	0.15	USEPA (2018)
Hg	3.00×10^{-4}	3.00×10^{-4}	—	USEPA (2018)
Ni	2.00×10^{-2}	5.40×10^{-3}	0.91	USEPA (2018)
Zn	3.00×10^{-1}	6.00×10^{-2}	—	USEPA (2018)
Pb	3.50×10^{-3}	5.25×10^{-4}	0.0085	USEPA (2018); Ukah *et al.* (2019)

RESULTS AND DISCUSSIONS

Heavy Metal Concentrations in River Water

The mean heavy metal concentrations used as inputs for health risk calculations are summarized in Table 3 by season and station. Nickel consistently registered the highest concentrations (wet season range: 0.88–0.93 mg/L; dry season range: 0.37–0.39 mg/L), followed by arsenic (wet: 0.16–0.21 mg/L; dry: 0.03–0.05 mg/L), cadmium (wet: 0.10–0.13 mg/L; dry: 0.01–0.02 mg/L), mercury (wet: 0.03–0.04 mg/L; dry: 0.01–0.02 mg/L), lead (wet: 0.02–0.04 mg/L; dry: 0.01 mg/L), and zinc (wet: 0.01–0.03 mg/L; dry: 0.01 mg/L). All metals except Zn and Pb exceeded WHO/NSDWQ guideline values in the wet season.

Table 3: Mean Heavy Metal Concentrations (mg/L) in Katsina-Ala River Water Used as Health Risk Inputs

Metal	**Site 1 Wet**	**Site 1 Dry**	**Site 2 Wet**	**Site 2 Dry**	**Site 3 Wet**	**Site 3 Dry**
Pb	0.030	0.010	0.030	0.010	0.040	0.010
Cd	0.120	0.010	0.110	0.020	0.100	0.020
Zn	0.010	0.010	0.010	0.010	0.030	0.010
Ni	0.920	0.390	0.880	0.370	0.930	0.390
As	0.170	0.030	0.160	0.040	0.210	0.050
Hg	0.030	0.010	0.030	0.010	0.040	0.010

Non-Carcinogenic Risk via Oral Ingestion

The potential chronic non-carcinogenic risk via oral ingestion is presented for children and adults in Tables 4 and 5 respectively. In children, the Hazard Index (HI) from oral ingestion exceeded unity across all stations and seasons, indicating unacceptable non-carcinogenic risk. During the wet season, arsenic contributed the highest HQ in children across all stations (Site 1: 43.00; Site 2: 40.67; Site 3: 55.11), followed by cadmium (HQ: 7.47–8.33) and mercury (HQ: 2.24–4.22). Nickel generated a medium HQ of 2.71–2.85 across all wet season sites. Zinc was negligible across all stations and seasons (HQ ≈ 0.00). The total HI for children via oral ingestion ranged from 53.85 to 70.07 during the wet season (classified as high risk) and from 5.06 to 5.90 during the dry season (also classified as high risk).

In adults, the oral HI was similarly elevated, ranging from 42.31 to 55.06 in the wet season and 3.98 to 4.64 in the dry season. Arsenic remained the dominant contributor to adult oral risk (HQ wet: 31.95–43.30), followed by cadmium (HQ wet: 5.87–6.55), nickel (HQ wet: 2.13–2.24), and mercury (HQ wet: 1.76–3.32). Lead was low risk across all scenarios, and zinc was negligible. In both age groups, wet season oral risk was approximately 10-fold higher than dry season risk, driven by elevated metal concentrations during rainfall-enhanced runoff events.

Table 4: Potential Chronic Non-Carcinogenic Risk (HQ) via Oral Ingestion in Children Exposed to Water from Katsina-Ala River (Wet and Dry Seasons)

Metal	**Site 1 Wet HQ**	**Site 1 Dry HQ**	**Site 2 Wet HQ**	**Site 2 Dry HQ**	**Site 3 Wet HQ**	**Site 3 Dry HQ**	**Risk Level (Wet)**
Pb	0.20	0.16	0.20	0.16	0.42	0.16	Low
Cd	8.33	0.93	7.93	1.47	7.47	1.33	High
Zn	0.00	0.00	0.00	0.00	0.00	0.00	Negligible
Ni	2.84	0.85	2.71	0.83	2.85	0.88	Medium
As	43.00	1.56	40.67	2.00	55.11	1.67	High
Hg	2.24	1.56	2.33	1.44	4.22	1.78	Medium–High
HI	56.62	5.06	53.85	5.90	70.07	5.82	High

Table 5: Potential Chronic Non-Carcinogenic Risk (HQ) via Oral Ingestion in Adults Exposed to Water from Katsina-Ala River (Wet and Dry Seasons)

Metal	Site 1 Wet HQ	Site 1 Dry HQ	Site 2 Wet HQ	Site 2 Dry HQ	Site 3 Wet HQ	Site 3 Dry HQ	Risk Level (Wet)
Pb	0.16	0.13	0.16	0.13	0.33	0.13	Low
Cd	6.55	0.73	6.23	1.15	5.87	1.05	High
Zn	0.00	0.00	0.00	0.00	0.00	0.00	Negligible
Ni	2.23	0.67	2.13	0.65	2.24	0.69	Medium
As	33.79	1.22	31.95	1.57	43.30	1.31	High
Hg	1.76	1.22	1.83	1.13	3.32	1.40	Low–Medium
HI	44.49	3.98	42.31	4.64	55.06	4.57	High

Non-Carcinogenic Risk via Dermal Absorption

The dermal exposure pathway contributed a lower but non-negligible risk, particularly from cadmium and mercury (Tables 6 and 7). In children, the HI from dermal exposure was 3.47 (Site 1, wet season), 3.32 (Site 2, wet season), and 3.28 (Site 3, wet season), classified as medium risk. The primary dermal risk contributor in children was Cd (HQ: 2.92–3.25 in wet season), followed by Hg (HQ: 0.13–0.24). All other metals were negligible or low via the dermal route. In the dry season, dermal HI in children dropped to 0.47–0.68, classified as low risk. In adults, dermal HI ranged from 1.33 to 1.40 in the wet season (medium risk), also driven predominantly by Cd, and declined to 0.19–0.27 in the dry season (medium risk).

Table 6: Potential Chronic Non-Carcinogenic Risk (HQ) via Dermal Absorption in Children Exposed to Water from Katsina-Ala River (Wet and Dry Seasons)

Metal	Site 1 Wet HQ	Site 1 Dry HQ	Site 2 Wet HQ	Site 2 Dry HQ	Site 3 Wet HQ	Site 3 Dry HQ	Risk Level (Wet)
Pb	0.02	0.02	0.02	0.02	0.04	0.02	Negligible
Cd	3.25	0.36	3.10	0.57	2.92	0.52	Medium
Zn	0.00	0.00	0.00	0.00	0.00	0.00	Negligible
Ni	0.01	0.00	0.01	0.00	0.01	0.00	Negligible
As	0.06	0.00	0.06	0.00	0.08	0.00	Negligible
Hg	0.13	0.09	0.13	0.08	0.24	0.10	Low
HI	3.47	0.47	3.32	0.68	3.28	0.64	Medium

Table 7: Potential Chronic Non-Carcinogenic Risk (HQ) via Dermal Absorption in Adults Exposed to Water from Katsina-Ala River (Wet and Dry Seasons)

Metal	Site 1 Wet HQ	Site 1 Dry HQ	Site 2 Wet HQ	Site 2 Dry HQ	Site 3 Wet HQ	Site 3 Dry HQ	Risk Level (Wet)
Pb	0.01	0.01	0.01	0.01	0.02	0.01	Negligible
Cd	1.31	0.15	1.25	0.23	1.18	0.21	Medium
Zn	0.00	0.00	0.00	0.00	0.00	0.00	Negligible
Ni	0.00	0.00	0.00	0.00	0.00	0.00	Negligible
As	0.03	0.00	0.02	0.00	0.03	0.00	Negligible
Hg	0.05	0.04	0.05	0.03	0.10	0.04	Negligible
HI	1.40	0.19	1.34	0.27	1.33	0.26	Medium

Carcinogenic Risk

The ILCR for carcinogenic metals (Cd, As, Ni, and Pb) via oral ingestion is presented in Tables 8 and 9 for children and adults respectively. Nickel generated the highest ILCR across all stations and age groups (children wet season: 0.0494–0.0519; adults wet season: 0.0388–0.0408), classified as very high carcinogenic risk ($>10^{-3}$). However, these ILCR values for Ni are attributable to the exceptionally high measured Ni concentrations (18-fold excess above WHO guideline), and the classification should be interpreted cautiously given the chronic nature of the exposure scenario assumed (70 years for adults, 10 years for children). Arsenic generated the second highest ILCR (children wet: 0.0018–0.0025; adults wet: 0.0014–0.0019), classified as very high. Cadmium ILCR ranged from 0.0001 to 0.0001 in the wet season (low risk).

Lead ILCR was negligible across all scenarios (children: <0.00002; adults: <0.00001). The dry season ILCR values for all metals were one to two orders of magnitude lower than wet season values, consistent with reduced metal concentrations. In both age groups and across all scenarios, the rank order of carcinogenic risk was: Ni > As > Cd > Pb.

Table 8: Carcinogenic Risk (ILCR) in Children Exposed to Heavy Metals via Oral Ingestion from Katsina-Ala River Water (Wet and Dry Seasons)

Metal	Site 1 Wet	Site 1 Dry	Site 2 Wet	Site 2 Dry	Site 3 Wet	Site 3 Dry
Pb	6.0×10^{-6}	4.8×10^{-6}	6.0×10^{-6}	4.8×10^{-6}	1.25×10^{-5}	4.8×10^{-6}
Cd	1.25×10^{-4}	1.40×10^{-5}	1.19×10^{-4}	2.20×10^{-5}	1.12×10^{-4}	2.00×10^{-5}
Ni	5.17×10^{-2}	1.55×10^{-2}	4.94×10^{-2}	1.50×10^{-2}	5.19×10^{-2}	1.60×10^{-2}
As	1.94×10^{-3}	7.00×10^{-5}	1.83×10^{-3}	9.00×10^{-5}	2.48×10^{-3}	7.50×10^{-5}

Table 9: Carcinogenic Risk (ILCR) in Adults Exposed to Heavy Metals via Oral Ingestion from Katsina-Ala River Water (Wet and Dry Seasons)

Metal	Site 1 Wet	Site 1 Dry	Site 2 Wet	Site 2 Dry	Site 3 Wet	Site 3 Dry
Pb	4.7×10^{-6}	3.8×10^{-6}	4.7×10^{-6}	3.8×10^{-6}	9.8×10^{-6}	3.8×10^{-6}
Cd	9.82×10^{-5}	1.10×10^{-5}	9.35×10^{-5}	1.73×10^{-5}	8.80×10^{-5}	1.57×10^{-5}
Ni	4.06×10^{-2}	1.22×10^{-2}	3.88×10^{-2}	1.18×10^{-2}	4.08×10^{-2}	1.26×10^{-2}
As	1.52×10^{-3}	5.50×10^{-5}	1.44×10^{-3}	7.07×10^{-5}	1.95×10^{-3}	5.89×10^{-5}

Non-Carcinogenic Risk via Oral Ingestion

The finding that oral HI exceeded unity across all sites, seasons, and age groups in this study indicates that chronic non-carcinogenic risk from drinking or ingesting Katsina-Ala River water is unacceptable by USEPA (1989) standards, with arsenic as the dominant hazard driver. Arsenic HQ values for children in the wet season (40.67–55.11) and adults (31.95–43.30) substantially exceed those reported in comparable Nigerian river studies; in literatures example, Eze *et al.* (2021) reported total non-carcinogenic HI values of 0.78–2.32 for adults in Njaba River, Imo State, and Muhammad *et al.* (2010) documented HI values of 2.4–6.8 in arsenic-contaminated groundwater in Pakistan. The particularly high arsenic HQ in this study is consistent with wet-season peak concentrations of 0.21–0.425 mg/L exceeding the WHO guideline of 0.01 mg/L by up to 42-fold and reflects the documented role of agricultural pesticide and herbicide inputs, including arsenical compounds, as non-point sources of As in tropical river systems (Tangahu *et al.*, 2011; Bhattacharya *et al.*, 2007).

These findings also situate Katsina-Ala River among a growing body of recent Nigerian freshwater assessments reporting unacceptable non-carcinogenic risk from heavy metal-contaminated surface water. Within the same Benue basin, Ezechi *et al.* (2026) reported cumulative Hazard Index values of 1.98 to 3.12 for dietary exposure to Benue River fish and aquatic species, while Onoja *et al.* (2022) documented lead and arsenic concentrations exceeding WHO limits in the Benue tributary River Enumabia at Orokam. The considerably higher oral HI values recorded at Buruku relative to these comparator studies may have likely reflect the combined influence of concentrated point-source effluent from the abattoir, engine repair, and canoe-painting activities and diffuse agricultural runoff converging within a single riverine catchment, rather than a single dominant contamination source.

Cadmium's contribution to oral HI (HQ 5.87–8.33 in children, wet season) is particularly concerning given its established nephrotoxicity, skeletal effects, and carcinogenicity (WHO, 2019; ATSDR, 2012). The major sources of Cd in the study area are consistent with global patterns: which may be from abattoir effluents, phosphate fertilisers, paint pigments, and metallic corrosion products from outboard engines (Paschal *et al.*, 2000; Jolly *et al.*, 2012). Nickel's medium-range HQ (2.71–2.85 in children) suggests a secondary but non-negligible contribution to non-carcinogenic risk, consistent with its source that may be from engine oil combustion and metallic paint at Site 2 (Nation *et al.*, 1985). Mercury's HQ in children ranged from medium (2.24–2.33 at Sites 1 and 2) to high (4.22 at Site 3) in the wet season. This is consistent with the elevated Hg concentrations observed and the multiple Hg sources in the study area which may include boat engine lubricants, paint preservatives, and naturally methylated Hg from sediment microorganisms (Basu , 2023;Wang *et al.*, 2026).

The consistently higher HI values in children compared to adults reflect differences in body weight-normalised ingestion rates and longer remaining lifetime of exposure used in children's risk calculations. This is consistent with the broader literature emphasising children as the highest-risk demographic for heavy metal exposure in contaminated water environments (Lanphear *et al.*, 2005; Mazumdar *et al.*, 2011; Khan *et al.*, 2012). The approximately 10-fold reduction in oral HI during the dry season relative to the wet season reflects reduced metal concentrations which may be due to lower runoff loading from agricultural and point-source effluents, but the persistence of HI > 1 in the dry season indicates that the river presents a year-round non-carcinogenic risk through the oral pathway.

Non-Carcinogenic Risk via Dermal Absorption

The dermal HI in children during the wet season (3.28–3.47) classified as medium risk was primarily driven by cadmium, which has a relatively high dermal permeability coefficient (Kp = 0.001 cm/hr) compared to other metals in this study (Riaz *et al.*, 2022). While dermal HI was substantially lower than oral HI, the medium-risk classification is not trivial given that dermal exposure is often continuous and involuntary for riparian communities who bathe, wash clothing, and engage in artisanal fishing in the river. Comparable findings were reported by Wongsasuluk *et al.* (2014) in Thailand, where Cd dermal HQ in children exceeded unity in agricultural areas, and by Seleem *et al.* (2021) in Egyptian groundwater systems. In adults, dermal HI of 1.33–1.40 (medium risk) confirms that this pathway is non-negligible for both age groups and should be incorporated in integrated exposure assessments and public health advisories for the Buruku riparian community.

A similarly cadmium-dominated dermal and dietary risk profile has recently been reported for the Bunza River in Kebbi State, where the average daily intake of cadmium through water use exceeded recommended limits even though the composite hazard index for individual metals remained below unity (Yahaya *et al.*, 2024), suggesting that cadmium behaves as a comparatively persistent, low-threshold hazard across diverse Nigerian riverine systems regardless of overall contamination severity.

Carcinogenic Risk

The carcinogenic risk hierarchy (Ni > As > Cd > Pb) identified in this study differs from patterns reported in many other Nigerian river systems, where Pb and Cd are typically the primary carcinogenic risk drivers (Eze *et al.*, 2021; Muhammad *et al.*, 2010). In the present study, nickel's dominance as a carcinogen reflects its exceptionally high-water concentrations, which was 18 times the WHO guideline combined with its high cancer slope factor (CSF = 0.91 mg/kg/day^{-1} for inhalation, the USEPA oral CSF is derived for soluble Ni compounds). It is important to note that the ILCR values for Ni in this study exceed the 10^{-3} threshold conventionally classified as very high risk under Bortey-Sam *et al.* (2015); however, the USEPA (1989) framework acknowledges that lifetime cancer risk estimates above 10^{-4} require further investigation rather than constituting an immediate emergency determination. Arsenic ILCR values (children: 1.83–2.48 × 10^{-3}; adults: 1.44–1.95 × 10^{-3}) in the wet season are consistent with globally documented high-arsenic water scenarios and confirm that As is an important independent carcinogen in this system, with bladder, skin, and lung cancers being the primary associated endpoints (Costa, 2019; Rosen and Liu, 2009). Cadmium ILCR (10^{-4} to 10^{-5} range) indicates a low to medium carcinogenic risk level in the classification of Bortey-Sam *et al.* (2015), consistent with Cd's classification as a Group 1 human carcinogen primarily associated with kidney and lung cancers (ATSDR, 2012). Lead ILCR values were negligible across all scenarios (< 2 × 10^{-5}), consistent with its relatively low oral CSF (0.0085 mg/kg/day^{-1}) despite concentrations approaching the WHO guideline at Site 3. The finding that cancer risk was higher in children than in adults for all metals and scenarios is consistent with the biological vulnerability of children and with comparable published assessments (Eze *et al.*, 2021; Bortey-Sam *et al.*, 2015).

The direct application of the USEPA carcinogenic and non-carcinogenic framework to the same two fish species examined in this study, Clarias gariepinus and Oreochromis niloticus, in the Ala River at Akure similarly identified cadmium, chromium, nickel, and lead concentrations exceeding WHO/FAO limits in both fish tissue and water, alongside measurable DNA damage in exposed fish, supporting the concern that chronic exposure to these metals carries genotoxic as well as carcinogenic implications beyond those captured by the ILCR metric alone (Alabi *et al.*, 2025). Taken together with the recent Benue River basin evidence from Ezechi *et al.* (2026) and Onoja *et al.* (2022), the present findings indicate that elevated carcinogenic risk from nickel and arsenic is not unique to Buruku but reflects a broader pattern of metal contamination emerging across Nigerian freshwater systems that warrants coordinated, basin-wide monitoring.

Public Health Implications and Recommendations

The convergence of non-carcinogenic oral HI values well above unity and carcinogenic ILCR values indicating elevated risk for Ni and As across all sites and seasons generates a compelling evidence base for urgent public health action in Buruku. The riparian community's dependence on Katsina-Ala River as a primary drinking water source, in the absence of alternative treated water supply infrastructure, makes this a high-priority intervention setting. Point-of-use water treatment options such as coagulation-flocculation, activated carbon filtration, reverse osmosis, and boiling (effective for reducing microbial load and some metals) should be evaluated for implementation feasibility and cost-effectiveness in this context (Balasubramanian *et al.*, 2017; Sombei *et al.*, 2025).

Regulatory enforcement of effluent discharge standards at the abattoir, paint workshops, and engine repair facilities around Site 2 should be prioritized, given the higher metal concentrations consistently observed at this station. Agricultural extension services should promote integrated pest management and reduced-application practices for arsenical and cadmium-containing fertilizers and agrochemicals (Mueller *et al.*, 2025) as observed in Site 3. Children under 10 years of age should be identified as a priority target group for health surveillance, including blood lead, arsenic, and cadmium screening, given their disproportionately high calculated risk across both pathways.

CONCLUSIONS

This study presents the first pathway-specific, age-stratified, seasonal health risk assessment for heavy metals in Katsina-Ala River at Buruku, Benue State, Nigeria, filling a critical evidence gap in the environmental health literature for this ecologically and demographically important river system. Oral ingestion constitutes an unacceptable non-carcinogenic health risk (HI > 1) for both adults and children across all sites and seasons, with arsenic and cadmium as the primary hazard drivers and children as the most vulnerable population group. Dermal absorption contributes a medium non-carcinogenic risk in children during the wet season, driven by cadmium. Carcinogenic risk was dominated by nickel and arsenic, with ILCR values indicating elevated cancer risk under the wet season exposure scenario. These findings mandate urgent intervention through water treatment, regulatory action, and targeted public health communication in Buruku riparian communities. Future research should incorporate biomonitoring data such as blood and urine metal levels to validate the modelled risk estimates and enable dose-response refinement under local exposure conditions.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This study was supported by the Department of Fisheries and Aquaculture, Joseph Sarwuan Tarka University (Formally known as Federal University of Agriculture), Makurdi, Benue State, Nigeria.

REFERENCES

Agaku, R. M., Ikyumbur, J. T., Amanyi, M. I. and Onwoke, E. E. (2025). Assessment of heavy metals concentration in ground water in Gboko, Nigeria. *Nigerian Journal of Physics, 34*(1), 122–133. https://doi.org/10.62292/njp.v34i1.2025.390

Alabi, O. A., Fatile, F. M. and Ashamo, M. O. (2025). Heavy metal concentration and DNA damage in tilapia (Oreochromis niloticus Linnaeus, 1758) and catfish (Clarias gariepinus Burchell, 1822) from contaminated Ala River, Akure, Nigeria. *Toxicology Research (Cambridge), 14*(5), tfaf141. https://doi.org/10.1093/toxres/tfaf141

ATSDR, S. (2012). Toxicological profile for chromium. Agency for toxic substances and disease registry. *Public Health Service, US Department of Health and Human Services*. http://www. atsdr. cdc. gov/toxprofiles/tp.asp, 24049864.

Balasubramanian, R., He, J., & Wang, L. K. (2017). Control, management, and treatment of metal emissions from motor vehicles. In *Handbook of Advanced Industrial and Hazardous Wastes Management* (pp. 1113-1128). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781315117423-34/control-management-treatment-metal-emissions-motor-vehicles-rajasekhar-balasubramanian-jun-lawrence-wang

Basu, M. (2023). Impact of mercury and its toxicity on health and environment: a general perspective. In *mercury toxicity: Challenges and solutions* (pp. 95-139). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-7719-2_4

Bhattacharya, P., Welch, A. H., Stollenwerk, K. G., McLaughlin, M. J., Bundschuh, J. and Panaullah, G. (2007). Arsenic in the environment: biology and chemistry. *Science of the Total Environment, 379*(2–3), 109–120. https://doi.org/10.1016/j.scitotenv.2007.02.037

Bodrud-Doza, M., Islam, A. R. M. T., Ahmed, F., Das, S., Saha, N. and Rahman, M. S. (2016). Characterization of groundwater quality using water evaluation indices, multivariate statistics and geostatistics in central Bangladesh. *Water Science, 30*: 19–40. https://doi.org/10.1016/j.wsj.2016.05.001

Bortey-Sam, N., Nakayama, S. M. M., Ikenaka, Y., Akoto, O., Baidoo, E., Mizukawa, H. and Ishizuka, M. (2015). Health risk assessment of heavy metals and metalloid in drinking water from communities near gold mines in Tarkwa, Ghana. *Environmental Monitoring and Assessment,* 187, 397. https://doi.org/10.1007/s10661-015-4630-3

Cobbina, S., Duwiejuah, A., Quansah, R., Obiri, S. and Bakobie, N. (2015). Comparative assessment of heavy metals in drinking water sources in two small-scale mining communities in northern Ghana. *International Journal of Environmental Research and Public Health, 12*(9), 10620–10634. https://doi.org/10.3390/ijerph120910620

Costa, M. (2019). Review of arsenic toxicity, speciation and polyadenylation of canonical histones. *Toxicology and Applied Pharmacology,* 375, 1–4. https://doi.org/10.1016/j.taap.2019.05.006

Dorne, J. L., Kass, G. E., Bordajandi, L. R., Amzal, B., Bertelsen, U., Castoldi, A. F., Heppner, C., Eskola, M., Fabiansson, S., Ferrari, P. and Scaravelli, E. (2011). Human risk assessment of heavy metals: principles and applications. *Metal Ions in Life Science, 8*(4), 27–60. https://doi.org/10.1039/9781849732116-00027

Duruibe, J. O., Ogwuegbu, M. O. C. and Egwurugwu, J. N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences, 2*(5), 112–118. http://www.academicjournals.org/IJPS

Eze, V. C., Ndife, C. T. and Muogbo, M. O. (2021). Carcinogenic and non-carcinogenic health risk assessment of heavy metals in Njaba River, Imo State, Nigeria. *Brazilian Journal of Analytical Chemistry, 8*(33),57–70. https://doi.org/10.30744/brjac.2179-3425.AR-05-2021

Ezechi, E. C., Usiabulu, G. I., Okpoji, A. U., Akpan, N. A., Onuchukwu, E. E., Ovuru, T. I., Okonkwo, P. C., Otuuk, A. G., Obi, J. N., Ahmad, S. I., Oji, N.

N. and Osuagwu, E. L. (2026). Hydrogeochemical characterisation, heavy metal bioaccumulation in fish and aquatic species, and public health risk assessment of River Benue, Nigeria. *Acta Biology Forum, 5*(1), Article 29. https://doi.org/10.51470/ABF.2026.5.1.29

Giri, S. and Singh, A. K. (2015). Human health risk assessment via drinking water pathway due to metal contamination in the groundwater of Subarnarekha River Basin, India. *Environmental Monitoring and Assessment,* 187, 63. https://doi.org/10.1007/s10661-015-4265-4

Gržetić, I. and Ghariani, A. R. H. (2008). Potential health risk assessment for soil heavy metal contamination in the central zone of Belgrade, Serbia. *Journal of the Serbian Chemical Society,* 73, 923–934. http://dx.doi.org/10.2298/JSC0809923G

Jolly, Y. N., Hossain, A., Sattar, A. and Islam, A. (2012). Impact of heavy metals on water and soil environment of the paint industry. *Journal of the Bangladesh Chemical Society, 25*(2), 159–165. https://doi.org/10.3329/jbcs.v25i2.15068

Karim, Z. (2011). Risk assessment of dissolved trace metals in drinking water of Karachi, Pakistan. *Bulletin of Environmental Contamination and Toxicology,* 86, 676–678. https://doi.org/10.1007/s00128-011-0261-8

Khan, K., Wasserman, G. A., Liu, X., Ahmed, E., Parvez, F., Slavkovich, V., Levy, D., Mey, J., van Geen, A., Garziano, J. H. and Factor-Litvak, P. (2012). Manganese exposure from drinking water and children's academic achievement. *Neurotoxicology, 33*(1), 91–97. https://doi.org/10.1016/j.neuro.2011.12.002

Lanphear, B. P., Hornung, R., Khoury, J., Yolton, K., Baghurst, P., Bellinger, D. C., Canfield, R. L., Dietrich, K. N., Bornschein, R., Greene, T. and Roberts, R. (2005). Low-level environmental lead exposure and children's intellectual function: an international pooled analysis. *Environmental Health Perspectives, 113*(7), 894–899. https://doi.org/10.1289/EHP5685

Li, S. and Zhang, Q. (2010). Risk assessment and seasonal variations of dissolved trace elements and heavy metals in the Upper Han River, China. *Journal of Hazardous Materials,* 181, 1051–1058. https://doi.org/10.1016/j.jhazmat.2010.05.120

Mazumdar, M., Bellinger, D. C., Gregas, M., Abanilla, K., Bacic, J. and Needleman, H. L. (2011). Low-level environmental lead exposure in childhood and adult intellectual function: a follow-up study. *Environmental Health, 10*(1), 1–7. https://doi.org/10.1186/1476-069X-10-24

Mohammadi, A. A., Zarei, A., Majidi, S., Ghaderpoury, A., Hashempour, Y., Saghi, M. H., Alinejad, A., Yousefi, M., Hosseingholizadeh, N. and Ghaderpur, M. (2019). Carcinogenic and non-carcinogenic health risk assessment of heavy metals in drinking water of Khorramabad, Iran. MethodsX, 6, 1642–1651. https://doi.org/10.1016/j.mex.2019.07.017

Mueller, D. S., Iles, L. C., Pilcher, C. L., Sisson, A. J., Magarey, R., Adams, R., ... & Zebelo, S. (2025). Integrated pest management: state infrastructure status after 50 yr of Federal support (1973 to 2023). *Journal of Integrated Pest Management, 16*(1), 30. https://doi.org/10.1093/jipm/pmaf016

Muhammad, S., Shah, M. T. and Khan, S. (2010). Arsenic health risk assessment in drinking water and source apportionment using multivariate statistical techniques in Kohistan region, northern Pakistan. *Food and Chemical Toxicology, 48*(10), 2855–2864. https://doi.org/10.1016/j.fct.2010.07.018

Nation, J. R., Hare, M. F., Baker, D. M., Clark, D. E. and Bourgeois, A. E. (1985). Dietary administration of nickel: Effects on behaviour and metallothionein levels. *Physiology and Behaviour, 34*(3), 349–353. https://doi.org/10.1016/0031-9384(85)90194-5

Okafor, C. P., Nduka, J. K., Okafor, P. O., & Offor, C. C. (2025). Behavioural dynamics of water quality parameters and human exposure assessment of trace metals in Agulu Lake Water, South-East Nigeria. *Cleaner Water,* 100127. https://doi.org/10.1016/j.clwat.2025.100127

Onoja, E. D., Amanyi, M. I., Onwoke, E. E., Ngbede, I. A. and Lukuman, B. (2022). Assessment of heavy metal loadings of water and sediment of River Enumabia in Orokam, Benue State, Nigeria. *Physics Access, 2*(1), 75–81. https://doi.org/10.47514/phyaccess.2022.2.1.009

Paschal, D. C., Burt, V., Caudill, S. P., Gunter, E. W., Pirkle, J. L., Sampson, E. J., Miller, D. T. and Jackson, R. J. (2000). Exposure of the US population aged 6 years and older to cadmium: 1988–1994. *Archives of Environmental Contamination and Toxicology, 38*(3), 377–383. https://doi.org/10.1007/s002449910050

Rafiee, A., Delgado-Saborit, J. M., Sly, P. D., Quémerais, B., Hashemi, F., Akbari, S. and Hoseini, M. (2020). Environmental chronic exposure to metals and effects on attention and executive function in the general population. *Science of the Total Environment,* 705, 135911. https://doi.org/10.1016/j.scitotenv.2019.135911

Rahman, M. M., Islam, M. A., Bodrud-Doza, M., Muhib, M. I., Zahid, A., Shammi, M., Tareq, S. M. and Kurasaki, M. (2017). Spatio-temporal assessment of groundwater quality and human health risk: a case study in Gopalganj, Bangladesh. *Exposure and Health,* 10, 167–188. https://doi.org/10.1007/s12403-017-0253-y

Riaz, R. M. Y., Murtaza, G., Farooqi, Z. U. R., Ali, S., Aziz, H., Mahboob, S., ... & Riaz, U. (2022). Assessment of arsenic contamination in groundwater and associated human health risk. *Sustainability, 14*(19), 12460. https://doi.org/10.3390/su141912460

Rosen, B. P. and Liu, Z. (2009). Transport pathways for arsenic and selenium: a minireview. *Environment International, 35*(3), 512–515. https://doi.org/10.1016/j.envint.2008.07.023

Seleem, E. M., Mostafa, A., Mokhtar, M. and Salman, S. A. (2021). Risk assessment of heavy metals in drinking water on the human health, Assiut City, Egypt. *Arabian Journal of Geosciences, 14*(6), 1–11. https://doi.org/10.1007/s12517-021-06784-2

Sharma, R. K. and Agrawal, M. (2005). Biological effects of heavy metals: an overview. *Journal of Environmental Biology, 26*(2), 301–313. https://www.researchgate.net/profile/Surendran-Udayar-Pillai/post/Are-there-critical-permissible-limits-for-Cadmium-in-rockphosphates-and-Phosphate-fertilizers-applied-to-Agricultural soils/attachment/59d655c379197b80779acd35/AS%3A527223700168704%401502711333965/download/Toxic+limits.pdf

Sombei, D. C., Mecha, C. A., & Chollom, M. N. (2025). A review of low-cost point-of-use water treatment solutions addressing water access and quality in resource-limited settings. *Water, 17*(12), 1827.

Soom, J. W., Solomon, S. G. and Ayuba, V. O. (2018). Assessment of some physico-chemical parameters of Katsina-Ala River at Buruku, Benue State, Nigeria. *International Journal of Fisheries and Aquatic Studies, 6*(2), 556–561. https://scholar.google.com/scholar?q=related:Xl_59PvYaMcJ:scholar.google.com/&scioq=Soom,+J.+W.,+Solomon,+S.+G.,+%26+Ayuba,+V.+O.+(2018).+Assessment+of+some+physico-chemical+parameters+of+River+Katsina-Ala+at+Buruku,+Benue+State,+Nigeria.+International+Journal+of+Fisheries+and+Aquatic+Studies,+6(2),+556-561.&hl=en&as_sdt=0,5

Tangahu, B. V., Sheikh Abdullah, S. R., Basri, H., Idris, M., Anuar, N. and Mukhlisin, M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering,* 2011, 939161. https://doi.org/10.1155/2011/939161

Ukah, B. U., Egbueri, J. C., Unigwe, C. O. and Ubido, O. E. (2019). Extent of heavy metals pollution and health risk assessment of groundwater in a densely populated industrial area, Lagos, Nigeria. I*nternational Journal of Energy and Water Resources, 3*, 291–303. https://doi.org/10.1007/s42108-019-00039-3

USEPA (1989). *Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual.* EPA/540/1-89/002. Office of emergency and remedial response, u.s. environmental protection agency, washington, dc. https://books.google.com/

USEPA (2018). *Edition of the Drinking Water Standards and Health Advisories.* EPA 822-F-18-001. Office of Water, U.S. Environmental Protection Agency, Washington, DC. https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=US+EPA+(2018).+Edition+of+the+Drinking+Water+Standards+and+Health+Advisories.+EPA+822-F-18-001.+Office+of+Water,+U.S.+Environmental+Protection+Agency,+Washington,+DC.

Vershima, A. J., Terkimbi, K. J., Terese, A. and Ibrahim, A. (2015). Heavy metals assessment of abattoir effluent on surface water quality of Katsina-Ala River, Benue State, Nigeria. *International Letters of Chemistry, Physics and Astronomy, 49,* 90–99. http://www.scipress.com/ILCPA.49.90

Wang, Y., Liu, Y., Cai, H., Zheng, D., & Cheng, Q. (2026). Mechanisms and environmental factors of mercury methylation in wetlands: a systematic review. *International Journal of Energy and Water Resources, 10*(2), 71. https://doi.org/10.1007/s42108-026-00495-8

WHO (2011). Guidelines for Drinking-Water Quality. 4th edn. *World Health Organization,* Geneva. https://iris.who.int/bitstream/handle/10665/254636/9789241550017-eng.pdf

WHO (2019). Preventing disease through healthy environments: exposure to cadmium: a major public health concern WHO/CED/PHE/EPE/19.4.3. *World Health Organization,* Geneva.

Wongsasuluk, P., Chotpantarat, S., Siriwong, W. and Robson, M. (2014). Heavy metal contamination and human health risk assessment in drinking water from shallow groundwater wells in an agricultural area, Thailand. *Environmental Geochemistry and Health, 36*(1), 169–182. https://doi.org/10.1007/s10653-013-9537-8

Wu, B., Zhao, D. Y., Jia, H. Y., Zhang, Y., Zhang, X. X. and Cheng, S. P. (2009). Preliminary risk assessment of trace metal pollution in surface water from Yangtze River in Nanjing Section, China. *Bulletin of Environmental Contamination and Toxicology, 82*(4), 405–409. https://doi.org/10.1007/s00128-008-9497-3

Xiao, M. S., Li, F., Zhang, J. D., Lin, S. Y., Zhuang, Z. Y. and Wu, Z. X. (2017). Investigation and health risk assessment of heavy metals in soils from partial areas of Daye city, China. IOP Conference Series: *Earth and Environmental Science, 64*(1), 012066. https://doi.org/10.1088/1755-1315/64/1/012066

Yahaya, T., Aisha, L. N., Kalgo, A. S., Muhammad, N., Abubakar, M. and Faruk, M. U. (2024). Contamination and risk assessment of heavy metals in water and fish obtained in bunza river in kebbi state, nigeria. *Environmental Health Engineering and Management, 11*(2), 191–199. https://doi.org/10.34172/EHEM.2024.19

Zheng, S., Wang, Q., Yuan, Y. and Sun, W. (2020). Human health risk assessment of heavy metals in soil and food crops in the pearl river delta urban agglomeration of China. *Food Chemistry, 316*, 126213. https://doi.org/10.1016/j.foodchem.2020.126213