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Research paper

Comparative Seasonal Assessment of Heavy Metals Bioaccumulation in Selected Tissues of Catfish and Tilapia from Zobe Dam, Nigeria

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Abstract

Bioaccumulation of persistent metals in aquatic organisms poses ecological and public health risks. This study assessed cadmium (Cd), nickel (Ni), lead (Pb), and zinc (Zn) in gill, head, and muscle tissues of Tilapia (Oreochromis niloticus) and Catfish (Clarias gariepinus) from Zobe Dam during dry and wet seasons. Water samples were collected using composite techniques, while fish were systematically sampled by weight and size. Samples were digested and analyzed using Microwave Plasma Atomic Emission Spectrometry (MP-AES). Bioaccumulation factors (BAFs) were calculated as tissue-to-water concentration ratios, revealing no significant seasonal and tissue-specific variations ($p > 0.05$).
BAFs ranged from negligible (<1) to low-level accumulation (1–20). Estimated daily intakes (EDIs) of metals were below oral reference doses. Hazard quotients (HQs) and hazard indices (HIs) were consistently below 1, indicating no non-carcinogenic risk, while carcinogenic risk (CR) values for Cd, Ni, and Pb were below the acceptable range (10^{-6}–10^{-4}), suggesting negligible lifetime cancer risk.
These findings indicate minimal metal accumulation in Zobe Dam fish and no significant ecological or health risks, confirming that consumption of Tilapia and Catfish from this reservoir is safe.

Keywords: *Bioaccumulation; Catfish; Dam; Heavy Metals; Tilapia; Tissues.*

1. Introduction

Aquatic environments are increasingly threatened by heavy metal contamination resulting from agricultural practices, industrial effluents, and other human activities. Unlike many organic pollutants that degrade naturally, being non-biodegradable, heavy metals persist in the environment and progressively accumulate in aquatic systems, including water, sediments, and organisms, via bioaccumulation and biomagnification [1]. Fish, being key components of aquatic food chains, are particularly useful as bioindicators of pollution, since they absorb metals directly from their surrounding water and also through feeding[2].
Metals such as cadmium (Cd), lead (Pb), nickel (Ni), and zinc (Zn) have attracted significant concern due to their persistence and potential toxicological impacts. While certain metals like zinc are essential micronutrients, their excessive accumulation can disrupt normal metabolic processes, induce oxidative stress, and cause organ damage in both fish and humans consuming contaminated fish[3]. Monitoring the extent of heavy metal accumulation in edible fish tissues is therefore crucial, not only for assessing environmental health but also for evaluating potential public health risks.
Different fish tissues vary in their capacity to take up and store metals. Organs such as the liver and kidney are primary sites of metal detoxification and storage, whereas gills serve as the first point of contact for waterborne contaminants, and muscle tissues, being the main edible portion, are most relevant for human exposure[4]. Comparative analysis of heavy metal accumulation across these tissues provides deeper insights into ecological exposure routes and food safety concerns.
Seasonal fluctuations further influence metal dynamics in aquatic environments. Changes in rainfall, temperature, and water chemistry alter the solubility and bioavailability of metals. During the rainy season, surface runoff often increases metal input from agricultural lands and settlements, whereas in the dry season, reduced water volume and evaporation may concentrate pollutants in water and sediments [5]. Hence, evaluating bioaccumulation patterns across wet and dry seasons is essential for understanding the temporal variability of metal contamination.
Zobe Dam, situated in Dutsin-Ma, Katsina State, Nigeria, plays a vital socio-economic role by supporting irrigation, domestic use, and artisanal fishing. However, the dam is increasingly subjected to environmental pressures from farming activities, urbanization, and local livelihoods, raising concerns about its water quality and potential contamination with heavy metals. Fish species such as catfish (Clarias gariepinus) and tilapia (Oreochromis niloticus) dominate the dam, serve as important protein sources for surrounding communities, and exhibit differences in feeding behavior, physiology, and ecological niches that may influence their capacity to bioaccumulate heavy metals.

Given these ecological, nutritional, and public health implications, it is essential to investigate the seasonal variations in heavy metal bioaccumulation in tissues of catfish and tilapia from Zobe Dam. Such a study will provide critical information on contamination levels, species-specific differences, and potential human health risks associated with fish consumption. Moreover, the findings can inform environmental monitoring programs and guide policy decisions aimed at safeguarding aquatic ecosystems and ensuring food safety in Katsina State and beyond.

2. Materials and Methods

All reagents were of analytical grade, with distilled water used for solution preparation and deionized water for analyses. Glassware and plastic containers were thoroughly cleaned, oven-dried at 105 °C, and all measurements performed on a calibrated analytical balance [6].

2.1. Study area

Zobe Dam, located in Dutsinma, Katsina State (12°23′18″ N; 7°28′29″ E) (Fig. 1), was completed in 1983 to enhance potable water supply and promote irrigation-based agriculture. The dam stands 19 m high, with a crest length of 2,750 m and a storage capacity of approximately 170 million m³, extending over an area of about 800 ha. It lies within the Guinea Savannah zone, which experiences a wet season from May to October and a dry season from November to April. Beyond its hydrological importance, Zobe Dam supports fishing, irrigated farming, and domestic water use, making it a crucial resource for local livelihoods and regional socio-economic development [7].

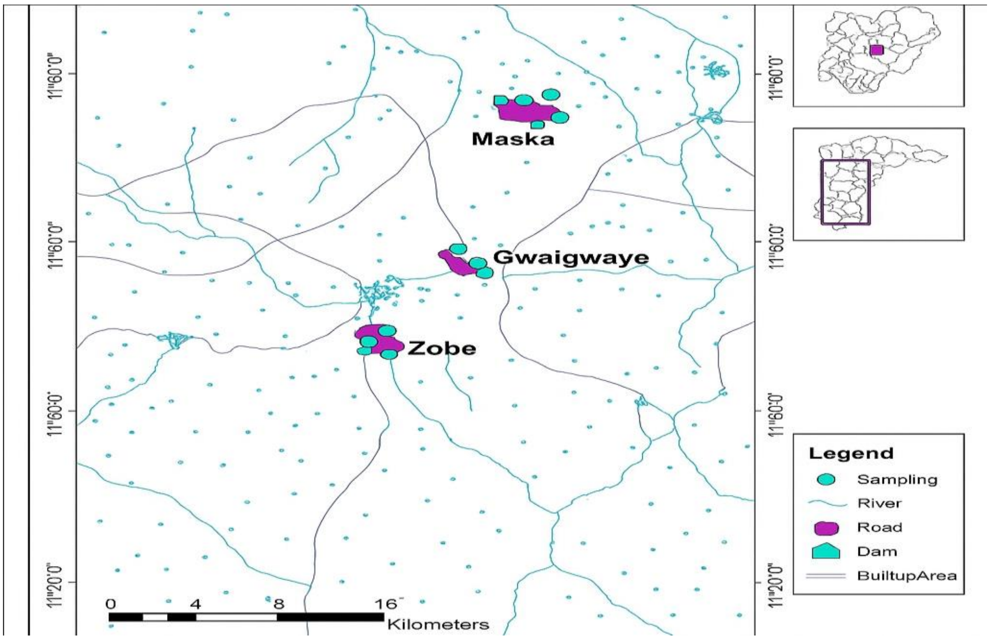

Fig. 1: Map showing Maska, Gwaigwaye, and Zobe Dams

2.2. Water samples collection

Water sampling was undertaken at five designated sites across Zobe Dam in both the rainy and dry seasons. Surface water was collected into pre-cleaned polythene bottles that had been washed with detergent, rinsed with deionized water, and conditioned on-site with dam water. Samples from the five points were pooled to produce a composite representative sample, preserved in ice during transport, and subsequently processed in the laboratory for digestion and analysis [8].

2.3. Fish samples collection

Sixty specimens of Nile tilapia (Oreochromis niloticus) and African catfish (Clarias gariepinus), representing different size classes and ecological niches, were systematically collected from Zobe Dam during the dry and wet seasons (April–August 2023). Species identity was verified by a taxonomic specialist at the Department of Animal Science, Bayero University, Kano. Head, muscle, and gill tissues were aseptically dissected with sterilized instruments, placed in pre-labeled polythene bags on ice, and swiftly transported to the laboratory for analysis in compliance with standard ethical procedures [9].

2.4. Digestion of water samples

We digested the Water samples (100 cm³) with concentrated HNO_3 on a sand bath at 100 °C, with incremental acid additions until the solutions were clear. The digests were filtered hot, cooled, and diluted to 100 cm³ with distilled water [10]. Metal concentrations were measured in triplicate using an Agilent Microwave Plasma Atomic Emission Spectrometer (MP-AES) equipped with an inert nebulizer and double-pass cyclonic spray chamber.

2.5. Analysis of some heavy metals using microwave plasma atomic emission spectroscopy(MPAES)

After digestion, the solutions were transferred into appropriately labeled cups, sealed, and introduced into the microwave plasma–atomic emission spectrometer (MP-AES) once the instrument had stabilized. Within the plasma torch, the samples were atomized and excited, causing the elements to emit characteristic wavelengths of light. Cd, Pb, Ni, and Zn concentrations were determined simultaneously, with analytical reliability maintained through the use of calibration standards, procedural blanks, and replicate measurements. All data were captured and processed via the MP-AES computer system [11].

Bioaccumulation describes the gradual accumulation of chemical substances — such as heavy metals or organic pollutants within the tissues of living organisms over time, often through exposure via water, food, or sediments. It occurs when the rate at which an organism absorbs or takes in a substance exceeds the rate at which it can eliminate or excrete it[12].

The Bioaccumulation Factor (BAF) is a quantitative measure that expresses the degree to which an organism accumulates a chemical from its surrounding environment relative to its concentration in the environment[13].

$$\{BAF\} = \frac{\text{Concentration of contaminant in the organism}}{\text{Concentration of contaminant in water or sediment}}$$

Where:
Concentration of contaminant in the organism (mg/kg or µg/g dry weight).
Concentration of contaminant in water or sediment (mg/L or µg/g).
Interpretation:

BAF < 1 → No significant accumulation.

1 < BAF < 1000 → Low accumulation.

1000 < BAF < 5000 → Bioaccumulative.

BAF > 5000 → Highly bioaccumulative[14].

2.6. Statistical analysis

The data from the two fish species were expressed as mean ± standard error and analyzed using one-way ANOVA in SPSS. Results showed no significant differences in metal concentrations between the species during both dry and wet seasons.

Table 1: ANOVA Results

Df	Sum Sq		Mean Sq			F value	Pr.(>F)	
Season Dry 1	0.0073		0.00725	0.557 0.46192		0.1223	0.06116	4.698
0.078 *								
Metals	0.8889		0.17777	13.655 1.09e-06 ***				
Residuals 27 0.3515.	0.01302							
Season Wet 1	0.0381		0.0381	2.965 0.0965.				
	2	0.0390		0.0195	1.518 0.2372			
Metals	3	1.7221		0.3444	26.809 1.12e-09 Residuals			
27 0.3469. 0.0128.								

3. Results

Table 2: The mean concentrations of selected heavy metals in water samples from Zobe dam in the dry and wet seasons.

Zobe dry Cd. Ni. Pb. Zn

ND ND. 0.03±0.00. ND. 0.06±0.02

Zobe wet. ND. 0.029±0.03. ND. 0.057±0.02

Table 3: Concentrations of Some Heavy Metals (Mg/Kg) in Catfish(Clarias gariepinus) Tissue in Zobe Dams in Dry Season.

Metals(mg/kg)	Cd	Ni	Pb	Zn
Gill	0.013±0.01	ND	0.003±0.00	0.143±0.003
Head	0.0196±0.03	0.2	0.323±0.003	0.29±0.03
Muscle	0.01±0.00	0.01±0.00	0.036±0.05	0.023±0.01

Table 4: Concentrations of Some Heavy Metals(Mg/Kg) in Catfish (Clarias gariepinus) Samples Collected from Zobe Dams in the Wet Season.

Metals(mg/kg)	Cd	Ni	Pb	Zn
Gill	0.057±0.02	0.019±0.01	ND	0.201±0.03
Head	0.019±0.01	0.0173±0.01	ND	0.32±0.01
Muscle	0.019±0.01	0.019±0.01	ND	0.057±0.02

Table 5: Concentrations of Some Heavy Metals (Mg/Kg) in Tilapia(Oreochromis Niloticus) Sample from Zobe Dam in Dry Season.

	Cd	Ni	Pb	Zn
Gill	0.013±0.001	0.072±0.01	0.003±0.03	0.32±0.003
Head	0.01±0.00	ND	ND	0.33±0.01
Muscle	0.002±0.003	ND	0.01±0.00	0.14±0.003

Table 6: Concentrations of Some Heavy Metals (Mg/Kg) in Tilapia(Oreochromis Niloticus) from Zobe Dam in Wet Season

Metals	Cd	Ni	Pb	Zn
Gill	0.057±0.02	0.019±0.01	ND	0.133±0.04
Head	0.027±0.01	0.12±0.02	ND	1.1±0.01

Muscle	0.020±0.01	0.041±0.01	ND	0.53±0.01

Table 7: Bioaccumulation Factors Some Heavy Metals in Catfish(Clarias gariepinus) Tissue from Zobe Dam in Dry Season

Metals	Cd	Ni	Pb	Zn
Gill	0.00	0.00	0.00	0.42
Head	0.00	6.7	0.00	0.19
Muscle	0.00	0.3	0.00	1.67

Table 8: Bioaccumulation Factors of Some Heavy Metals in Catfish(Clarias gariepinus) Tissues from Zobe Dam in Wet Season

Metals	Cd	Ni	Pb	Zn
Gill	0.00	0.66	0.00	2.33
Head	0.00	0.59	0.00	5.62
Muscle	0.00	0.66	0.00	1.00

Table 9: Bioaccumulation Factors of Some Heavy Metals in Tilapia Fish (Oreochromis Niloticus) Tissues from Zobe Dam in Dry Season

Metals	Cd	Ni	Pb	Zn
Gill	0.00	2.40	0.00	5.33
Head	0.00	0.00	0.00	5.50
Muscles	0.00	0.00	0.00	2.33

Table 10: Bioaccumulation Factors of Some Heavy Metals in Tilapia Fish(Oreochromis Niloticus) Tissues from Zobe Dam in Wet Season

Metals	Cd	Ni	Pb	Zn
Gill	0.00	0.66	0.00	2.33
Head	0.00	4.14	0.00	19.30
Muscles	0.00	1.41	0.00	9.30

Metal RfD (mg/kg/day) Cancer Slope Factor (CSF, mg/kg/day^{-1})
Oral reference doses
Cd 0.001 6.3
Ni 0.02 0.91 Cancer slope factors
Pb 0.0035 0.0085
Zn 0.3 – (non-carcinogenic)

$$EDI = C\times\frac{FIR}{BW} \quad (1)$$

$$THQ = \frac{EDI}{RFD} \quad (2)$$

$$HI = THQ\ (Cd) + THQ\ (Ni) + THQ\ (Pb) + THQ\ (Zn) \quad (4)$$

$$CR = CDI\times CSF \quad (5)$$

Where
FIR =Ingestion rate (FIR) = 0.04 kg/day
Body weight (BW) = 70 kg
EDI Estimated daily intake
CSF = Cancer slope factor
CR= Cancer Risk
C = Metal Concentration in the fish tissues
THQ = Hazard Quotients
HI Hazard indices.

Table 11: Catfish (Clarias Gariepinus) — Dry Season

Tissue		EDI	HQ.	CR.	HI
Gill	Cd	1.56E-06	0.0016	9.84E-06.	0.00176
	Ni	–	–	–	
	Pb	3.6E-07	0.0001	3.06E-09	
	Zn	1.72E-05	0.00006	–	
Head	Cd	2.35E-06	0.0024	1.48E-05.	0.0147
	Ni	2.4E-05	0.0012	2.18E-05	
	Pb	3.88E-05	0.011.	3.30E-07	
	Zn	3.48E-05	0.00012	–	
Muscle.	Cd	1.20E-06	0.0012	7.56E-06.	0.0025
	Ni	1.20E-06	0.00006	1.09E-06	
	Pb	4.32E-06	0.0012	3.67E-08	
	Zn	2.76E-06	0.000009	–	

Table 12: Catfish (Clarias Gariepinus) — Wet Season

Tissues.		EDI.	HQ.	CR.	HI
Gill	Cd	6.85E-06	0.0069	4.32E-05.	0.0071
	Ni	2.28E-06	0.00011	2.07E-06	
	Pb		–	–	–
	Zn 2.41E-05		0.00008	–	
Head	Cd	2.28E-06	0.0023	1.44E-05.	0.0025
	Ni	2.08E-06	0.0001	1.89E-06	

	Pb		–	–	–
	Zn	3.84E-05	0.00013	–	
Muscle		2.28E-06	0.0023	1.44E-05.	0.0024
	Ni	2.28E-06	0.00011	2.07E-06	
	Zn	6.84E-06	0.00002	–	

Table 13: Tilapia (Oreochromis Niloticus) — Dry Season

Tissues		EDI.	HQ	CR	HI
Gill	Cd	1.56E-06	0.0016	9.84E-06.	0.00223
	Ni	8.64E-06	0.00043	7.86E-06	
	Pb	3.6E-07	0.0001	3.06E-09	
	Zn	3.84E-05	0.00013	–	
Head	Cd	1.20E-06	0.0012	7.56E-06.	0.00133
	Ni	–	–	–	
	Pb		–	–	–
	Zn	3.96E-05	0.00013	–	
Muscle	Cd	2.40E-07	0.00024	1.51E-06.	0.00064
	Ni	–	–	–	
	Pb	1.20E-06	0.00034	1.02E-08	
	Zn	1.68E-05	0.00006	–	

Table 14: Tipia (Oreochromis Niloticus) — Wet Season

Tissue.		EDI	HQ	CR.	HI.
Gill	Cd	6.85E-06	0.0069	4.32E-05.	0.0071
	Ni	2.28E-06	0.00011	2.07E-06.	
	Pb		–	–	–
	Zn	1.60E-05	0.00005	–	
Head	Cd	3.24E-06	0.0032	2.04E-05.	0.00436
	Ni	1.44E-05	0.00072	1.31E-05	
	Pb		–	–	–
	Zn	1.32E-04	0.00044	–	
Muscle	Cd	2.40E-06	0.0024	1.51E-05.	0.00286
	Ni	4.92E-06	0.00025	4.48E-06	
	Zn	6.36E-05	0.00021	–	

3.1. Discussions

Cadmium (Cd)

Cd was not detected in the dam water during either season (Table 2), indicating concentrations below the permissible limit of 0.003 mg/L [15]. This suggests negligible human-induced inputs, such as industrial effluents or phosphate fertilizers, which are common Cd sources [16]. The absence of Cd is significant, given its high toxicity even at trace levels, with chronic exposure linked to kidney dysfunction, bone demineralization, and carcinogenicity [17].

In contrast, elevated Cd concentrations have been reported elsewhere, including 0.04 ± 0.01 mg/L in Dareta Stream [18], 0.64 ± 0.01 mg/L in Cika Koshi Reservoir [19], 0.331 ± 0.013 mg/L in Kaduna River [20], 0.288 mg/L in Wasai Reservoir, Kano State, and 0.9289 ± 0.095 mg/L in the Ionian Sea, Italy [21].

In fish tissues (Tables 3–6), Cd levels ranged from 0.002 ± 0.03 mg/kg in tilapia muscle (dry season) to 0.0571 ± 0.02 mg/kg in catfish gills (dry season) and tilapia gills (wet season). The elevated concentrations in gills are attributed to their direct contact with water and their role in metal uptake and gas exchange [9]. Muscle tissues consistently showed lower Cd levels, as Cd tends to accumulate in metabolically active and detoxifying organs rather than in muscles [36]. All values were well below the permissible limit of 1.0 mg/kg [15]. Comparatively, higher Cd levels have been recorded elsewhere: 0.18 mg/kg in tilapia muscle from Onuimo River [37], 0.383 mg/kg in fish muscle from Wasai Reservoir [38], 0.11 ± 0.01 mg/kg in tilapia head and non-detectable levels in some tissues from Badagry Creek [39], and 0.30 ± 0.00 mg/kg in tilapia muscle from an abandoned mining pond [27]. Internationally, Cd levels ranged from 0.0008 ± 0.001 mg/kg in fish muscle from the Ionian Sea, Italy [21], to 0.107 mg/kg in freshwater fish from Slovakia [40] and 0.26 mg/kg in fish gills from Temsah Lake, Egypt [41].

Nickel (Ni)

Ni concentrations in water (Table 2) declined slightly from 0.030 ± 0.00 mg/L in the dry season to 0.029 ± 0.00 mg/L in the wet season. Despite this minor reduction, both values exceeded the guideline of 0.02 mg/L [15], suggesting potential health risks. Elevated Ni levels may originate from geological weathering, leaching from surrounding soils, and agricultural runoff [22], while the slight seasonal decrease likely reflects rainfall dilution [23]. Chronic Ni exposure in drinking water has been linked to dermatitis, respiratory problems, and carcinogenic effects [24]. Comparable Ni concentrations have been reported in Gurara Dam (0.0276 mg/L) [25], River Hadejia (0.029 mg/L) [26], an abandoned mining pond (0.71 ± 0.02 mg/L) [27], and Warsak Dam, Pakistan (0.757 ± 0.465 mg/L) [28].

In fish tissues (Tables 3–6), Ni concentrations ranged from 0.01 ± 0.00 mg/kg in catfish muscle to 0.20 ± 0.01 mg/kg in catfish head during the dry season. Ni was undetectable in catfish gills (dry season) and tilapia head and muscle (wet season). Such variations reflect tissue-specific accumulation influenced by Ni's strong affinity for metallothionein-binding proteins [22]. The head region often shows higher accumulation due to the presence of metabolically active tissues such as the brain and sensory organs, which require metal-regulated enzymes. The observed seasonal differences, with higher Ni levels during the dry season, likely result from reduced water dilution [42]. All concentrations were within the permissible range of 0.5–0.6 mg/kg [15]. Comparable studies recorded 0.19 ± 0.01 mg/kg in tilapia gills from Badagry Creek [39], 0.59 ± 0.02 mg/kg in catfish muscle from an abandoned mining pond [27], and 38.7 mg/kg in Clupisoma species muscle from Pakistan [28].

Lead (Pb)

Pb was not detected in water during either season (Table 2), remaining below the permissible limit of 0.01 mg/L [15]. This absence suggests limited contamination from industrial discharges or Pb-based agrochemicals and highlights the dam's effective natural self-purification [29]. Pb is a highly toxic element associated with neurological impairment, hypertension, nephrotoxicity, and cognitive deficits in children

[17]. In comparison, 0.03 ± 0.02 mg/L was reported in Koramar Wanke, Gusau [30], and 0.422 ± 0.147 to 0.65 ± 0.24 mg/L in Challawa Dam, Kano State [31].

In fish tissues (Tables 3–6), Pb was found only in gills (0.003 ± 0.03 mg/kg) across both species and seasons, with no detection in heads or muscles. The occurrence in gills reflects direct waterborne exposure, while its absence in other tissues indicates low uptake or efficient physiological regulation [43]. All detected values were far below the permissible limit of 0.2–0.3 mg/kg [15]. Comparatively, Pb levels reported elsewhere include 0.16 mg/kg in tilapia muscle and 0.096 mg/kg in Challawa River, Kano State [31], 0.044 mg/kg in Wasai Reservoir [38], 0.49 mg/kg in tilapia gills from Bangladesh [44], and 5.21 mg/kg in farmed barramundi from the northern Bengal coast [45].

Zinc (Zn)

Zn concentrations in water (Table 2) slightly declined from 0.060 ± 0.01 mg/L in the dry season to 0.057 ± 0.02 mg/L in the wet season, both far below the 3.0 mg/L permissible limit [15]. This suggests no contamination risk, with the minor seasonal variation attributed to rainfall dilution and reduced runoff. Zn is an essential micronutrient vital for enzymatic functions, protein synthesis, and immune regulation; however, excessive exposure can cause gastrointestinal distress and impaired copper metabolism [32]. Reported Zn concentrations elsewhere include 0.151 ± 0.027 mg/L in Galma Dam, Zaria [33], 937.5 mg/L in Hashenge Lake, Tigray, Ethiopia [34], and 0.002 mg/L in the transboundary river Tangoar Hoar, Bangladesh [35].

In fish (Tables 3–6), Zn was detected in all tissues and both seasons, ranging from 0.036 ± 0.05 mg/kg in catfish muscle (dry) to 1.1 ± 0.01 mg/kg in tilapia head (wet). The higher Zn levels in the head and gills may be linked to their greater metabolic activity and the presence of Zn-dependent enzymes such as carbonic anhydrase and superoxide dismutase, which are vital for respiration, ion regulation, and antioxidant defense [46]. Ecologically, tilapia and catfish often feed near the bottom, where sediment ingestion exposes them to Zn-rich detritus and microorganisms, enhancing uptake [47]. Seasonal increases during the wet season likely result from nutrient runoff from surrounding farmland and increased microbial cycling [48]. All Zn values were well below the 10 mg/kg permissible limit [15]. For comparison, Zn levels reported elsewhere include 1.6 ± 0.2 mg/kg in catfish muscle from Niger State [49], 0.088 mg/kg in Challawa River [31], 24.80 mg/kg in barramundi from Bengal [45], 19.30 ± 2.08 mg/kg in tilapia muscle from the Ionian Sea [21], 24.945 mg/kg in fish from Hashenge Lake, Ethiopia [33], and 1.05 ± 0.30 mg/kg in Barbus xanthopterus gills [50].

The bioaccumulation of nickel, lead, and zinc in the tissues of Clarias gariepinus (catfish) and Oreochromis niloticus (tilapia) displayed clear tissue-, species-, and season-dependent patterns (Tables 7–10).

The bioaccumulation factors (BAF) for the studied metals ranged from <1 to <20, indicating that metal uptake by fish was generally minimal to low. According to USEPA guidelines, BAF values <1 indicate no contamination, while values between 1 and 1000 indicate low contamination [14], confirming that Zobe Dam fish experience only limited metal accumulation (Table 7).

Cadmium (Cd): Cd did not bioaccumulate in any tissue of catfish or tilapia across both seasons, with all bioaccumulation factor (BAF) values below 1 (Table 8). This absence reflects Cd's poor assimilation in fish due to its strong binding affinity for gill mucus, which limits internal transfer and tissue deposition [51]. Efficient detoxification and excretion mechanisms further restrict retention [22]. These results confirm Cd's low tissue accumulation compared to other metals. In contrast, a BAF of 0.088 was reported in tilapia gills from Challawa River, Kano State [31], 366 in fish muscle from Hangzhou Bay, China [52], and 0.000861 in tilapia muscle from the Ionian Sea, Italy [21].

Nickel (Ni): Ni showed the highest bioaccumulation potential among the metals studied (Table 9). The maximum BAF (6.7) occurred in catfish head during the dry season, followed by 2.4 in tilapia gills. The lowest values were recorded in catfish muscle, while Ni was absent in catfish head and muscle during the wet season. The preferential accumulation in head and gills is likely due to their vascularization and direct exposure to waterborne Ni [53]. Higher BAFs observed during the dry season likely reflect reduced dilution of pollutants from decreased water volume [54] and have been similarly noted for other studies. Other studies have reported considerably higher BAFs, including 36.07 and 3.93 in tilapia muscle from Egypt [55], 17.24 and 310.34 in tilapia and catfish muscles from Nigeria [26], and 51.12 in Clupisoma fish muscle from Warsak Dam, Pakistan [28].

Lead (Pb): Pb did not bioaccumulate in either species (BAF < 1) (Table 9). This can be explained by its strong affinity for gill mucus, which restricts uptake and systemic distribution [56], together with efficient detoxification and excretion mechanisms that limit tissue accumulation [57]. These findings indicate Pb's low tendency for tissue retention. In contrast, [37] reported a BAF of 0.05 for Pb in tilapia muscle from Challawa River, Kano State, while [58] recorded a slightly higher value of 0.51 in the same location. Internationally, [43] reported a BAF of 0.069 for Pb in tilapia gills from Bangladesh.

Zinc (Zn): Zn was the only element that consistently bioaccumulated in all tissues (Table 10). The highest BAF (19.3) was found in tilapia head during the wet season, followed by 9.3 in tilapia muscle, while the lowest occurred in catfish head during the dry season. Greater Zn uptake in tilapia likely reflects its omnivorous, sediment-ingesting feeding habits [46]. Seasonal increases in wet-season BAFs may be linked to Zn-rich agricultural and domestic runoff [47]. Unlike Cd and Pb, Zn is an essential micronutrient, and its distribution across tissues corresponds to its key roles in enzymatic and metabolic functions [45]. Reported BAFs elsewhere include 0.027 in fish muscle from Hashenge Lake, Ethiopia [33] and 22.22 in gills of grey mullet from the Ionian Sea, Italy [21].

Pattern of Bioaccumulation

Across metals: Ni > Zn > Pb (Pb showed no bioaccumulation).

Across tissues, accumulation followed the trend head and gills > muscle, reflecting exposure pathways and tissue-specific affinity. Between species, tilapia > catfish, with tilapia showing consistently higher Zn levels. Seasonally, Ni accumulated more in the dry season, while Zn bioaccumulation was higher in the wet season, likely due to runoff inputs. Cd showed no bioaccumulation in any tissue of either species across both seasons, with all BAF values < 1, consistent with USEPA guidelines and indicating no significant contamination.

Table 15: Summary table for Bioaccumulation Factors (BAF) trend

Metal	Bioaccumulation Pattern:	Highest BAF Observed,	Lowest BAF Observed	General Conclusion
Cd	No accumulation in any species, tissue, or season	0.00	0.00	Cd does not bioaccumulate in Zobe Dam fish.
Ni	Tissue- and species-dependent; highest in catfish head (dry season)	6.7. (Catfish Head, Dry)	0.00.	Moderate Ni accumulation; seasonal effect evident
Pb	No accumulation across all samples	0.00	0.00	Pb uptake is negligible; no tissue retention.
Zn:	Only metal with consistent accumulation; notably high in tilapia tissues.	19.3 (Tilapia Head, Wet)	0.19 (Catfish Head, Dry)	Zn accumulation is significant, species- and season-dependent

All the computed HQ values for the assessed metals (Cd, Ni, Pb, and Zn) were below unity, and the cumulative HI values for each tissue, season, and species were likewise substantially less than one (Tables 11–14). This demonstrates that consumption of fish from Zobe Dam presents no immediate non-carcinogenic health risk for adults when evaluated under the assumed ingestion rate (0.04 kg day^{-1}) and reference body weight (70 kg).

These low HQ and HI values are consistent with the observations of Oboh & Okpara (2019) [59], who similarly reported HQ values below unity in fish from Nigerian rivers, indicating minimal health risks for local populations. Likewise, Adegbola et al. (2021)[60] found HI values less than one for most heavy metals in fish from rivers affected by industrial activities, suggesting exposure levels within acceptable safety thresholds. The present findings therefore correspond with national benchmarks, supporting the view that moderate consumption of fish from non-industrialized freshwater systems generally falls within safe health limits (Tables 11–14).

Multiple factors account for the low HQ and HI values obtained (Tables 11–14). The moderate ingestion rate and the use of a 70 kg reference body weight reduce the exposure dose per unit mass. The conversion factor (0.21) also lowers the effective daily intake. Additionally, metal concentrations in the edible muscle tissues were comparatively low, resulting in correspondingly small EDI values. Since HQ is directly proportional to EDI, this relationship explains the consistently low hazard indices across species and seasons.

Carcinogenic Risk (CR)

The CR values calculated for the potentially carcinogenic metals (Cd, Ni, and Pb) were all below the acceptable risk range of 10^{-6}–10^{-4}, indicating negligible lifetime carcinogenic risk (Tables 11–14). This pattern aligns with the findings of [59], who documented similarly low CR values for Cd and Pb in fish from Nigerian freshwater systems. When compared with other Nigerian and international studies, the carcinogenic risk associated with fish from Zobe Dam appears relatively favourable (Table 14). For instance,[60] reported substantially higher THQ and HI values for Pb and Cd in Clarias gariepinus and Sarotherodon melanotheron from the industrially contaminated Ogun and Eleyele Rivers, with several indices exceeding unity and indicating potential non-carcinogenic health concerns. Furthermore, in more heavily industrialized environments such as the Ogun River, carcinogenic risk values for certain metals exceeded 10^{-4} [60], underscoring the profound influence of site-specific contamination on long-term cancer risk. Comparable trends have been reported internationally; for example, [61] documented CR values above recommended screening thresholds in some fish tissues from Idku Lake, Egypt, again highlighting the impact of localized contamination. Conversely, [62] found all THQ and HI values below unity in ten commercial fish species from Konya, Türkiye, suggesting no major non-carcinogenic concerns for consumers. Collectively, these comparisons demonstrate that metal-related health risks associated with fish from Zobe Dam are lower than those reported for more polluted aquatic systems.

The relatively low CR values observed in this study likely reflect the limited industrial effluent entering the reservoir and the predominantly rural nature of its catchment. Because CR is determined by EDI and the cancer slope factor, the low EDI values recorded here constitute the primary mechanism behind the favourable CR outcomes (Tables 11–14).

Internationally,[62] evaluated ten commercial fish species from Konya and reported THQ and HI values below one, indicating minimal non-carcinogenic risk, although some species exhibited elevated carcinogenic risk (CR) associated with inorganic arsenic.[63], In assessing heavy-metal-related human health risks from fish in the Buriganga River, Bangladesh, found that individual THQs for heavy metals were generally below unity, suggesting low non-carcinogenic risk; however, the combined hazard indices exceeded one, and the target cancer risks (TCR) for Ni and As were within levels of concern. In South Korea, [64] also reported HQ and HI values below one for Pb, Cd, and Hg in fishery products, indicating low non-carcinogenic risk to consumers. In contrast, assessments from heavily industrialized regions of North China have documented occasional HI values exceeding unity for fish, suggesting potential health risks [65].

Collectively, these comparative findings indicate that fish from Zobe Dam exhibit lower exposure and health-risk potentials than those from more industrially or agriculturally impacted water bodies, consistent with the reservoir's relatively unpolluted and rural catchment (Tables 11–14).

4. Conclusion

The concentrations of cadmium (Cd), nickel (Ni), lead (Pb), and zinc (Zn) in both water and selected tissues (gill, head, and muscle) of Clarias gariepinus (catfish) and Oreochromis niloticus (tilapia) from Zobe Dam were found to be below the permissible limits established by FAO/WHO. The bioaccumulation factors (BAFs) for all metals across the analyzed tissues of both species ranged from no significant contamination to low contamination, as classified by the United States Environmental Protection Agency (USEPA).

Furthermore, the estimated daily intake (EDI) values for all analyzed metals were below their respective oral reference doses (RfD), while the calculated hazard quotient (HQ) and hazard index (HI) values were all less than one, indicating no potential non-carcinogenic risk from the consumption of these fish species. Similarly, the carcinogenic risk (CR) values for Cd, Ni, and Pb were below the acceptable threshold range (10^{-6}–10^{-4}), confirming negligible lifetime cancer risk to consumers.

Overall, these findings indicate minimal bioaccumulation, low exposure risk, and safe consumption levels of Clarias gariepinus and Oreochromis niloticus from Zobe Dam. The results further suggest that the reservoir is characterized by low ecological and public health risks associated with trace metal contamination, reflecting a relatively unpolluted aquatic environment suitable for sustainable fishery and human use.

4.1. Recommendations

Based on the findings on heavy metal bioaccumulation in the tissues of Tilapia and Catfish, the following recommendations are hereby made:

1) Regulatory and Policy Measures

Stricter effluent discharge regulations should be enforced by relevant authorities, permissible limits should be harmonized with international standards (FAO/WHO/USEPA), and routine monitoring of water bodies and fish tissues should be established.

2) Aquaculture and Fisheries Practices

Safe aquaculture practices should be adopted, including the use of uncontaminated water sources, regular monitoring of feed quality, and periodic testing of fish tissues before distribution. Biofiltration systems and constructed wetlands should be applied to minimize pollutant entry into aquaculture environments.

3) Public Health and Community Engagement

Early warning systems should be implemented by public health agencies, communities should be sensitized to the risks of consuming contaminated fish, and dietary diversification should be encouraged to minimize prolonged exposure. Pollution incidents should be promptly reported, and community-based monitoring initiatives should be supported.

4) Research and Capacity Building

Further research on biomarkers of heavy metal exposure should be undertaken, low-cost and portable monitoring tools should be developed, and training workshops on pollution management and food safety should be organized for farmers, regulators, and health workers.

5) Consumers and Food Safety

Fish should be sourced from certified and monitored markets, safe preparation practices, such as the removal of gills and viscera (where metals accumulate), should be encouraged, and dietary protein sources should be diversified to minimize health risks.

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