



Environmental and Health Implications of Heavy Metal Exposure in *Oreochromis niloticus* from Sabke Reservoir Katsina State, Nigeria

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KEYWORDS

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ABSTRACT

This study assessed heavy metal contamination (Cd, Cr, Cu, Ni, Pb, and Zn) in water, sediment, and *Oreochromis niloticus* tissues from Sabke Reservoir, Katsina State, Nigeria, over six months (June–November 2024) at three stations. Water and sediment samples were analysed using APHA protocols, while fish gills, liver, and muscle were analysed by Atomic Absorption Spectrophotometry (AAS). The liver accumulated the highest concentrations, particularly Cr (1.08 ± 0.64 mg/kg) and Pb (4.21 ± 2.59 mg/kg), while gills recorded the highest Zn (0.068 ± 0.035 mg/kg) and positive correlations with sediment-derived Cr ($r = 0.623$, $p < 0.05$) and Ni ($r = 0.789$, $p < 0.01$). Muscle recorded the lowest concentrations. Health risk assessment indicated significant non-carcinogenic risks from Cr (HQ = 4.79) and Pb (HQ = 9.49), exceeding the safe threshold of 1.0. Carcinogenic risks for Cr (CR = 7.18×10^{-3}) and Cd (CR = 1.14×10^{-4}) exceeded the acceptable level of 1×10^{-4} . Bioaccumulation Factor analysis confirmed accumulation of Cd (BAF = 1.51) and Ni (BAF = 1.06). Histopathology revealed epithelial loss and lamellar detachment in gills, hepatic congestion and hepatocellular necrosis, and slight muscle fibre fragmentation, indicating chronic tissue stress. The findings demonstrate significant heavy metal pollution with ecological and human health implications through fish consumption, attributed to agricultural runoff, improper waste disposal, and illegal mining. Continuous monitoring, public awareness, stringent regulation, and sustainable agricultural and industrial practices are recommended.

CITATION

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INTRODUCTION

The study of heavy metal concentrations and their potential effects on *Oreochromis niloticus* addresses important environmental and public health concerns associated with aquatic pollution in Sabke Reservoir, Katsina State, Nigeria. Heavy metals are persistent environmental contaminants that can accumulate in aquatic organisms and may be transferred through aquatic food webs, thereby creating potential ecological and human health concerns (Emon *et al.*, 2023). Fish are particularly useful in environmental assessment because they can accumulate contaminants from water, sediment and dietary sources, while tissue-specific accumulation can provide information about environmental exposure and internal metal burden. Preserving aquatic ecosystem health is essential for maintaining ecological balance, biodiversity and the availability of fish as a source of food. Assessment of contaminant concentrations and their biological effects in economically important fish species can therefore provide useful information for evaluating ecological risks and potential human-health implications. Histopathological alterations in fish tissues are also useful indicators of environmental stress because they reflect the biological effects of exposure to contaminants over time (Abdel-Moneim *et al.*, 2012; Dane, 2025). In particular, the gills and liver are sensitive organs for detecting pollutant-induced effects because of their direct environmental exposure and roles in respiration, osmoregulation, metabolism and detoxification.

The assessment of heavy metals in fish consumed by local communities is important for evaluating potential dietary exposure and supporting appropriate environmental-management measures. Previous studies have demonstrated that heavy-metal accumulation in fish can present potential health risks to consumers depending on the concentration of metals, consumption rate and duration of exposure (Emon *et al.*, 2023; Ibrahim *et al.*, 2024). Therefore, the present study was designed to determine the concentrations of selected heavy metals in

Oreochromis niloticus from Sabke Reservoir, Mai'adua, Katsina State, Nigeria, and to assess their potential health implications and associated histopathological alterations.

MATERIALS AND METHODS

Study Area

The study was conducted in Sabke Reservoir, located between latitude 12°57'30"–13°05'N and longitude 8°11'00"–8°14'E, approximately 451m above sea level and about 35 km northwest of Daura, Katsina State, Nigeria. The reservoir was formed through the impoundment of the seasonal Bulbula and BabbarRuga rivers, located around Mai'adua and Mashi Local Government Areas, respectively (Bala and Abdullahi, 2011; Suleiman and Rabi'u, 2024). The reservoir is also supported by smaller streams and receives water from surrounding drainage systems. Sabke Reservoir has an active storage capacity of approximately 31.60 million m³ and a flood-storage capacity of about 56 million m³ (Suleiman and Rabi'u, 2024). The reservoir was developed partly for irrigation, with approximately 1,000 hectares proposed for dry-season farming using a surface-lift irrigation system (Zango and Rafindadi, 2015; Suleiman and Rabi'u, 2024). Agricultural activities, fishing and domestic uses constitute important uses of the reservoir and its surrounding environment (Suleiman and Rabi'u, 2024).

Sampling Stations and Water Sampling

Three sampling stations were established within Sabke Reservoir to provide spatial coverage of the study area. Station S1 represented the upstream section, S2 represented the middle section, and S3 represented the downstream section of the reservoir. The geographical coordinates of the sampling stations were recorded using a GPS device and were 13°01'12.0"N, 8°10'12.0"E (S1), 13°01'48.0"N, 8°09'36.0"E (S2), and 13°03'36.0"N, 8°09'00.0"E (S3), respectively. The stations were selected based on accessibility, variation in water depth and their potential exposure to anthropogenic influences.

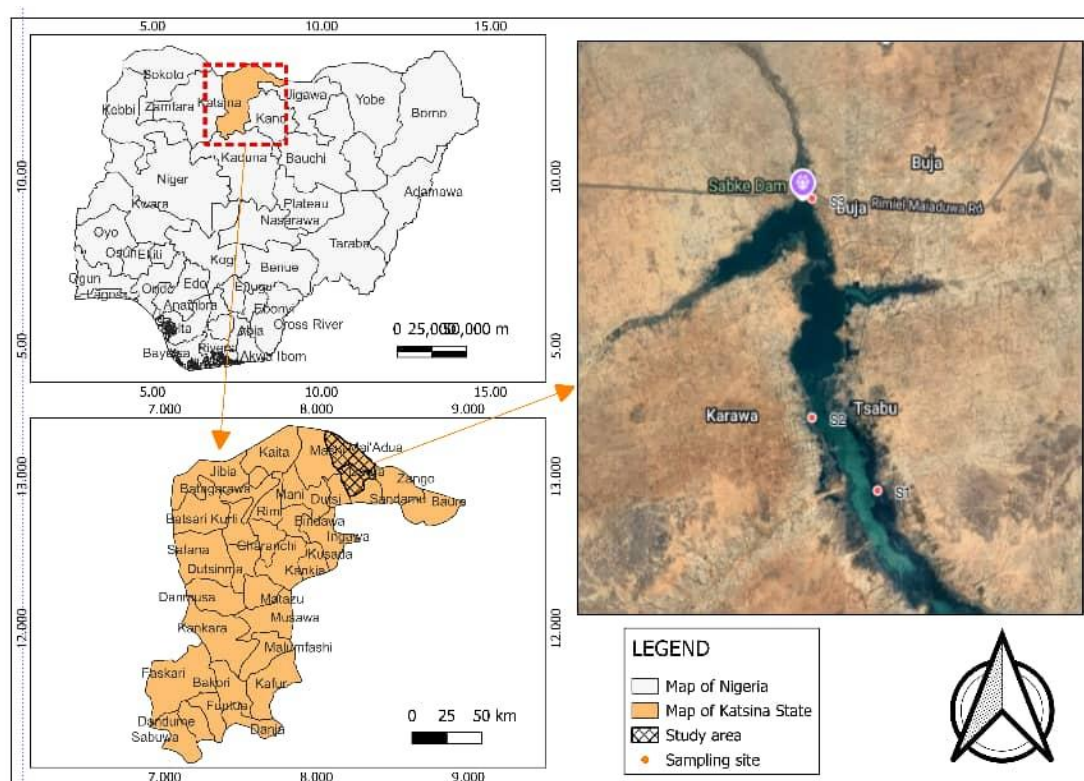


Figure 1: Map of Nigeria showing Katsina State and the sampling area/sites

Study Design

This study was conducted over a period of six months, from June to November 2024. Sampling was carried out fortnightly. Fish specimen *Oreochromis niloticus* samples were collected for the analysis of selected heavy metals (Cd, Cr, Cu, Ni, Pb, and Zn) across all stations named as stations S1, S2 and S3.

Collection of water sample for heavy metals analysis

Water samples were collected from the three sampling stations between 7:00 a.m. and 12:00 noon from June to November 2024. Sampling was conducted fortnightly for the assessment of heavy metals.

Collection of Sediment Samples

Surface sediment samples were collected from the three designated sampling stations using a stainless-steel grab sampler. At each station, three replicate samples were obtained and combined to form a representative composite sample. The upper 5 cm of the sediment layer was targeted, as surface sediments are known to reflect recently deposited contaminants and are widely used in aquatic pollution assessments. Samples were transferred into clean polyethylene bags, properly labeled according to sampling location, and transported to the laboratory for further processing and analysis. Comparable sediment-sampling methods have been reported in recent Nigerian studies on heavy-metal contamination in aquatic systems (Ehiemere *et al.*, 2022; Bwala *et al.*, 2023).

Collection of Fish Samples for Heavy-Metal Analysis

A total of 60 *Oreochromis niloticus* specimens were collected from local fishermen at landing sites around Sabke Reservoir during the study period, with approximately 20 specimens obtained from each sampling station. Fish of different sizes were collected to provide representative samples of the fish population available for consumption within the study area. The specimens were transported to the laboratory for tissue preparation and analysis.

Fish Sample Digestion Procedure

The fish specimens were rinsed with distilled water to remove adhering materials. The muscles, liver and gills were carefully excised, dried in an oven at 105°C for 24 hours and subsequently ground using a clean mortar and pestle. Approximately 2g of each homogenized tissue sample was transferred into a digestion vessel and treated with 5 mL of nitric acid (HNO₃) and 2 mL of hydrochloric acid (HCl). The samples were heated on a hot plate at approximately 85°C for 30 minutes until digestion was completed. After cooling, the digested samples were filtered into 50-mL volumetric flasks and made up to volume with distilled water. The resulting solutions were transferred into pre-cleaned sample bottles and stored appropriately until instrumental analysis. (Yi *et al.*, 2011).

Water Sample Digestion

Water samples were prepared for heavy-metal analysis using an acid digestion procedure. Briefly, 100 mL of each well-mixed water sample was transferred into a digestion vessel and treated with concentrated nitric acid (HNO₃). The samples were heated on a hot plate under controlled conditions until complete digestion was achieved and a clear solution was obtained. After cooling, the digests were filtered and diluted to a final volume of 100 mL with distilled water. The resulting solutions were transferred into clean, labeled containers and preserved until instrumental analysis. Acid digestion followed by Atomic Absorption Spectrophotometry (AAS) is a well-established method for metal determination in aquatic samples and has been widely applied in recent Nigerian studies (Ogan, 2023; Mustapha *et al.*, 2022).

Sediment Sample Digestion

Sediment samples were prepared for heavy-metal analysis using an aqua regia digestion procedure. The collected samples were first oven-dried at 60 °C for 24 hours to remove moisture. The dried sediments were then disaggregated, homogenized using a porcelain mortar and pestle, and sieved to obtain a uniform fine fraction. Approximately 1.0 g of each homogenized sample was weighed into a digestion vessel, after which 10 mL of freshly prepared aqua regia (a mixture of concentrated hydrochloric acid (HCl) and nitric acid (HNO₃) in a 3:1 ratio) was added. The mixture was heated on a hot plate until digestion was nearly complete and the volume was reduced close to dryness. After cooling, the digest was filtered and quantitatively transferred into a 50 mL volumetric flask, then made up to volume with distilled water. The final solutions were stored in appropriately labeled containers pending heavy-metal analysis. Aqua regia digestion followed by AAS determination has been widely used in recent studies assessing heavy metals in sediments from Nigerian aquatic environments (Ehiemere *et al.*, 2022; Ogan, 2023; Caroline *et al.*, 2023).

Heavy Metal Analysis

The concentrations of selected heavy metals, namely cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn), were determined in the gills, liver and muscle tissues of *Oreochromis niloticus*. Analysis was performed using a Buck Scientific Model 230 Atomic Absorption Spectrophotometer (AAS) at the Central Laboratory, Umaru Musa Yar'Adua University, Katsina State, Nigeria.

Health-Risk Assessment

The potential long-term health risks associated with consumption of *Oreochromis niloticus* contaminated with heavy metals were evaluated using average daily dose (ADD), hazard quotient (HQ) and carcinogenic risk (CR).

The assessment followed established approaches for evaluating human exposure to heavy metals through fish consumption (Yi *et al.*, 2011; Emon *et al.*, 2023).

Average Daily Dose (ADD)

The average daily dose of each heavy metal was estimated using:

$$ADD = (C \times IR \times EF \times ED) / (BW \times AT)$$

where:

- C = concentration of the heavy metal in fish tissue (mg/kg);
- IR = fish ingestion rate (kg/day);
- EF = exposure frequency (365 days/year);
- ED = exposure duration (70 years);
- BW = average body weight (60 kg); and
- AT = averaging time.

For non-carcinogenic effects, the averaging time corresponds to the exposure duration expressed in days, whereas for carcinogenic risk assessment, lifetime averaging time is generally used.

Non-Carcinogenic Risk

The potential non-carcinogenic risk associated with consumption of contaminated *Oreochromis niloticus* was estimated using the hazard quotient:

$$HQ = ADD / RfD$$

where:

- HQ = hazard quotient;
- ADD = average daily dose; and
- RfD = oral reference dose for the respective heavy metal.

An HQ value greater than 1 is generally interpreted as indicating a potential non-carcinogenic health concern, whereas an HQ below 1 suggests that adverse non-carcinogenic effects are less likely under the assumptions of the exposure assessment (Yi *et al.*, 2011; Emon *et al.*, 2023).

Histopathological Examination

Histopathological evaluation was performed on the gills, liver and muscle tissues of *Oreochromis niloticus*. Immediately after dissection, tissue samples were fixed in 10% formal saline for 48 hours. The fixed tissues were subsequently dehydrated through ascending concentrations of alcohol, cleared in xylene, infiltrated with paraffin wax and embedded. Sections approximately 5 µm thick were obtained using a rotary microtome and stained with haematoxylin and eosin (H and E) for microscopic examination. The histopathological assessment was conducted to identify structural alterations associated with environmental stress and contaminant exposure. Histological examination of fish gills and liver is widely used in aquatic pollution studies because these organs are sensitive to environmental contaminants (Abdel-Moneim *et al.*, 2012; Al-Ghanim *et al.*, 2019; Yacoub *et al.*, 2021; Dane, 2025).

Data Analysis

Data obtained from the study were entered and coded using Microsoft Excel and subsequently analyzed using Statistical Package for the Social Sciences (SPSS). Descriptive statistics were used to summarize the results as mean $\pm$ standard deviation. Differences in heavy-metal concentrations among sampling stations and sampling months were evaluated using analysis of variance (ANOVA) at a 95% confidence level ($p \leq 0.05$). Pearson correlation analysis was used to evaluate relationships among heavy-metal concentrations in fish tissues, water and sediment. The resulting correlation coefficients were interpreted as measures of association and were not considered evidence of direct causation.

RESULTS AND DISCUSSION

Heavy Metal Concentrations in Tissues of *Oreochromis niloticus* from Sabke Reservoir

The analysis of heavy metal concentrations in *Oreochromis niloticus* from Sabke Reservoir as showing in

Figure 2, showed variation across different tissues. The cadmium (Cd) concentrations were highest in the liver (0.043 ± 0.029 mg/kg), followed by the gills (0.042 ± 0.030 mg/kg) and muscles (0.036 ± 0.031 mg/kg). Zinc (Zn) concentrations were highest in the gills (0.068 ± 0.035 mg/kg), followed by the liver (0.024 ± 0.008 mg/kg) and muscles (0.022 ± 0.008 mg/kg). Chromium (Cr) concentrations were considerably elevated, especially in the gills (2.23 ± 1.38 mg/kg) and muscles (1.72 ± 0.62 mg/kg), with lower levels in the liver (1.08 ± 0.64 mg/kg). Copper (Cu) accumulation was most pronounced in the liver (0.19 ± 0.13 mg/kg), with lower concentrations in the muscles (0.014 ± 0.014 mg/kg) and gills (0.015 ± 0.008 mg/kg). Nickel (Ni) concentrations were highest in the liver (0.097 ± 0.053 mg/kg), followed by the gills (0.089 ± 0.068 mg/kg) and muscles (0.070 ± 0.053 mg/kg). Lead (Pb) concentrations were notably high in the liver (4.21 ± 2.59 mg/kg), followed by muscles (3.99 ± 2.91 mg/kg), and gill with (3.24 ± 2.82 mg/kg).

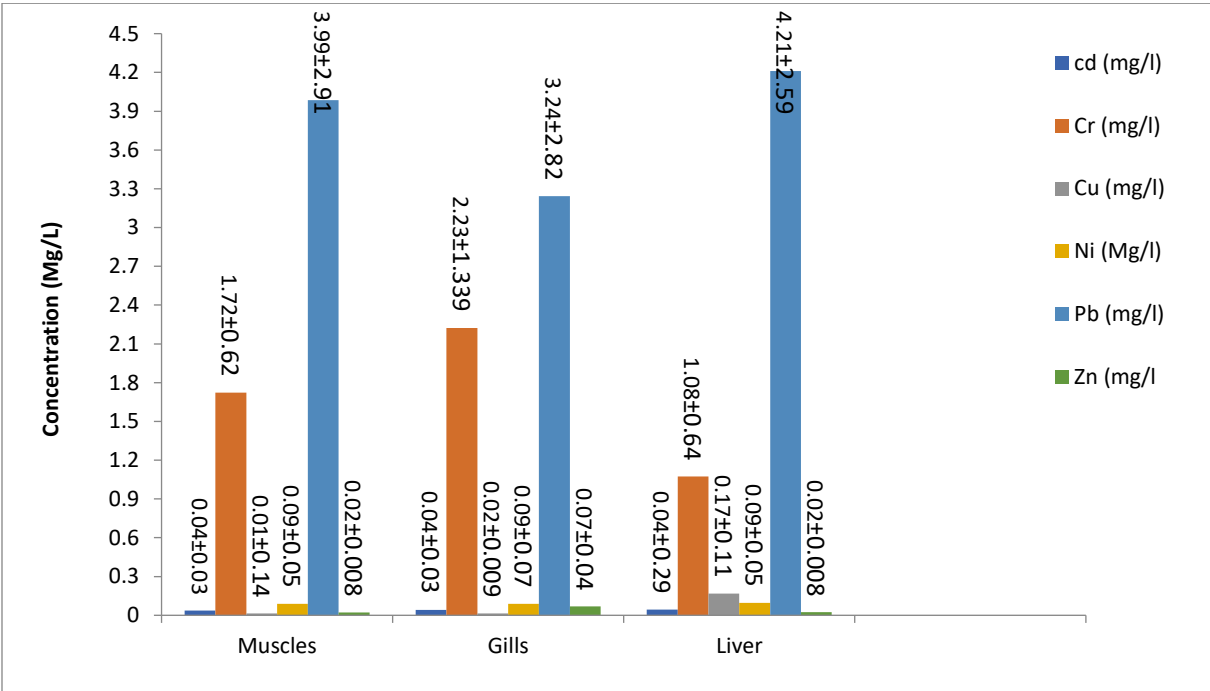


Figure 2: Mean concentrations of heavy metals in tissues of *Oreochromis niloticus* from Sabke Reservoir

Correlation Coefficient of Heavy Metals in Water, Sediment and Tissues of *Oreochromis niloticus*

As shown in Table 1 In *Oreochromis niloticus*, the muscle tissue did not show statistically significant correlations with water or sediment metal levels, underscoring its limited role as a biomarker for recent exposure. Gills displayed significant positive correlations with sediment-derived Cr ($r = 0.623$, $p < 0.05$) and Ni ($r = 0.789$, $p < 0.01$), highlighting direct uptake from resuspended particulates. Conversely, sediment Cu correlated negatively with gill Cu ($r = -0.778$, $p < 0.01$), and waterborne Pb showed a negative

relationship with gill Ni ($r = -0.861$, $p < 0.01$). The liver showed strong associations with sediment metals, especially Cr ($r = 0.585$, $p < 0.05$), indicating long-term storage. An antagonistic interaction was noted between sediment Zn and liver Cu ($r = -0.720$, $p < 0.01$).

The health risk assessment of tissues of *Oreochromis niloticus* in Sabke Reservoir

Table 2 shows the health risk assessment in *Oreochromis niloticus* from Sabke Reservoir which reveals that Chromium (Cr) and Lead (Pb) pose significant non-

carcinogenic health risks, with HQ values of 4.79 and 9.49 respectively, both exceeding the safety threshold of 1.0. Cadmium (Cd) is also near the threshold with an HQ of 0.30. Zinc (Zn), Nickel (Ni), and Copper (Cu) have HQ values well below 1, indicating minimal risk. In terms of cancer risk, Chromium shows the highest CR at 7.18×10^{-3} , far exceeding the acceptable lifetime risk level (1×10^{-4}). Cadmium and Lead also present concerning CR values (1.14×10^{-4} and 2.82×10^{-5} , respectively). In contrast, CR values for Zn, Cu, and Ni are extremely low, suggesting negligible cancer risk from these metals.

Histopathological examination in *Oreochromis niloticus* from Sabke Reservoir

Histopathological examination of *Oreochromis niloticus* revealed varying degrees of tissue alterations in the gills, liver, and muscle tissues. The gills showed loss of epithelium and lamellar detachment (Plate I), indicating structural disruption of the respiratory surface. The liver exhibited vascular congestion and necrosis of hepatocytes (Plate II), suggesting cellular and tissue damage. In the muscle tissue, slight fragmentation of muscle fibres was observed (Plate III), indicating mild structural alteration.

Table 1: Correlation Coefficient of Heavy Metals in Water and Sediment and the Tissues of *Oreochromis niloticus*

		Water						Sediment					
		Cd	Zn	Cr	Cu	Ni	Pb	Cd	Zn	Cr	Cu	Ni	Pb
Muscles	Cd	0.15	0.415	0.006	-0.186	-0.275	0.313	-0.251	0.053	-0.443	-0.243	0.29	0.302
	Zn	0.063	0.269	0.012	-0.322	-0.286	0.134	0.117	-0.016	-0.31	-0.506	0.155	0.365
	Cr	-0.2	-0.382	-0.059	-0.07	0.03	0.033	0.491	-0.521	0.024	-0.112	-0.372	-0.157
	Cu	0.032	0.21	0.004	-0.418	-0.333	0.09	0.209	-0.063	-0.244	-0.504	0.142	0.391
	Ni	-0.046	-0.177	0.146	-0.347	-0.044	-0.258	0.255	0.27	0.567	-0.146	0.017	0.065
	Pb	0.101	0.306	-0.027	-0.205	-0.29	0.386	-0.21	-0.137	-0.451	-0.117	0.218	0.221
Gills	Cd	0.12	0.354	-0.079	-0.147	-0.296	0.313	-0.306	-0.107	-0.482	0.042	0.283	0.243
	Zn	0.005	-0.039	0.109	0.17	0.259	-0.422	0.177	0.458	0.353	-0.311	-0.078	-0.002
	Cr	-0.244	-0.475	-0.164	0.371	0.354	-.589*	.623*	-0.283	0.21	0	-0.499	-0.222
	Cu	-0.198	-0.279	-0.386	0.013	-0.158	-0.192	0.259	-.778**	-0.263	.618*	-0.163	-0.021
	Ni	-0.263	-0.362	-0.356	0.13	0.066	-.861**	.789**	-0.427	0.029	0.038	-0.34	0.132
	Pb	0.188	0.43	0.017	-0.164	-0.288	0.469	-0.517	0.059	-0.418	0.075	0.377	0.197
Liver	Cd	0.14	0.375	-0.066	-0.161	-0.308	0.337	-0.383	-0.062	-0.454	0.108	0.329	0.237
	Zn	0.122	0.113	0.223	-0.45	-0.272	.648*	-0.464	0.095	0.136	0.197	0.292	-0.047
	Cr	-0.159	-0.263	-0.068	0.303	0.303	-0.436	.585*	-0.117	0.058	-0.408	-0.415	-0.08
	Cu	-0.157	-0.258	-0.221	-0.105	-0.17	0.153	0.167	-.720**	-0.221	0.425	-0.161	-0.099
	Ni	0.062	-0.076	0.288	-0.326	-0.069	0.5	-0.301	0.18	0.393	0.119	0.113	-0.206
	Pb	0.178	0.421	-0.014	-0.153	-0.292	0.413	-0.499	0.04	-0.422	0.118	0.378	0.211

Table 2: Average Daily Dose (ADD), Non – Cancer Risk (HQ), Cancer Risk (CR) and Bioaccumulation Factor (BAF) of *Oreochromis niloticus* from Sabke Reservoir

Metal	ADD (mg/kg/day)	HQ	CR	BAF
Cd	0.000300	0.300	1.14×10^{-4}	1.51
Cr	0.014356	4.785	7.18×10^{-3}	0.93
Cu	0.000119	0.003	2.25×10^{-17}	0.64
Ni	0.000733	0.037	7.40×10^{-16}	0.25
Pb	0.033208	9.488	2.82×10^{-5}	1.06
Zn	0.000189	0.001	1.15×10^{-10}	0.47

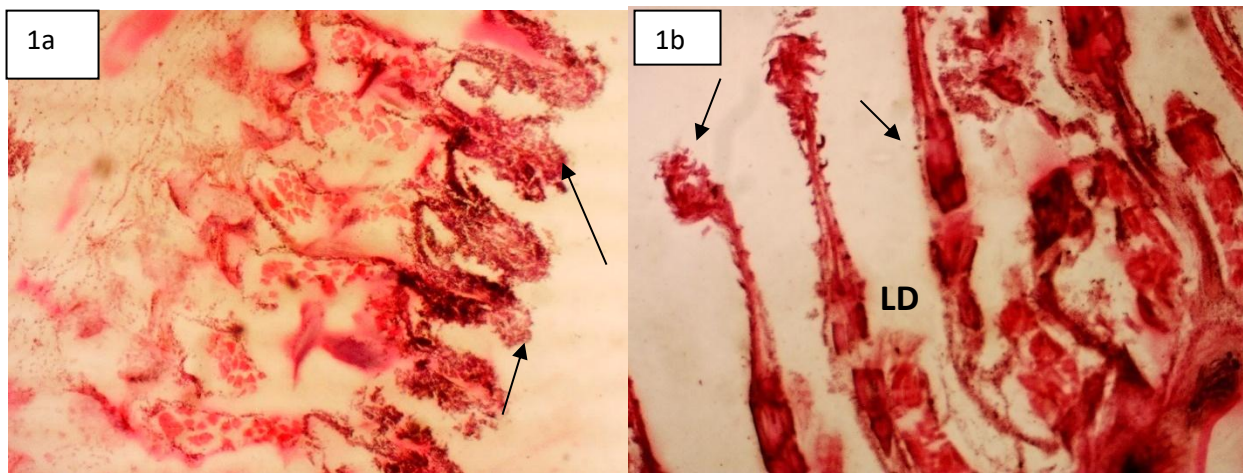


Plate 1: Photomicrograph of gills of *Oreochromis niloticus* in the Sabke Reservoir

Plate 1a: Photomicrograph of gills of *Oreochromis niloticus* showing loss of epithelia (arrows). H And E x 100

Plate 1b: Photomicrograph of gills of *Oreochromis niloticus* showing lamellar detachment (LD). H And E x 100

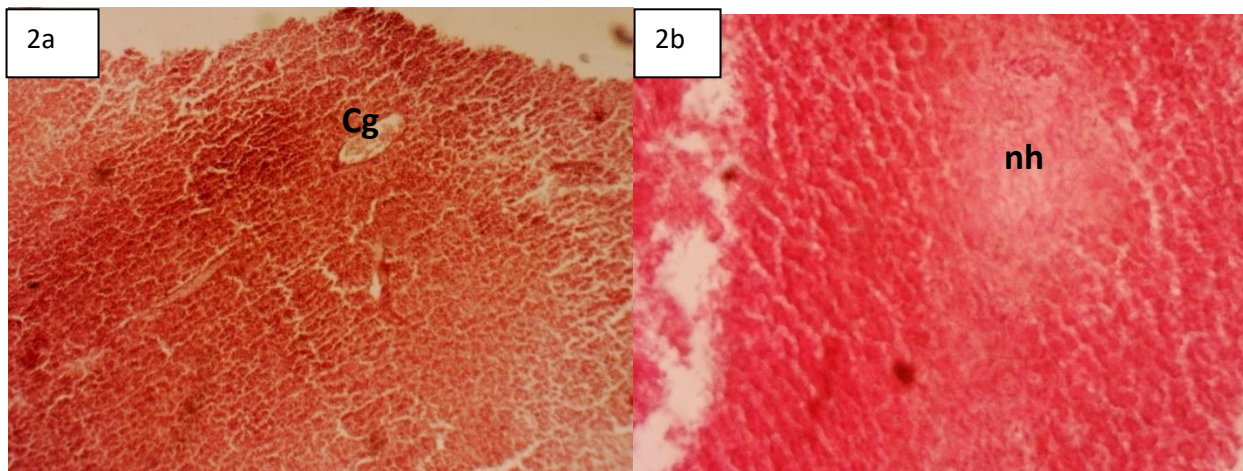


Plate 2: Photomicrograph of liver of *Oreochromis niloticus* in the Sabke manmade Reservoir

Plate 2a: Photomicrograph of liver of *Oreochromis niloticus* showing congestion (cg). H And E x 100.

Plate 2b: Photomicrograph of liver of *Oreochromis niloticus* showing necrotic hepatocytes (nh). H And E x 100

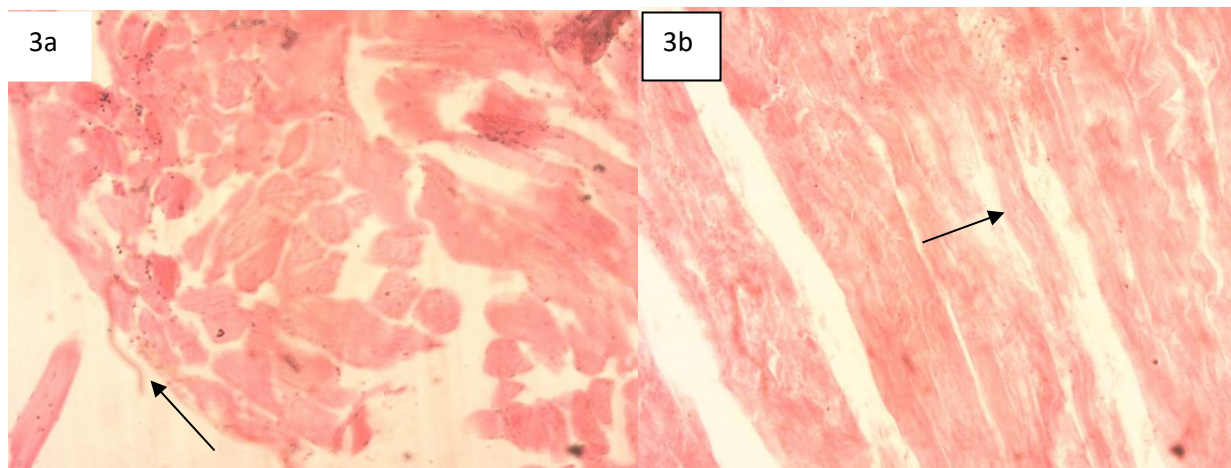


Plate 3: Photomicrograph of muscles of *Oreochromis niloticus* in the Sabke manmade Reservoir

Plate 3a: Photomicrograph of muscles of *Oreochromis niloticus* showing Note slightly fragmented muscle fibres (arrow). H And E x 100

Plate 3b: Photomicrograph of muscles of *Oreochromis niloticus* showing Note slightly fragmented muscle fibres (arrow). H And E x 100.

Discussion

The mean concentrations of heavy metals detected in *Oreochromis niloticus* from Sabke Reservoir indicate that the fish are exposed to varying levels of metal contamination, with Pb representing the most prominent contaminant. The highest mean concentration was recorded for Pb (3.81 ± 2.72 mg/kg), which exceeded the 2 mg/kg value commonly reported as the maximum permissible concentration for Pb in fish. This elevated Pb burden may constitute a potential food-safety concern for communities that depend on fish from the reservoir. Heavy metals can enter aquatic systems through a combination of anthropogenic activities and can subsequently become available to aquatic organisms through water, sediments and food-chain pathways. Emon *et al.*, (2023) emphasized that heavy metals can bioaccumulate in fish tissues and may subsequently be transferred through the food chain, creating ecological and human-health concerns. Chromium concentrations were also relatively high, particularly in the gills (2.23 ± 1.38 mg/kg) and muscle (1.72 ± 0.62 mg/kg). The relatively high concentration in gills may be associated with the direct and continuous contact of this organ with the surrounding water. Gills are important sites of interaction between fish and their aquatic environment and are therefore particularly susceptible to pollutants. Studies on *Oreochromis niloticus* have demonstrated that environmental metal exposure can result in substantial metal accumulation and pathological changes in gill tissues (Abdel-Moneim *et al.*, 2012; Yacoub *et al.*, 2021). In addition, heavy-metal exposure has been associated with impaired physiological functions, including growth and reproduction, in fish (Emonet *et al.*, 2023). The relatively large variability observed in hepatic Cu concentration (0.166 ± 1.12 mg/kg) may indicate spatial or temporal differences in Cu exposure within the reservoir. Copper is an essential trace element required for several physiological processes; however, excessive exposure can result in toxic effects in aquatic organisms. The comparatively lower concentrations of Zn (0.038 ± 0.029 mg/kg) and Ni (0.091 ± 0.057 mg/kg) indicate lower tissue burdens than those recorded for Pb and Cr. Nevertheless, the presence of these metals demonstrates that *Oreochromis niloticus* is exposed to a mixture of trace elements rather than to a single contaminant. Emonet *et al.*, (2023) noted that metal accumulation in fish varies according to the type of metal, exposure conditions, environmental availability and physiological characteristics of the fish. The results obtained in Sabke Reservoir can also be compared with findings from other reservoirs in northern Nigeria. Ibrahim *et al.*, (2024) reported the occurrence of heavy metals, including Ni and Pb, in *Oreochromis niloticus* from Ajiwa Reservoir, Katsina State, and identified potential health risks associated with fish consumption. Similarly, Adenuga *et al.*, (2022) assessed heavy metals in sediment and fish, including

Oreochromis niloticus, from Bonny Estuary and demonstrated the importance of evaluating metal accumulation in fish tissues in relation to human-health risks. Differences in metal concentrations among reservoirs may be associated with differences in catchment characteristics, pollutant sources, sediment properties, water chemistry and the biological characteristics of the fish populations.

The tissue-specific bioaccumulation pattern observed in *Oreochromis niloticus* provides further insight into the interaction between environmental metal concentrations and fish physiology. Muscle tissue did not show statistically significant correlations with metal concentrations in either water or sediment. This observation may reflect the relatively lower and less dynamic accumulation of some metals in muscle compared with metabolically active organs such as the liver and gills. Emon *et al.*, (2023) reported that heavy-metal accumulation differs considerably among fish tissues and that organs involved in metabolism, detoxification and direct environmental exchange may accumulate metals differently from muscle tissue. Because muscle is the principal tissue consumed by humans, however, its metal concentration remains important for assessing dietary exposure even when it does not closely reflect recent environmental contamination. The gills of *Oreochromis niloticus* exhibited significant positive correlations with sediment-derived Cr ($r = 0.623$, $p < 0.05$) and Ni ($r = 0.789$, $p < 0.01$). These relationships suggest that sediment-associated Cr and Ni may contribute to the metal burden of gills, although the correlation does not by itself establish a direct causal pathway. The gills have a large surface area and remain continuously exposed to the aquatic environment, making them an important interface for contaminant uptake. Yacoub *et al.*, (2021) similarly demonstrated substantial accumulation of several metals in the gills of tilapia species and reported associated histopathological changes. A significant negative correlation was observed between sediment Cu and gill Cu ($r = -0.778$, $p < 0.01$). This inverse relationship may reflect differences in metal bioavailability, physicochemical conditions, uptake and elimination processes, or physiological regulation. However, it should not be interpreted as direct evidence of a specific detoxification mechanism because correlation analysis alone cannot establish the underlying physiological process. Similarly, the strong negative correlation between waterborne Pb and gill Ni ($r = -0.861$, $p < 0.01$) may indicate interactions among environmental and physiological factors influencing metal uptake and accumulation. Such relationships demonstrate that tissue concentrations may not always vary proportionally with total environmental metal concentrations. The liver showed a significant positive association with sediment-derived Cr ($r = 0.585$, $p < 0.05$). This finding is consistent with the recognized role

of the liver in metabolism, detoxification and storage of contaminants. The liver can accumulate metals following prolonged exposure and may therefore provide useful information about the internal metal burden of fish. Emonet *et al.*, (2023) emphasized that fish organs differ in their ability to accumulate and regulate heavy metals. Similarly, Yacoub *et al.*, (2021) reported accumulation of several metals, including Cr, Pb, Cd, Ni, Cu and Zn, in tilapia tissues and documented associated histopathological changes in the liver, gills and muscles. The significant negative correlation between sediment Zn and liver Cu ($r = -0.720$, $p < 0.01$) may indicate interactions between environmental metal availability and physiological regulation. Competition among trace metals for uptake, transport and binding sites is one possible explanation; however, the present correlation analysis cannot confirm a specific metallothionein-mediated mechanism. Therefore, the relationship is better interpreted as evidence of an interaction between Zn exposure and hepatic Cu accumulation rather than definitive evidence of competitive binding.

The health-risk assessment further indicates that consumption of *Oreochromis niloticus* from Sabke Reservoir may warrant attention. The calculated hazard quotient (HQ) values for Cr and Pb were above 1, with values of 4.79 and 9.49, respectively, indicating potential non-carcinogenic health risks under the assumptions of the exposure model. In contrast, Cd produced a lower HQ value of 0.30, suggesting a comparatively lower non-carcinogenic risk. Ibrahim *et al.*, (2024) similarly reported potential health risks associated with consumption of *Oreochromis niloticus* from Ajiwa Reservoir, Katsina State, following assessment of heavy-metal exposure. The bioaccumulation factor (BAF) results further showed significant accumulation of Cd (BAF = 1.51) and Ni (BAF = 1.06) in *Oreochromis niloticus*. BAF values greater than one indicate that the concentration in the fish is greater than the corresponding environmental concentration used in the calculation and may indicate bioaccumulation. However, the interpretation of BAF should take into consideration the environmental matrix used, metal bioavailability and the physiological characteristics of the fish. Emon *et al.*, (2023) emphasized that bioaccumulation is influenced by metal-specific properties, environmental conditions, exposure pathways and species-specific physiological processes. The carcinogenic-risk assessment showed that the CR values for Cr and Cd exceeded the commonly applied acceptable lifetime cancer-risk level of 1×10^{-4} , with Cr producing the highest estimated risk (7.18×10^{-3}) in *Oreochromis niloticus*. These results indicate that long-term consumption of fish containing the measured concentrations of these metals may present potential carcinogenic concerns under the assumptions of the risk model. Similar concerns have been reported for fish from contaminated aquatic

environments. Adenuga *et al.*, (2022), for example, assessed heavy-metal contamination and associated human-health implications in *Oreochromis niloticus* from Bonny Estuary.

Histological examination of *Oreochromis niloticus* from Sabke Reservoir revealed pathological alterations in the gills, liver and muscle tissues. The observed lesions included epithelial loss and lamellar detachment in the gills, congestion and hepatocellular necrosis in the liver, and slight fragmentation of muscle fibres. Histopathology is widely used as a biological indicator of environmental pollution because tissue alterations integrate the effects of contaminants over time and can provide evidence of physiological stress (Abdel-Moneim *et al.*, 2012; Dane, 2025). The loss of gill epithelium and lamellar detachment observed in the present study indicate disruption of normal gill architecture. Because the gills are directly exposed to the surrounding water and perform essential respiratory, ionic and osmoregulatory functions, they are particularly vulnerable to aquatic contaminants. Abdel-Moneim *et al.*, (2012) documented histopathological alterations in the gills and liver of *Oreochromis niloticus* collected from polluted wetland environments, supporting the usefulness of these organs as indicators of aquatic pollution. More recently, Aldoghachi *et al.*, (2025) reported bioaccumulation and structural and histological changes in the gills of *Oreochromis niloticus* following exposure to heavy metals, further demonstrating the sensitivity of gill tissue to metal-induced stress. The liver of *Oreochromis niloticus* showed congestion and hepatocellular necrosis. The liver is a major organ involved in metabolism, detoxification and the processing of substances absorbed from the aquatic environment. Consequently, prolonged exposure to contaminants may result in hepatic cellular injury. Abdel-Moneim *et al.*, (2012) reported histopathological alterations in the liver of *Oreochromis niloticus* from polluted aquatic environments, while Yacoub *et al.*, (2021) documented relationships between heavy-metal accumulation and histopathological changes in the liver of tilapia. The hepatocellular necrosis observed in the present study may therefore reflect cellular stress associated with exposure to environmental contaminants, including the heavy metals detected in the reservoir. Although the present study focused on heavy metals, other environmental contaminants may also contribute to histological alterations. Hamed *et al.*, (2021), for example, reported hepatic vacuolation, degeneration and deformation in *Oreochromis niloticus* exposed experimentally to heavy metals. This demonstrates that histopathological lesions in fish may result from multiple environmental stressors and should therefore not be attributed exclusively to one contaminant without supporting experimental evidence. The findings of Yacoub *et al.*, (2021) are particularly relevant to the present study because the authors reported accumulation of Fe, Zn, Cu,

Mn, Pb, Cd and Ni in tilapia tissues and associated histopathological alterations in the gills, liver and muscles. Similarly, Al-Ghanim *et al.*, (2019) reported mercury accumulation and histological changes in the gills, liver, muscles and skin of *Oreochromis niloticus*. These findings support the interpretation that prolonged exposure to environmental metals can be associated with structural alterations in fish tissues. The muscle tissue in the present study exhibited comparatively mild alterations, characterized by slight fragmentation of muscle fibers. Yacoub *et al.*, (2021) also documented histopathological changes in the muscles of tilapia associated with heavy-metal accumulation, while Al-Ghanim *et al.*, (2019) reported histological alterations in skeletal muscle following mercury exposure. The relatively mild muscle alterations compared with those observed in the gills and liver may reflect differences in tissue sensitivity, exposure pathways and physiological functions. Overall, the more pronounced lesions observed in the gills and liver suggest that these tissues may provide more sensitive histological indicators of environmental stress than muscle tissue

CONCLUSION

The elevated levels of heavy metals in Sabke Reservoir can be attributed to various anthropogenic activities, including improper waste disposal, agricultural runoff, and industrial discharges. In Katsina State, illegal mining and armed banditry have been identified as significant contributors to heavy metal pollution, affecting both aquatic and terrestrial ecosystems. These activities not only contaminate water bodies but also pose direct health risks to local communities relying on these resources. The findings from Sabke Reservoir, corroborated by studies in Katsina State and other regions, highlight the urgent need for comprehensive environmental monitoring and public health interventions. Regular assessment of heavy metal concentrations in water bodies and aquatic organisms is crucial. Public awareness campaigns and policy measures aimed at regulating industrial activities and waste management practices are essential to mitigate the risks associated with heavy metal contamination. Implementing stringent environmental regulations and promoting sustainable agricultural and industrial practices can significantly reduce the influx of heavy metals into aquatic ecosystems. Moreover, educating local communities about the potential health risks associated with consuming contaminated fish can aid in reducing exposure and safeguarding public health.

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