



Research Article

Heavy Metal Distribution and Human Health Risk Assessment in Water, Sediments and Vegetables around Ajiwa Reservoir, Katsina State, Northwestern Nigeria

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ABSTRACT

Ajiwa Reservoir is an important freshwater resource for domestic water supply, irrigation, fishing, and ecosystem support in Katsina State, northwestern Nigeria. Growing anthropogenic activities within the reservoir catchment have raised concerns about heavy-metal contamination and its potential health implications. This study investigated the distribution of lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) in surface water, sediments, and commonly consumed vegetables—pepper (*Capsicum annum*), tomato (*Solanum lycopersicum*), and onion (*Allium cepa*)—collected from Site 1 (Kwatani), Site 2 (Masabo), and Site 3 (Kadaji/Mallamawa). Samples were analyzed using Microwave Plasma Atomic Emission Spectroscopy (MP-AES). Metal concentrations were evaluated against WHO drinking-water guideline values, FAO/WHO food standards, and consensus-based Sediment Quality Guidelines (SQGs). Non-carcinogenic health risks were assessed using Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI). Reservoir water was slightly alkaline (pH 8.03–8.53), while turbidity (30.80–34.60 NTU) and total suspended solids (229.80–297.40 mg/L) exceeded recommended limits. Copper concentrations reached 8.767 ± 7.308 mg/L in water and 15.86 ± 1.852 mg/kg in sediments, whereas cadmium (0.177 ± 0.263 mg/L) and lead (0.013 ± 0.006 mg/L) in water exceeded WHO guideline values. Children exhibited greater non-carcinogenic risks than adults, with cumulative HI values of 40.897 and 11.709, respectively. The highest HQ values were recorded for copper (21.918) and cadmium (17.700) through the water exposure pathway in children. These findings provide baseline information for environmental monitoring and public health protection in the Ajiwa Reservoir catchment.

Keywords: Ajiwa Reservoir; Heavy metals; Human health risk assessment; Katsina State; Sediment contamination; Vegetables; Water quality

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INTRODUCTION

Ajiwa Reservoir, located in Katsina State, northwestern Nigeria, is an important freshwater resource that supports domestic water supply, irrigation farming, fishing, livestock production, and other socio-economic activities within the surrounding communities. The reservoir plays a vital role in sustaining agricultural productivity and food security, particularly during the prolonged dry season when irrigation becomes the major source of crop production. Owing to its strategic importance,

maintaining the environmental quality of the reservoir is essential for protecting ecosystem integrity and safeguarding public health (Akan *et al.*, 2015; Emenike *et al.*, 2020; World Health Organization, 2017).

Despite its socio-economic importance, the reservoir is increasingly threatened by anthropogenic activities occurring within its catchment. Intensive irrigation farming, indiscriminate application of fertilizers and agrochemicals, domestic wastewater discharge, livestock activities, soil erosion, and surface runoff

contribute to the continuous introduction of pollutants into the aquatic environment. Among these pollutants, heavy metals are of particular concern because they are persistent, non-biodegradable, and capable of accumulating in water, sediments, and living organisms. Once introduced into aquatic systems, these metals may partition between the dissolved phase, suspended particles, bottom sediments, and agricultural crops irrigated with contaminated water, thereby increasing the possibility of human exposure through multiple pathways (Kabata-Pendias, 2011; Förstner and Wittmann, 1981; Kumar *et al.*, 2023).

Lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) are among the heavy metals frequently reported in aquatic environments because of their environmental persistence and potential health implications. Lead and cadmium have no known beneficial biological function and are highly toxic even at relatively low concentrations, whereas copper and zinc are essential trace elements but may become harmful when present above physiological requirements. Continuous exposure to these metals through contaminated drinking water and food may result in neurological disorders, kidney dysfunction, impaired growth, oxidative stress, and other chronic health conditions. Children are generally more susceptible than adults because of their lower body weight, higher intake rates relative to body mass, and developing physiological systems (Briffa *et al.*, 2020; Tchounwou *et al.*, 2012; Gaetke *et al.*, 2014; Genchi *et al.*, 2020; World Health Organization, 2021).

Several studies have investigated heavy metal contamination in surface water, sediments, agricultural soils, and edible vegetables in different parts of Nigeria and elsewhere. These studies have demonstrated that irrigation water and contaminated soils can serve as important pathways for the transfer of heavy metals into vegetables, thereby increasing potential health risks to consumers (Oyeyemi *et al.*, 2021; Antoniadis *et al.*, 2019; Sagagi *et al.*, 2022; Sadiq *et al.*, 2023; Danladi *et al.*, 2025). However, most previous investigations have focused on individual environmental matrices or specific exposure pathways rather than evaluating contaminant transfer across interconnected environmental compartments.

Although Ajiwa Reservoir is an important source of water for domestic use and irrigation in Katsina State, comprehensive information on the simultaneous distribution of heavy metals in water, sediments, and edible vegetables, together with the associated human health risks, remains limited. To the best of

our knowledge, no previous study has comprehensively evaluated the transfer of heavy metals across these environmental matrices while integrating human health risk assessment for both children and adults around the Ajiwa Reservoir. Addressing this knowledge gap is essential for understanding contaminant transfer pathways and providing scientific evidence for effective environmental monitoring and public health protection.

Therefore, this study aimed to determine the concentrations of lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) in water, sediments, and commonly consumed vegetables collected around Ajiwa Reservoir using Microplasma Atomic Emission Spectroscopy (MP-AES), and to evaluate the potential non-carcinogenic health risks for children and adults using Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) models.

MATERIALS AND METHODS

Study Area

The study was conducted at Ajiwa Reservoir, located in Rimi Local Government Area of Katsina State, northwestern Nigeria. The reservoir lies approximately at 12°57'04" N and 7°44'59" E (12.95106° N, 7.74979° E), at an elevation of about 468 m above sea level. It is an earth-fill dam constructed on the Tagwai River in 1973 and commissioned in 1975. The reservoir has an estimated storage capacity of approximately 22 million m³ and was primarily developed to provide potable water, support irrigation farming, and promote fisheries in Katsina State. It currently serves as an important source of domestic water supply for Katsina metropolis and neighbouring communities, while also supporting extensive irrigation farming, livestock watering, and fishing activities.

The study area falls within the Sudan Savannah ecological zone of Nigeria and experiences two distinct seasons: a rainy season extending from May to October and a dry season from November to April. Mean annual temperatures generally range from 25 to 35 °C, while annual rainfall varies between 700 and 900 mm. The catchment is dominated by intensive agricultural activities, particularly dry-season irrigation, which encourages the use of fertilizers and agrochemicals. Other anthropogenic activities, including livestock grazing, fishing, and domestic activities around the reservoir, may contribute to contaminant inputs through surface runoff, soil erosion, and direct human activities.

Samples were collected from three representative agricultural zones surrounding the reservoir. These locations were selected because they receive runoff from the surrounding farming communities and represent areas of varying anthropogenic influence.

For ease of interpretation, the sampling locations were grouped into three monitoring sites: Site 1 (Kwatani), Site 2 (Masabo), and Site 3 (Kadaji–Mallamawa). The geographical location of the study area and the sampling sites is presented in Figure 1.

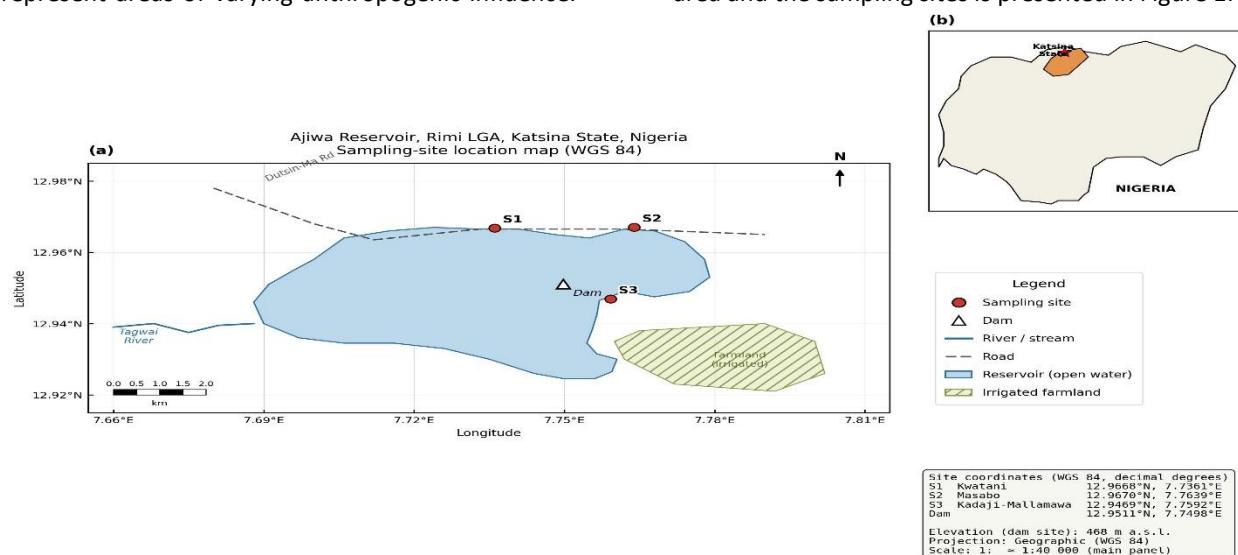


Figure 1. Map of Ajiwa Reservoir, Katsina State, Nigeria, showing the study area and sampling locations (Site 1: Kwatani, Site 2: Masabo, and Site 3: Kadaji–Mallamawa)

Sample Collection and Coding

Sampling was carried out during the dry season at three monitoring sites around Ajiwa Reservoir designated as Site 1 (Kwatani), Site 2 (Masabo), and Site 3 (Kadaji–Mallamawa). At each site, surface water, bottom sediment, and edible vegetable samples comprising pepper (*Capsicum annuum*), tomato (*Solanum lycopersicum*), and onion (*Allium cepa*) were collected. Three independent samples of each matrix were obtained approximately 50 m apart

to account for spatial variability. The samples were labelled immediately after collection, transported to the laboratory in clean polyethylene containers, and prepared for subsequent analysis. Samples were identified using a coding system based on sample matrix and sampling location. Water, sediment, pepper, tomato, and onion samples collected from Sites 1–3 were designated as WS1–WS3, SS1–SS3, PS1–PS3, TS1–TS3, and OS1–OS3, respectively (Table 1).

Table 1. Sampling matrices and identification codes used for sample collection and laboratory analysis

Sample Matrix	Material Description	Systematic Identification Codes
Water	Surface water column samples	WS1, WS2, WS3
Sediment	Bottom surficial sediment layer samples	SS1, SS2, SS3
Pepper	Fresh fruit tissue (<i>Capsicum annuum</i>)	PS1, PS2, PS3
Tomato	Fresh fruit tissue (<i>Solanum lycopersicum</i>)	TS1, TS2, TS3
Onion	Fresh bulb tissue (<i>Allium cepa</i>)	OS1, OS2, OS3

Values represent the coding system used for sample identification during field collection and laboratory analysis. WS = water sample; SS = sediment sample; PS = pepper sample; TS = tomato sample; OS = onion sample.

Physicochemical Analysis

Water samples were analyzed on-site and in the laboratory for temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), and turbidity using standard analytical procedures as described by the American Public Health Association (APHA, 2017). The electrical

conductivity meter was calibrated using standard (KCl) solutions, and readings were verified to confirm the correct reporting unit.

Sample Preparation and Metal Analysis

Water samples were filtered through 0.45 µm membrane filters and acidified with pure nitric acid HNO₃ to pH < 2 immediately after collection.

Sediment and vegetable samples were thoroughly washed first with running tap water to remove adhering soil particles, followed by multiple rinses with deionized water.

Vegetable preparation steps were specific to crop type: fresh tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) samples were processed whole (including skins and seed cores) without peeling, whereas onion (*Allium cepa*) samples were stripped of their outer papery epidermal layers to isolate the clean edible bulb matrix. All tissues were air-dried to a constant weight at 65°C in a ventilated oven, homogenized, and sieved through a 2 mm mesh.

For elemental extraction, exactly 1.0 g of dried, powdered sediment or vegetable tissue was weighed into digestion tubes. Vegetable portions were digested with 5 mL of an optimized ultra-pure concentrated acid mixture 4 HNO₃: 1 H₂O₂, while sediment samples were processed using a complementary block digestion ratio 4 HNO₃: 1 HClO₄. Digestion was conducted on an automated heating block at 120 °C for approximately 2.5 hours until the emission of dense white fumes ceased and a completely clear solution was obtained. Digested matrices were cooled, diluted to 50 mL with deionized water, and filtered.

Quantitative determination of Pb, Cd, Cu, and Zn was conducted using an Agilent 4210 MP-AES. The analytical procedure included QA/QC measures such as reagent blanks and duplicate analyses. Calibration curves for Pb, Cd, Cu, and Zn showed good linearity ($R^2 > 0.999$), and replicate analyses indicated acceptable analytical precision.

Health Risk Assessment Models

Non-carcinogenic health risks associated with the ingestion of water and contaminated vegetables were calculated for both children and adults using the standard United States Environmental Protection Agency framework. Exposure parameters including specific ingestion rates (IR), body weight (BW), exposure frequency (EF), and exposure duration (ED) were adopted from the USEPA Exposure Factors Handbook (USEPA, 2011).

Estimated Daily Intake (EDI)

The daily mass of trace elements consumed per unit body weight was modeled via Equation 1. EDI values were modeled using the mean concentration profiles of each respective environmental matrix. For a standard non-carcinogenic risk profile, the exposure frequency (EF) = 365 days/year and exposure duration (ED) mathematically cancel out against the

non-carcinogenic averaging time (AT) = (ED) 365 days) following USEPA methodology:

$$EDI = \frac{C}{IR \times BW} \dots\dots EQ 1$$

Where:

C = Heavy metal concentration in sample. For water, C is expressed directly as mg/L. For vegetable tissues, because raw laboratory outputs represent a dry weight (dw) basis while standard ingestion rates (IR) are based on a wet weight (ww) basis, concentration values were converted to a fresh-weight basis prior to risk calculations using a measured moisture conversion factor (Wf): $C(ww) = C(dw) \times (1 - Wf)$. Mean moisture content values were determined experimentally via oven drying to constant weight: pepper (Wf = 0.88), tomato (Wf = 0.93), and onion (Wf = 0.86).

(IR) = Ingestion rate (Water): 2.0 L/day for adults, 1.5 L/day for children; (Vegetables): 0.345 kg/day for adults, 0.232 kg/day for children on a wet-weight basis.

(BW) = Average body weight 70 kg for adults, 15 kg for children.

Hazard Quotient (HQ) and Hazard Index (HI)

The risk from individual elements was expressed as the Hazard Quotient (Equation 2):

$$HQ = \frac{EDI}{RfD} \dots\dots EQ 2$$

Where (RfD) represents the oral reference dose established by the USEPA (Zn) = 0.30, (Cu) = 0.04, and (Cd) = 0.001 mg/kg/day. Because the USEPA does not establish an official consensus oral reference dose for lead (Pb) due to the absence of a verified safe blood threshold, an operational value of 0.0035 mg/kg/day was adopted from established risk assessment literature derived from the historical provisional tolerable weekly intake framework (WHO, 2017). To account for the interactive toxic effects of multiple co-occurring elements, individual quotients were summed to derive the cumulative Hazard Index (Equation 3):

$$Hi = HQ Zn + HQ Cd + HQ Cu + HQ Pb \dots\dots EQ 3$$

An (HI) = 1.0 indicates that exposed populations are unlikely to experience adverse non-carcinogenic health impacts, whereas an (HI) >1.0 signals potential toxic risks.

Data Analysis

Statistical analyses were conducted using SPSS version 20.0. Descriptive statistics were computed for all variables, and differences among sample matrices were assessed using one-way analysis of variance (ANOVA) at a 95% confidence level ($p < 0.05$). Data

are presented as mean $\pm$ standard deviation ($n = 3$). Variations in target metal distributions among environmental matrices (WS), (SS), (PS), (TS), (OS) were evaluated using a One-way Analysis of Variance (ANOVA). The reported F-values and p-values were obtained directly from the SPSS output log, tracking statistical significance at a 95% confidence threshold ($p < 0.05$). Results are expressed as mean $\pm$ standard deviation ($n = 3$).

RESULTS

Physicochemical Properties of Reservoir Water

The physical and chemical baseline properties of the surface water column across three distinct agricultural zones of the Ajiwa Reservoir are presented in Table 2.

Heavy Metal Concentrations in Environmental Matrices

The distribution profiles of the four studied heavy metals across the water column, benthic sediment deposits, and edible crop tissues are summarized in Table 3.

One-way ANOVA identified a statistically significant difference in (Zn) concentrations among sample types ($F_{(4, 10)} = 6.43$, $p = 0.008$). Values varied from 0.003 ± 0.006 (mg/kg) in pepper to a maximum of 0.040 ± 0.010 (mg/kg) in onion bulbs. No statistically

significant difference in (Cd) concentrations was observed between the distinct matrices ($F_{(4, 10)} = 0.68$, $p = 0.622$). However, mean values in water (0.177 ± 0.263 (mg/L) and sediments (0.350 ± 0.555 (mg/kg) both exceeded standard health parameters. Distribution data for (Cu) exhibited significant matrix-specific variation ($F_{(4, 10)} = 4.03$, $p = 0.034$). Distinct accumulation zones were observed, with sediments (15.86 ± 1.852 (mg/kg), surface water (8.767 ± 7.308 (mg/L), and pepper tissues (11.53 ± 7.893 (mg/kg) recording high levels. Lead tracking showed no significant variation between sample groups ($F_{(4, 10)} = 0.53$, $p = 0.717$). Average concentrations remained within a narrow range from 0.010 ± 0.010 (mg/kg) in tomato to 0.020 ± 0.020 (mg/kg) in pepper.

Estimated Daily Intake (EDI)

The modeled masses of heavy metals entering human exposure pathways daily through the consumption of municipal/reservoir water and local vegetable crops (adjusted for fresh weight conversion) are summarized in Table 4.

Quantification of Human Health Risks (HQ and HI)

The non-carcinogenic hazard profiles, representing individual target quotients and integrated hazard index metrics, are summarized in Table 5.

Table 2. Physicochemical characteristics of surface water collected from Ajiwa Reservoir, Katsina State, Nigeria

Parameter	Site 1	Site 2	Site 3	WHO guideline
pH	8.53 ± 0.06	8.33 ± 0.06	8.03 ± 0.06	6.5–8.5
Electrical conductivity (mS/cm)	0.37 ± 0.28	0.87 ± 0.06	0.67 ± 0.06	–
Total dissolved solids (mg/L)	355.70 ± 0.58	337.70 ± 0.58	295.30 ± 0.58	500
Total suspended solids (mg/L)	297.40 ± 0.06	278.00 ± 0.06	229.80 ± 0.06	–
Turbidity (NTU)	31.81 ± 0.01	34.60 ± 0.06	30.80 ± 0.01	5
Temperature (°C)	28.43 ± 0.06	28.63 ± 0.06	28.83 ± 0.12	–

Values are presented as mean $\pm$ standard deviation ($n = 3$). WHO guideline values are based on the World Health Organization Guidelines for Drinking-water Quality (WHO, 2017). EC = electrical conductivity; TDS = total dissolved solids; TSS = total suspended solids; NTU = nephelometric turbidity units.

Table 3. Heavy metal concentrations in water, sediment, and vegetable samples collected from Ajiwa Reservoir, Katsina State, Nigeria

Heavy metal	Water	Sediment	Pepper	Tomato	Onion	WHO water	FAO/WHO	Sediment TEC
Zn	0.007 ± 0.006	0.010 ± 0.010	0.003 ± 0.006	0.013 ± 0.015	0.040 ± 0.010	3.000	60.00	121.0
Cd	0.177 ± 0.263	0.350 ± 0.555	0.073 ± 0.110	0.060 ± 0.069	0.017 ± 0.015	0.003	0.20	0.99
Cu	8.767 ± 7.308	15.86 ± 1.852	11.53 ± 7.893	3.850 ± 5.086	0.027 ± 0.012	2.000	40.00	31.6
Pb	0.013 ± 0.006	0.020 ± 0.000	0.020 ± 0.020	0.010 ± 0.010	0.013 ± 0.006	0.010	0.30	35.8

Values are expressed as mean $\pm$ standard deviation ($n = 3$). Water concentrations are reported in mg/L, whereas sediment and vegetable concentrations are expressed on a dry-weight basis (mg/kg dw). WHO = World Health Organization; FAO = Food and Agriculture Organization of the United Nations; TEC = Threshold Effect Concentration (MacDonald *et al.*, 2000).

Note: Water concentrations are expressed on a volume basis (mg/L), whereas sediment and vegetable concentrations are expressed on a dry-weight basis (mg/kg dw) to reflect direct experimental metrics.

Table 4: Estimated daily intake (EDI) of heavy metals through water and vegetable consumption for children and adults

Population group	Metal	Water (mg/kg/day)	Pepper (mg/kg/day)	Tomato (mg/kg/day)	Onion (mg/kg/day)
Children	Zn	0.00070	0.00001	0.00001	0.00009
	Cd	0.01770	0.00014	0.00006	0.00004
	Cu	0.87670	0.02140	0.00417	0.00006
	Pb	0.00130	0.00004	0.00001	0.00003
Adults	Zn	0.00020	< 0.00001	< 0.00001	0.00003
	Cd	0.00510	0.00004	0.00002	0.00001
	Cu	0.25050	0.00682	0.00133	0.00002
	Pb	0.00040	0.00001	< 0.00001	0.00001

Table 5. Hazard quotient (HQ) and hazard index (HI) for non-carcinogenic health risk associated with heavy metal exposure through water and vegetable consumption

Population group	Metal	HQ (Water)	HQ (Pepper)	HQ (Tomato)	HQ (Onion)
Children	Zn	0.002	< 0.001	< 0.001	< 0.001
	Cd	17.700	0.140	0.060	0.040
	Cu	21.918	0.535	0.104	0.002
	Pb	0.371	0.011	0.003	0.009
	Hazard Index (HI)	40.897			
Adults	Zn	0.001	< 0.001	< 0.001	< 0.001
	Cd	5.050	0.040	0.020	0.010
	Cu	6.263	0.171	0.033	< 0.001
	Pb	0.114	0.003	0.001	0.003
	Hazard Index (HI)	11.709			

DISCUSSION

The baseline physicochemical profile of Ajiwa Reservoir water indicates a stable, slightly alkaline buffering capacity (pH 8.03 - 8.53), which aligns with characteristic surface drainage behaviors in semi-arid zones of northwestern Nigeria. Electrical conductivity values (0.37 - 0.87 mS/cm) indicate moderate ionic strength and correspond well with the measured TDS concentrations, suggesting that dissolved salts remain within acceptable limits for freshwater systems. However, the high turbidity values (30.80 - 34.60 NTU) and markedly elevated Total Suspended Solids (TSS) 229.80 - 297.40 (mg/L) across all monitoring sites compared to the WHO turbidity guideline value of 5 (NTU) reveal heavy environmental loading. This acute particulate concentration is tied directly to intense seasonal dry-season irrigation pumping, high cattle wading traffic along the shallow banks, and low reservoir water levels which accelerate sediment resuspension.

The heavy metal assessment indicates that copper (Cu), cadmium (Cd), and lead (Pb) act as active contaminants within the reservoir ecosystem. The elevated level of (Cu) in benthic sediments (15.86 ± 1.852 mg/kg) is tied to historical copper affinity for organic fractions and clay minerals in sediment profiles. While sediment (Cu) remained below the

consensus-based Threshold Effect Concentration (TEC) = 31.6 (mg/kg) established by MacDonald *et al.* (2000) which represents the concentration below which adverse biological effects are expected to occur only rarely—aqueous copper levels (8.767 ± 7.308 mg/L) significantly exceeded the WHO guideline value for drinking water (2.0 mg/L). This indicates enhanced mobilization of copper from sediments into the overlying water column, possibly promoted by sediment resuspension, hydrodynamic mixing, and anthropogenic disturbances within shallow irrigation zones.

Similarly, dissolved cadmium levels (0.177 ± 0.263 mg/L) significantly exceeded the WHO guideline value (0.003 mg/L). This widespread distribution points to non-point source agricultural contamination, heavily driven by the intensive use of phosphate-based fertilizers, which are a well-documented source of environmental cadmium (Kabata-Pendias, 2011; Sadiq *et al.*, 2023)

Dissolved lead (Pb) levels also presented an environmental threshold breach, with a mean water column concentration of 0.013 ± 0.006 (mg/L) slightly exceeding the current WHO drinking water guideline value (0.010 mg/L). Interestingly, sediment (Pb) remained exceptionally low (0.020 mg/kg), well below the MacDonald *et al.* (2000) TEC ceiling of 35.8 (mg/kg). This mismatch suggests that

lead contamination in Ajiwa Reservoir is driven primarily by contemporary, transient inputs rather than historical deposition. Potential sources include atmospheric deposition, fuel combustion associated with irrigation pumps and fishing boats, surface runoff, and other diffuse anthropogenic activities within the catchment. Because lead has a high affinity for suspended organic particles, it remains mobile within the highly turbid water column (TSS) >200 (mg/L) rather than settling into the lower benthic bed layers.

The heavy metal concentrations in vegetables highlight clear differences in uptake pathways. Zinc accumulation peaked within onion bulb matrices (0.040 ± 0.010 (mg/kg)), matching its role as an essential plant micronutrient. In contrast, copper accumulation was highest in pepper fruits (11.53 ± 7.893 (mg/kg)), though it remained below the formal FAO/WHO guideline value (40.00 (mg/kg)). This spatial bioaccumulation pattern is consistent with trends identified by Sagagi *et al.* (2022, who reported that solanaceous crops display elevated translocational preferences for trace copper elements compared to root crops under dryland wastewater irrigation conditions.

The accumulation of non-essential cadmium in crop tissues (0.073 (mg/kg) in pepper, 0.060 (mg/kg) in tomato) indicates that soil-bound cadmium is highly bioavailable in these farming plots. Divalent cadmium Cd^{2+} ions often utilize the same transport pathways as essential divalent nutrients Ca^{2+} and Fe^{2+} within root systems, facilitating root uptake and translocation into edible plant structures. While these absolute vegetable concentrations currently fall within the FAO/WHO permissible guideline value (0.20 (mg/kg)), using contaminated reservoir water for long term irrigation could lead to further metal accumulation in local agricultural soils (Antoniadis *et al.*, 2019).

The human health risk models reveal important insights by converting environmental concentration data into toxic risk metrics. The cumulative Hazard Index calculations demonstrate clear non-carcinogenic health risks for both children (HI) = 40.897) and adults (HI) = 11.709). These values significantly exceed the standard target threshold of unity (HI) >1.0). This markedly elevated hazard index (HI) = 40.897 for children) reflects the substantial potential exposure risks of an environment where regional populations rely directly on untreated, turbid raw water sources coupled with heavy local dietary consumption of crops irrigated by heavy metals. This severe baseline threshold breach directly mirrors the

acute non-carcinogenic health indexes recently tracked in adjacent agrarian sectors of northern Nigeria by Sadiq *et al.* (2023).

Crucially, the risk allocation varies substantially by exposure pathway. In the water pathway (direct water consumption), copper is the dominant risk contributor, generating a child hazard quotient HQ Water = 21.918 that surpasses even that of cadmium HQ Water = 17.700. This is due to the high aqueous concentrations of dissolved copper (8.767 (mg/L) remaining in suspension within the reservoir, which poses an immediate hazard when measured against the WHO guideline value. This finding is an important environmental warning sign, showing that localized copper contamination from agricultural chemical inputs poses an immediate threat to the catchment. Conversely, after converting dry-basis metrics to a fresh-weight basis using experimental moisture factors (Wf, the dietary vegetable pathway exhibits safer, sub-unity risks HQ < 1.0) for individual elements. For instance, child cadmium risk via pepper ingestion drops to HQ Pepper = 0.140, and copper drops to HQ Pepper = 0.535. Unlike the findings of Danladi *et al.* (2025), where dietary vegetable ingestion served as the primary driver of heavy metal risks due to extreme topsoil loading in urban plots, the toxic hazard around the Ajiwa Reservoir is driven primarily by the direct consumption of untreated surface water. Lead exposure via drinking water (HQ Water = 0.371) also contributes significantly to the cumulative index, confirming that multiple contaminants act together to increase health risks.

The health risk models also confirm that children are much more vulnerable to these contaminants than adults. This higher risk is driven by children's lower average body weight and higher relative ingestion rates, which deliver a larger proportional dose of toxic metals to their developing organ systems (ATSDR, 2020; USEPA, 2011). These findings demonstrate that evaluating environmental safety solely on the basis of individual guideline concentrations may underestimate the cumulative health risks arising from multiple exposure pathways.

CONCLUSION

This study assessed heavy metal distributions and human health risks across the water, sediment, and vegetable agricultural continuum of Ajiwa Reservoir, Katsina State, Nigeria. While the reservoir water maintains stable, slightly alkaline physicochemical conditions, high turbidity and suspended solids levels indicate significant particle loading from surrounding lands. Analytical assessment revealed that copper,

cadmium, and lead act as the primary contaminants, with dissolved concentrations exceeding WHO drinking water guideline values due to agricultural activities, livestock traffic, and localized fuel runoff in the catchment.

The detection of these metals in pepper, tomato, and onion crops confirms active transfer from irrigation water and soil into the local food supply. The human health risk assessment indicated potential non-carcinogenic health risks for the local population, with children being the most vulnerable group. Ingestion of copper via the water pathway represents the dominant risk pathway in the fluid phase, whereas cadmium is the principal contributor to the dietary vegetable consumption pathway. These findings demonstrate that even when individual crop concentrations meet international food standards, combined exposure pathways can create significant health risks. Establishing routine water quality monitoring and introducing targeted catchment management are critical steps to protect communities relying on the Ajiwa Reservoir.

Regular environmental monitoring should be established through seasonal testing of heavy metal concentrations in water, sediment, and irrigated crops around the reservoir to track long-term contamination trends. To minimize exposure to surface-bound contaminants, public health campaigns are recommended to inform local communities about effective preparation methods for harvested vegetables, such as thorough washing with clean water. Furthermore, regional authorities should actively encourage the use of treated water sources for drinking and domestic needs to reduce the direct ingestion of untreated reservoir water.

From a management perspective, feasibility studies on localized dredging or sediment management in high-activity zones should be conducted to limit the release of accumulated metals back into the water column. Finally, expanding research into broader clinical and epidemiological studies will be essential to track heavy metal levels in biomarkers, such as blood or hair, within local populations—particularly among vulnerable children.

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Conflicts of Interest

The authors declare no conflicts of interest related to this study.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Musa Abubakar: Conceptualization, fieldwork, measurements (pH, EC, TDS, TSS, turbidity, and temperature), sample preparation, data processing, statistical analysis, writing – original draft. Abdulhakim Sani Lawal: Manuscript review, structural editing, and quality control. Musbahu Buhari: Data validation, manuscript review, and project coordination.

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