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Tissue-Specific Bioaccumulation of Zinc, Lead, Copper, Cadmium and Manganese in *Clarias gariepinus* from Lake Alau, Northeastern Nigeria

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Abstract

Heavy metal contamination of freshwater ecosystems poses significant ecological and public health concerns due to the persistence, toxicity, and bioaccumulative nature of these pollutants. This study investigated the tissue-specific bioaccumulation of zinc (Zn), lead (Pb), copper (Cu), cadmium (Cd), and manganese (Mn) in the gills, liver, and muscle tissues of Clarias gariepinus collected from Lake Alau, Borno State, Nigeria, between January 2025 and June 2026. Fish samples were obtained monthly from artisanal fishermen, and heavy metal concentrations were determined using Flame Atomic Absorption Spectrophotometry (FAAS) following acid digestion. The data were analyzed using descriptive statistics and one-way analysis of variance (ANOVA) at a significance level of $P < 0.05$. Results revealed significant tissue-specific variations in metal accumulation, with the liver recording the highest concentrations, followed by the gills and muscles (Liver > Gills > Muscle). The overall order of metal abundance was Zn > Mn > Cu > Cd > Pb. Mean concentrations (mg kg^{-1} wet weight) in liver tissues were Zn (0.49 ± 0.05), Pb (0.30 ± 0.03), Cu (0.45 ± 0.05), Cd (0.31 ± 0.03), and Mn (0.46 ± 0.05). Zinc was the predominant essential metal, whereas lead and cadmium concentrations in the edible muscle tissues exceeded the permissible limits recommended by WHO/FAO, indicating potential health risks associated with fish consumption. One-way ANOVA showed significant differences ($P < 0.001$) among tissues for all metals analyzed. The findings demonstrate that C. gariepinus is an effective bioindicator of heavy metal pollution in Lake Alau and suggest that anthropogenic activities within the lake catchment contribute to metal contamination. Continuous environmental monitoring and effective pollution control measures are therefore recommended to safeguard aquatic ecosystem health and protect consumers from heavy metal exposure.

Keywords: Clarias gariepinus; heavy metals; bioaccumulation; Lake Alau; atomic absorption spectrophotometry; food safety; aquatic pollution; Nigeria.

Introduction

Aquatic ecosystems are increasingly threatened by anthropogenic pollutants resulting from rapid industrialization, urbanization, agricultural intensification, and population growth. Among the various classes of environmental contaminants, heavy metals have received considerable attention because of their persistence, toxicity, non-biodegradable nature, and capacity to accumulate in living organisms. Once introduced into aquatic systems, heavy metals may remain in water, sediments, and biota for extended periods, thereby posing significant ecological and human health risks (Ali *et al.*, 2019). The persistence and bioaccumulative nature of heavy metals make them particularly important environmental contaminants because they can enter aquatic food chains and eventually reach humans through the consumption of contaminated aquatic organisms (Emon *et al.*, 2023).

Heavy metals occur naturally in the environment through geological weathering, volcanic activities, and erosion processes. However, anthropogenic activities such as mining, industrial effluent discharge, agricultural runoff, municipal wastewater disposal, and atmospheric deposition have significantly increased their concentrations in aquatic ecosystems beyond natural background levels (Sharma *et al.*, 2024). These metals may accumulate in sediments and subsequently become bioavailable to aquatic organisms, particularly fish, through direct absorption from water, ingestion of contaminated food, and uptake from sediments (Singh & Sharma, 2024).

Fish are widely recognized as excellent bioindicators of aquatic pollution because they occupy different trophic levels and have the ability to accumulate contaminants in their tissues over time. Bioaccumulation refers to the uptake and retention of contaminants from the surrounding environment at concentrations higher than those present in water or sediments. The accumulation of heavy metals in fish tissues depends on several factors, including metal bioavailability, water chemistry, feeding habits, age, size, trophic position, and metabolic activities of the fish species (Jabeen *et al.*, 2024). The liver, gills, and muscles are among the most important organs used in biomonitoring studies because they exhibit different capacities for metal uptake, storage, and detoxification. The liver is an important organ for detoxification and metabolism and may accumulate considerable concentrations of heavy metals, while the muscles are of particular concern because they constitute the major edible portion of fish consumed by humans (Emon *et al.*, 2023; Jabeen *et al.*, 2024).

Heavy metals are broadly classified into essential and non-essential elements. Essential metals such as zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), and cobalt (Co) play important physiological roles in enzyme activation, metabolism, cellular functions, and growth. Nevertheless, these metals may become toxic when their concentrations exceed physiological requirements. In contrast, non-essential metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) have no established essential physiological role and may induce severe toxic effects when organisms are exposed to elevated concentrations (Ali *et al.*, 2019). Excessive exposure to toxic heavy metals has been associated with oxidative stress, cellular damage, carcinogenicity, mutagenicity, neurotoxicity, reproductive impairment, and developmental abnormalities in aquatic organisms and humans (Singh & Sharma, 2024).

Among aquatic organisms, freshwater fish are particularly susceptible to heavy-metal contamination because they are continuously exposed to pollutants through their gills, skin, and digestive systems. The gills represent one of the major routes of metal uptake because of their large surface area and intimate contact with the surrounding water. Following absorption, heavy metals may be transported and accumulated in different organs depending on the physicochemical characteristics of the metal, exposure duration, fish species, and tissue function (Emon *et al.,* 2023). Prolonged exposure to elevated concentrations of heavy metals may alter respiratory functions, impair growth and reproduction, induce physiological and histopathological changes, and reduce the health and survival of fish populations (Sharma *et al.,* 2024; Singh & Sharma, 2024). Furthermore, contaminated fish may transfer toxic metals to humans through dietary exposure, thereby posing substantial public-health concerns, particularly in communities that depend heavily on fish as a source of animal protein (Emon *et al.,* 2023).

Globally, numerous studies have documented elevated concentrations of heavy metals in freshwater fishes inhabiting contaminated aquatic ecosystems. The distribution of metals among fish tissues is often species-specific and influenced by environmental conditions, feeding behaviour, trophic position, and the physicochemical properties of individual metals (Jabeen *et al.,* 2024). Studies of fish tissues have demonstrated that heavy metals can show different patterns of accumulation among organs, with metabolically active organs such as the liver and organs directly exposed to the surrounding environment, such as the gills, frequently showing substantial metal burdens (Emon *et al.,* 2023). These findings highlight the importance of tissue-specific assessments in evaluating ecological risks and food-safety concerns associated with fish consumption.

In Nigeria, freshwater ecosystems are increasingly threatened by anthropogenic pressures, including agricultural expansion, urban runoff, domestic waste disposal, industrial activities, and unsustainable exploitation of natural resources. Lake Alau, located in Borno State, is an important freshwater reservoir in northeastern Nigeria and supports various human activities, including fisheries and other domestic and agricultural uses. Previous investigations have documented the physicochemical characteristics and elemental composition of Lake Alau, indicating the influence of human activities within the lake and its surrounding environment (Usman *et al.*, 2014a). The lake also supports a variety of fish species of economic and nutritional importance, including Clarias gariepinus (Usman *et al.,* 2014b). Consequently, increasing anthropogenic activities within the catchment area may contribute to deterioration of water quality and the introduction of potentially toxic metals into the aquatic environment.

Evidence of heavy-metal contamination in the Lake Alau environment has also been reported. Bwala (2023) assessed heavy metals in sediments, water, and Clarias gariepinus from Alau Dam, Borno State, and demonstrated the presence of heavy metals in components of the aquatic ecosystem. Similarly, Dimari and Hati (2009) investigated the distribution of arsenic, cadmium, chromium, and lead in different tissues of fish species collected from Lake Alau, including Clarias lazera. Their findings demonstrate the importance of investigating metal accumulation in different fish tissues and provide an important basis for continued monitoring of heavy-metal contamination in Lake Alau (Dimari & Hati, 2009; Bwala, 2023).

Despite the ecological and socio-economic importance of Lake Alau, information on the tissue-specific bioaccumulation of heavy metals in commercially important fish species remains limited. Clarias gariepinus (African catfish) is an important fish species occurring in Lake Alau and has considerable nutritional and economic value (Usman *et al.*, 2014b). Its ecological characteristics, including its association with bottom habitats and ability to tolerate varying environmental conditions, make it potentially useful for monitoring aquatic contamination. Previous studies on Lake Alau have

investigated heavy metals in water, sediments, and fish tissues (Dimari & Hati, 2009; Bwala, 2023); however, continued assessment is necessary to establish the current concentrations and tissue distribution of metals of environmental and public-health importance in C. gariepinus.

Therefore, this study was designed to determine the concentrations of zinc (Zn), lead (Pb), copper (Cu), cadmium (Cd), and manganese (Mn) in the gills, liver, and muscle tissues of Clarias gariepinus collected from Lake Alau, Nigeria. The study further evaluated temporal variations in metal concentrations and examined the implications of heavy-metal accumulation for environmental quality and public health.

MATERIALS AND METHODS

Study Area

Lake Alau is located in Borno State, northeastern Nigeria and was created in 1985 by impounding River Ngadda. The lake occupies an area of approximately 56 km² and serves as a major source of potable water for Maiduguri metropolis, irrigation for over 8,000 ha of agricultural land, fisheries production and livestock watering. The area is characterized by a Sahelian climate with three distinct seasons: the rainy season (June–September), the Harmattan season (October–February), and the hot dry season (March–May). Water levels are generally lowest during the dry season, exposing large portions of the littoral zone.

The major source of inflow into Lake Alau is the seasonal River Ngadda, supplemented by runoff from adjacent catchments. Rivers Yedzeram and Gombole also contribute to the lake hydrology through their connection with the Sambisa wetlands. The lake receives an estimated annual inflow of approximately 239 million cubic metres of water.

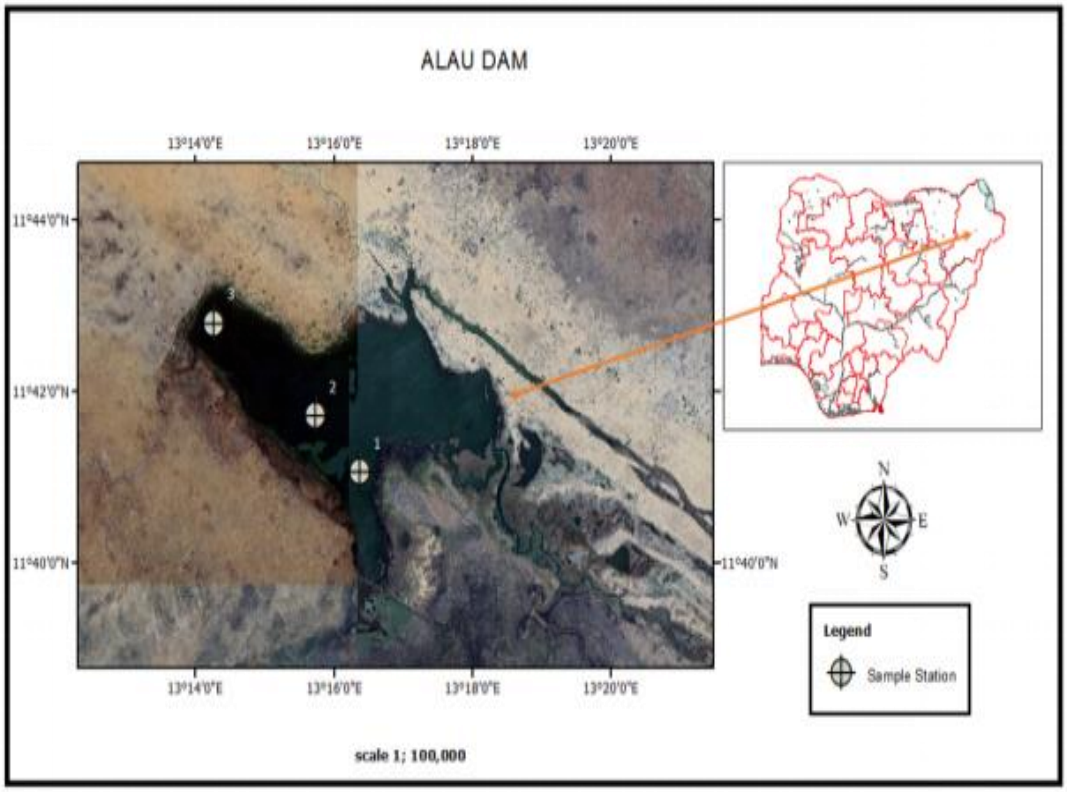


Figure 1: Ecological Map of Lake Alau Showing the Three Stations and their Prominent Features

Sampling Stations

Three sampling stations were selected based on accessibility, ecological characteristics, anthropogenic activities, and security considerations.

Station 1: This station is situated approximately 500 m from the shoreline and serves as the principal landing site for artisanal fishermen. The station is characterized by intensive fishing activities, livestock watering, educational and research activities, and water abstraction by the Borno State Water Board. The water width is approximately 255 m.

Station 2: This station is located near Alau town and is characterized by moderate fishing activities, irrigation farming, and domestic water use. The water is relatively deeper and faster flowing than at other stations, with an approximate width of 102 m.

Station 3: This station is situated approximately 500 m north of Daban Ali Zaki. It is characterized by artisanal fishing, canoe transportation and sand excavation activities, which may influence water quality and sediment characteristics.

Fish Collection and Preservation

Fish samples of *Clarias gariepinus* were obtained monthly from artisanal fishermen operating within Lake Alau between January 2025 and June 2026. Three specimens were collected during each sampling period at Station 1, which serves as the major fish landing site in the lake.

Immediately after collection, fish samples were placed in clean ice boxes and transported to the laboratory for analysis. Standard morphometric measurements, including total length and body weight, were recorded prior to dissection.

Sample Preparation and Digestion

The gills, liver, and muscle tissues were carefully excised using sterilized stainless-steel instruments. Approximately 5 g of each tissue sample was weighed and digested according to the procedures described by Olaifa *et al*. (2004) and APHA (2022).

The samples were digested using a freshly prepared mixture of concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) in a 1:1 ratio. The digestion vessels were covered with watch glasses to minimize contamination and heated on a water bath at 150–160°C for approximately 2 h until a clear solution was obtained.

After cooling, the digests were filtered and transferred into 50 mL volumetric flasks. The final volume was adjusted with deionized water and stored in acid-washed polyethylene bottles pending analysis.

Heavy Metal Analysis

The concentrations of zinc (Zn), lead (Pb), copper (Cu), cadmium (Cd), and manganese (Mn) were determined using Flame Atomic Absorption Spectrophotometry (FAAS).

All reagents used were of analytical grade. Instrument calibration was carried out using certified standard solutions, while reagent blanks and duplicate analyses were employed to ensure quality assurance and quality control.

Metal concentrations were expressed as mg/kg wet weight (ww).

Statistical Analysis

The data obtained were analysed using descriptive statistics and one-way Analysis of Variance (ANOVA). Results are presented as mean ± standard deviation (SD). Statistical significance was determined at $P < 0.05$.

Heavy Metal Concentrations in Gill Tissues

The monthly mean concentrations of Zn, Pb, Cu, Cd and Mn in the gills of Clarias gariepinus are presented in Table 1. Zinc exhibited the highest concentration among the metals analysed, with values ranging from 0.29 ± 0.04 to 0.53 ± 0.22 mg/kg. The mean zinc concentration throughout the study period was 0.39 ± 0.06 mg/kg.

Lead concentrations ranged from 0.16 ± 0.11 to 0.30 ± 0.04 mg/kg, with an overall mean value of 0.24 ± 0.04 mg/kg. Copper concentrations varied between 0.27 ± 0.05 and 0.50 ± 0.09 mg/kg and recorded a mean concentration of 0.36 ± 0.07 mg/kg.

Cadmium concentrations were relatively stable, varying from 0.26 ± 0.05 to 0.34 ± 0.03 mg/kg, while manganese ranged between 0.33 ± 0.06 and 0.46 ± 0.13 mg/kg. The overall mean concentrations of Cd and Mn were 0.29 ± 0.04 mg/kg and 0.38 ± 0.04 mg/kg, respectively.

Heavy Metal Concentrations in Liver Tissues

Table 2 presents the monthly mean concentrations of heavy metals in the liver tissues of Clarias gariepinus. The liver accumulated relatively higher concentrations of most metals compared with the gills and muscles.

Zinc concentrations ranged from 0.43 ± 0.07 to 0.58 ± 0.21 mg/kg with a mean concentration of 0.49 ± 0.05 mg/kg. Lead concentrations varied from 0.24 ± 0.06 to 0.35 ± 0.11 mg/kg, whereas copper concentrations ranged between 0.34 ± 0.04 and 0.57 ± 0.17 mg/kg.

Cadmium concentrations ranged from 0.24 ± 0.06 to 0.35 ± 0.02 mg/kg with a mean concentration of 0.31 ± 0.03 mg/kg. Manganese concentrations varied between 0.33 ± 0.07 and 0.60 ± 0.12 mg/kg and recorded an overall mean value of 0.46 ± 0.05 mg/kg.

Heavy Metal Concentrations in Muscle Tissues

The monthly mean concentrations of heavy metals in the muscle tissues are presented in Table 3.

Zinc concentrations ranged from 0.24 ± 0.11 to 0.39 ± 0.07 mg/kg, with a mean value of 0.29 ± 0.04 mg/kg. Lead concentrations varied from 0.18 ± 0.05 to 0.31 ± 0.08 mg/kg, while copper concentrations ranged between 0.23 ± 0.06 and 0.45 ± 0.12 mg/kg.

Cadmium concentrations ranged from 0.22 ± 0.05 to 0.29 ± 0.06 mg/kg with a mean concentration of 0.25 ± 0.03 mg/kg. Manganese recorded concentrations between 0.22 ± 0.05 and 0.31 ± 0.05 mg/kg, with an overall mean concentration of 0.26 ± 0.03 mg/kg.

Overall, the liver recorded the highest concentrations of most metals, followed by the gills and muscles. The general order of metal accumulation was: Zn > Mn > Cu > Cd > Pb.

One-way Analysis of Variance (ANOVA) revealed significant differences ($P < 0.05$) in the concentrations of Zn, Pb, Cu, Cd and Mn among the gills, liver and muscle tissues of Clarias gariepinus (Table 4). The liver accumulated significantly higher concentrations of all metals than the gills and muscles. Zinc exhibited the highest F-value among the essential metals ($F = 58.20$, $P < 0.001$), while manganese recorded the greatest overall tissue variation ($F = 99.42$, $P < 0.001$). Lead, copper and cadmium also differed significantly among tissues, indicating tissue-specific bioaccumulation patterns.

The concentrations of heavy metals varied significantly among tissues of Clarias gariepinus. The liver recorded the highest mean concentrations for all the metals analyzed, whereas the muscles generally exhibited the lowest concentrations. The order of metal accumulation among tissues was:

Liver > Gills > Muscle

Similarly, the overall order of metal abundance was:

Zn > Mn > Cu > Cd > Pb

Zinc was the predominant metal in all tissues, with mean concentrations of 0.49 ± 0.05 mg kg^{-1} in the liver, 0.39 ± 0.06 mg kg^{-1} in the gills and 0.29 ± 0.04 mg kg^{-1} in the muscles. The high accumulation of Zn may be related to its essential physiological role and its availability in the aquatic environment.
Lead concentrations ranged from 0.24 ± 0.04 mg kg^{-1} in the gills to 0.30 ± 0.03 mg kg^{-1} in the liver. The mean Pb concentration in the muscle tissues (0.27 ± 0.03 mg kg^{-1}) exceeded the permissible limit of 0.20 mg kg^{-1} recommended by WHO and FAO, indicating potential health risks associated with fish consumption.
Cadmium concentrations also exceeded the recommended limit of 0.05 mg kg^{-1} in edible fish tissues. The persistence of Cd in muscle tissues suggests continuous exposure of fish to environmental contamination sources within the lake ecosystem.
Copper and manganese concentrations remained below international permissible limits but exhibited considerable temporal variation, suggesting the influence of seasonal changes and anthropogenic inputs. Overall, the elevated concentrations of Pb and Cd in edible tissues raise concerns regarding food safety and underscore the need for continuous environmental monitoring and pollution control measures in Lake Alau.

Table 1: Monthly mean concentrations of heavy metals (mg kg^{-1} wet weight) in the gills of *Clarias gariepinus* collected from Lake Alau, Borno State, Nigeria (January 2019–June 2020).

Month	Zn	Pb	Cu	Cd	Mn
Jan. 2025	0.39 ± 0.10	0.17 ± 0.13	0.40 ± 0.16	0.27 ± 0.07	0.46 ± 0.13
Feb. 2025	0.34 ± 0.11	0.20 ± 0.06	0.47 ± 0.28	0.30 ± 0.16	0.45 ± 0.14
Mar. 2025	0.45 ± 0.18	0.29 ± 0.08	0.44 ± 0.09	0.34 ± 0.09	0.47 ± 0.16
Apr. 2025	0.53 ± 0.22	0.28 ± 0.05	0.34 ± 0.09	0.28 ± 0.07	0.35 ± 0.04
May 2025	0.43 ± 0.16	0.22 ± 0.08	0.30 ± 0.05	0.29 ± 0.04	0.37 ± 0.06
Jun. 2025	0.41 ± 0.11	0.22 ± 0.04	0.32 ± 0.05	0.30 ± 0.07	0.36 ± 0.05
Jul. 2025	0.37 ± 0.23	0.21 ± 0.08	0.41 ± 0.16	0.28 ± 0.08	0.34 ± 0.05
Aug. 2025	0.41 ± 0.23	0.19 ± 0.10	0.32 ± 0.06	0.26 ± 0.05	0.32 ± 0.03
Sept. 2025	0.37 ± 0.30	0.27 ± 0.05	0.35 ± 0.12	0.32 ± 0.02	0.38 ± 0.02
Oct. 2025	0.38 ± 0.25	0.25 ± 0.02	0.29 ± 0.02	0.25 ± 0.03	0.38 ± 0.04
Nov. 2025	0.29 ± 0.04	0.22 ± 0.03	0.36 ± 0.07	0.33 ± 0.10	0.37 ± 0.04
Dec. 2025	0.31 ± 0.11	0.25 ± 0.05	0.40 ± 0.11	0.25 ± 0.09	0.36 ± 0.03
Jan. 2026	0.33 ± 0.06	0.30 ± 0.04	0.34 ± 0.05	0.34 ± 0.06	0.40 ± 0.03
Feb. 2026	0.43 ± 0.15	0.27 ± 0.03	0.35 ± 0.06	0.29 ± 0.10	0.38 ± 0.02
Mar. 2026	0.35 ± 0.05	0.22 ± 0.08	0.27 ± 0.01	0.26 ± 0.05	0.37 ± 0.05
Apr. 2026	0.49 ± 0.31	0.25 ± 0.01	0.30 ± 0.04	0.31 ± 0.07	0.41 ± 0.02
May 2026	0.35 ± 0.20	0.27 ± 0.04	0.23 ± 0.07	0.22 ± 0.00	0.33 ± 0.03
Jun. 2026	0.34 ± 0.30	0.27 ± 0.02	0.29 ± 0.04	0.23 ± 0.03	0.37 ± 0.02
Mean	**0.39 ± 0.06**	**0.24 ± 0.04**	**0.36 ± 0.07**	**0.29 ± 0.04**	**0.38 ± 0.04**

Note: Values are presented as mean ± standard deviation (SD), $n = 3$. Concentrations are expressed as mg kg^{-1} wet weight (ww).

Table 2: Monthly mean concentrations of heavy metals (mg kg⁻¹ wet weight) in the liver of *Clarias gariepinus* collected from Lake Alau, Borno State, Nigeria (January 2019–June 2020).

Month	Zn	Pb	Cu	Cd	Mn
Jan. 2025	0.52 ± 0.21	0.27 ± 0.08	0.34 ± 0.04	0.24 ± 0.06	0.42 ± 0.05
Feb. 2025	0.48 ± 0.15	0.26 ± 0.07	0.43 ± 0.12	0.28 ± 0.08	0.60 ± 0.15
Mar. 2025	0.55 ± 0.10	0.27 ± 0.10	0.43 ± 0.06	0.34 ± 0.03	0.45 ± 0.03
Apr. 2025	0.53 ± 0.17	0.28 ± 0.06	0.54 ± 0.15	0.29 ± 0.05	0.48 ± 0.09
May 2025	0.52 ± 0.11	0.28 ± 0.08	0.39 ± 0.07	0.34 ± 0.06	0.45 ± 0.05
Jun. 2025	0.53 ± 0.11	0.33 ± 0.06	0.40 ± 0.05	0.35 ± 0.02	0.43 ± 0.04
Jul. 2025	0.49 ± 0.11	0.30 ± 0.02	0.51 ± 0.18	0.30 ± 0.06	0.56 ± 0.20
Aug. 2025	0.47 ± 0.04	0.35 ± 0.11	0.48 ± 0.15	0.24 ± 0.12	0.44 ± 0.03
Sept. 2025	0.45 ± 0.05	0.28 ± 0.08	0.40 ± 0.10	0.33 ± 0.08	0.46 ± 0.02
Oct. 2025	0.48 ± 0.11	0.26 ± 0.08	0.47 ± 0.17	0.28 ± 0.06	0.45 ± 0.07
Nov. 2025	0.43 ± 0.01	0.31 ± 0.04	0.43 ± 0.08	0.33 ± 0.07	0.49 ± 0.11
Dec. 2025	0.58 ± 0.21	0.31 ± 0.04	0.54 ± 0.13	0.33 ± 0.10	0.45 ± 0.05
Jan. 2026	0.42 ± 0.06	0.36 ± 0.05	0.47 ± 0.04	0.32 ± 0.04	0.42 ± 0.03
Feb. 2026	0.47 ± 0.06	0.29 ± 0.07	0.49 ± 0.04	0.34 ± 0.03	0.51 ± 0.14
Mar. 2026	0.40 ± 0.03	0.32 ± 0.03	0.54 ± 0.12	0.31 ± 0.05	0.47 ± 0.10
Apr. 2026	0.43 ± 0.07	0.28 ± 0.08	0.45 ± 0.02	0.32 ± 0.05	0.39 ± 0.06
May 2026	0.43 ± 0.08	0.26 ± 0.05	0.52 ± 0.14	0.30 ± 0.07	0.46 ± 0.15
Jun. 2026	0.49 ± 0.07	0.29 ± 0.05	0.39 ± 0.02	0.30 ± 0.04	0.39 ± 0.03
Mean	**0.49 ± 0.05**	**0.30 ± 0.03**	**0.45 ± 0.05**	**0.31 ± 0.03**	**0.46 ± 0.05**

Note: Values are presented as mean ± standard deviation (SD), $n = 3$. Concentrations are expressed as mg kg⁻¹ wet weight (ww).

Table 3: Monthly mean concentrations of heavy metals (mg kg⁻¹ wet weight) in the muscle tissues of *Clarias gariepinus* collected from Lake Alau, Borno State, Nigeria (January 2019–June 2020).

Month	Zn	Pb	Cu	Cd	Mn
Jan. 2025	0.25 ± 0.06	0.25 ± 0.05	0.36 ± 0.20	0.27 ± 0.12	0.22 ± 0.05
Feb. 2025	0.32 ± 0.03	0.19 ± 0.07	0.23 ± 0.06	0.24 ± 0.03	0.23 ± 0.07
Mar. 2025	0.32 ± 0.06	0.26 ± 0.09	0.39 ± 0.15	0.29 ± 0.02	0.30 ± 0.05
Apr. 2025	0.29 ± 0.07	0.28 ± 0.06	0.26 ± 0.06	0.25 ± 0.05	0.29 ± 0.06
May 2025	0.27 ± 0.12	0.27 ± 0.10	0.40 ± 0.25	0.26 ± 0.03	0.26 ± 0.07
Jun. 2025	0.24 ± 0.11	0.28 ± 0.05	0.42 ± 0.18	0.28 ± 0.05	0.24 ± 0.08
Jul. 2025	0.26 ± 0.10	0.29 ± 0.06	0.32 ± 0.19	0.22 ± 0.03	0.20 ± 0.09
Aug. 2025	0.26 ± 0.07	0.26 ± 0.02	0.34 ± 0.14	0.17 ± 0.08	0.22 ± 0.04
Sept. 2025	0.28 ± 0.04	0.29 ± 0.03	0.35 ± 0.14	0.22 ± 0.05	0.26 ± 0.04
Oct. 2025	0.25 ± 0.05	0.21 ± 0.09	0.41 ± 0.31	0.25 ± 0.06	0.27 ± 0.08
Nov. 2025	0.36 ± 0.04	0.30 ± 0.04	0.31 ± 0.11	0.25 ± 0.02	0.23 ± 0.05
Dec. 2025	0.29 ± 0.07	0.30 ± 0.03	0.32 ± 0.08	0.30 ± 0.05	0.31 ± 0.02
Jan. 2026	0.34 ± 0.02	0.31 ± 0.07	0.30 ± 0.09	0.27 ± 0.04	0.25 ± 0.05
Feb. 2026	0.28 ± 0.02	0.28 ± 0.01	0.39 ± 0.13	0.27 ± 0.05	0.29 ± 0.02
Mar. 2026	0.31 ± 0.11	0.28 ± 0.03	0.39 ± 0.19	0.25 ± 0.03	0.26 ± 0.06

Month	Zn	Pb	Cu	Cd	Mn
Apr. 2026	0.32 ± 0.02	0.30 ± 0.03	0.41 ± 0.11	0.26 ± 0.09	0.27 ± 0.03
May 2026	0.35 ± 0.07	0.23 ± 0.07	0.37 ± 0.11	0.27 ± 0.06	0.31 ± 0.05
Jun. 2026	0.36 ± 0.07	0.31 ± 0.03	0.29 ± 0.08	0.26 ± 0.06	0.26 ± 0.03
Mean	**0.29 ± 0.04**	**0.27 ± 0.03**	**0.35 ± 0.05**	**0.25 ± 0.03**	**0.26 ± 0.03**

Note: Values are presented as mean ± standard deviation (SD), $n = 3$. Concentrations are expressed as mg kg^{-1} wet weight (ww).

Table 4. Comparative mean concentrations (mg kg^{-1} wet weight) of heavy metals in different tissues of *Clarias gariepinus* from Lake Alau.

Tissue	Zn	Pb	Cu	Cd	Mn
Gills	0.39 ± 0.06^{b}	0.24 ± 0.04^{b}	0.36 ± 0.07^{b}	0.29 ± 0.04^{b}	0.38 ± 0.04^{b}
Liver	$\mathbf{0.49 \pm 0.05^{a}}$	$\mathbf{0.30 \pm 0.03^{a}}$	$\mathbf{0.45 \pm 0.05^{a}}$	$\mathbf{0.31 \pm 0.03^{a}}$	$\mathbf{0.46 \pm 0.05^{a}}$
Muscle	0.29 ± 0.04^{c}	0.27 ± 0.03^{ab}	0.35 ± 0.05^{b}	0.25 ± 0.03^{c}	0.26 ± 0.03^{c}
F-value	**58.20**	**11.14**	**21.24**	**12.06**	**99.42**
P-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

Note: Values are mean ± SD. Means within a column bearing different superscripts differ significantly at **$P < 0.05$**.

Table 5: Comparison of heavy metal concentrations in muscle tissues of *Clarias gariepinus* with WHO/FAO permissible limits

Metal	Mean concentration (mg kg^{-1})	WHO/FAO limit (mg kg^{-1})	Status
Zn	0.29	30.00	Within limit
Pb	0.27	0.20	Exceeds limit
Cu	0.35	30.00	Within limit
Cd	0.25	0.05	Exceeds limit
Mn	0.26	1.00	Within limit

Source: FAO (2024).

DISCUSSION

The present study demonstrated significant tissue-specific accumulation of heavy metals in Clarias gariepinus inhabiting Lake Alau. The liver recorded higher concentrations of most of the investigated metals than the gills and muscles. This pattern indicates the important role of the liver in metal metabolism, sequestration, storage, and detoxification. The observed differences among tissues are consistent with previous studies showing that metabolically active organs, particularly the liver, can accumulate substantial concentrations of heavy metals in fish (Emon *et al.*, 2023; Jabeen *et al.*, 2024).

The significant differences observed among the tissues ($P < 0.05$) indicate that heavy-metal accumulation in C. gariepinus was tissue-dependent. In the present study, the liver accumulated significantly higher concentrations of Zn, Pb, Cu, Cd, and Mn than the gills and muscles. This finding may be associated with the physiological functions of the liver in metabolism, detoxification, and sequestration of potentially toxic substances. Similar tissue-specific accumulation patterns have been reported in freshwater fishes, where the liver functions as an important organ for the storage and detoxification of heavy metals (Emon *et al.*, 2023; Jabeen *et al.*, 2024). The comparatively lower concentrations recorded in muscle tissues may be related to differences in tissue physiology, metabolic

activity, and metal-binding capacity. Since muscle constitutes an important edible portion of fish, however, even relatively lower concentrations are important from a food-safety perspective.

Zinc was the predominant metal detected in all the tissues examined. As an essential trace element, zinc plays important roles in several physiological processes, including enzyme activity, protein synthesis, cellular metabolism, growth, and development. However, excessive concentrations can become toxic to aquatic organisms. The relatively high concentration of zinc observed in the present study may reflect its greater environmental availability and biological requirement compared with some of the other metals investigated. Anthropogenic sources, including agricultural activities, domestic wastewater, municipal wastes, and other human activities around aquatic ecosystems, can contribute to elevated zinc concentrations. Similar concerns regarding heavy-metal contamination and accumulation in freshwater fish have been reported in recent reviews (Sharma *et al.,* 2024; Singh & Sharma, 2024).

Lead concentrations were comparatively lower than zinc concentrations but were of particular concern because Pb is a non-essential and potentially toxic metal. In some sampling periods, the concentrations recorded in the present study exceeded the maximum level of 0.2 mg/kg used for lead in fish under Codex Alimentarius standards (FAO/WHO Codex Alimentarius Commission, 2005). The presence of Pb in C. gariepinus may be associated with anthropogenic activities within the catchment, including domestic waste disposal, agricultural activities, vehicular emissions, and the remobilization of contaminated sediments. Because lead can accumulate in aquatic organisms and may be transferred to humans through consumption of contaminated fish, its occurrence warrants continued monitoring (Ali *et al.,* 2019; Emon *et al.,* 2023). Chronic human exposure to lead is associated with adverse effects on the nervous system, kidneys, development, and other physiological functions.

Copper concentrations varied among the tissues and sampling periods, with relatively higher concentrations observed in the liver. Copper is an essential micronutrient required for several physiological and enzymatic processes, including iron metabolism and haemoglobin formation. However, excessive copper accumulation can adversely affect fish health and physiological functions. The higher concentrations observed in the liver may be related to the capacity of hepatic tissues to accumulate and regulate metals through binding to proteins and other cellular components involved in detoxification and metal homeostasis. Similar tissue-dependent patterns of heavy-metal accumulation have been reported in freshwater fishes (Jabeen *et al.,* 2024; Emon *et al.,* 2023).

Cadmium concentrations remained relatively stable across the examined tissues but are of considerable ecological and public-health concern because cadmium is a non-essential metal with a high toxic potential. Unlike essential elements such as Zn, Cu, and Mn, cadmium has no established beneficial physiological function in humans or fish. Exposure to cadmium has been associated with renal damage, skeletal effects, cellular toxicity, and carcinogenicity. The detection of Cd in the tissues of C. gariepinus therefore indicates the need for continued environmental monitoring, particularly because persistent environmental exposure can result in bioaccumulation in aquatic organisms (Ali *et al.,* 2019; Emon *et al.,* 2023).

Manganese concentrations were appreciable in all tissues, with the highest concentrations recorded in the liver. Manganese is an essential element involved in several metabolic and enzymatic processes; however, excessive exposure may adversely affect aquatic organisms. The higher concentration observed in the liver may be associated with its role in metal metabolism and storage. The occurrence of Mn in all the tissues examined suggests that the fish were exposed to this element in their surrounding environment. Similar observations concerning tissue-dependent accumulation of heavy metals in freshwater fishes have been reported in recent reviews (Sharma *et al.,* 2024; Singh & Sharma, 2024).

The tissue accumulation pattern observed in the present study was:

Liver > Gills > Muscle

This pattern indicates that the liver was the principal tissue for accumulation of the investigated metals, followed by the gills, while the muscles generally contained the lowest concentrations. The finding agrees with previous studies reporting considerable accumulation of heavy metals in metabolically active tissues, particularly the liver, compared with muscle tissues (Emon *et al.,* 2023; Jabeen *et al.*, 2024). The relatively high metal concentrations in the gills may be explained by their continuous contact with the surrounding water and their role as an important interface between the fish and its aquatic environment.

The overall order of metal abundance in the present study was:

Zn > Mn > Cu > Cd > Pb

This order suggests differences in the environmental availability, uptake, accumulation, and physiological regulation of the individual metals. The predominance of Zn may partly reflect its essential biological role and relatively greater environmental availability, whereas the lower concentration of Pb may reflect differences in its sources, bioavailability, uptake, and tissue retention. Nevertheless, concentration alone does not determine the potential risk of a metal; the toxicity, chemical form, exposure duration, bioavailability, and amount of fish consumed are also important considerations (Ali *et al.,* 2019; Emon *et al.*, 2023).

The findings of the present study are also important in relation to previous investigations conducted in the Lake Alau environment. Dimari and Hati (2009) reported the occurrence and tissue distribution of metals including As, Cd, Cr, and Pb in fishes from Lake Alau, demonstrating that fish in the lake can accumulate potentially toxic metals. More recently, Bwala (2023) reported heavy metals in sediments, water, and Clarias gariepinus from Alau Dam, further demonstrating the presence of metal contamination within components of the lake ecosystem. The present findings therefore provide additional evidence of heavy-metal exposure in C. gariepinus from Lake Alau, while extending the assessment to the tissue-specific distribution of Zn, Pb, Cu, Cd, and Mn.

Overall, the findings indicate that Clarias gariepinus from Lake Alau is exposed to measurable concentrations of heavy metals and that the accumulation of these metals differs significantly among tissues. The higher concentrations observed in the liver demonstrate the usefulness of this organ for biomonitoring aquatic contamination, while the detection of metals in muscle tissue is particularly relevant to food safety because muscle is commonly consumed by humans. The results therefore emphasize the importance of regular monitoring of heavy-metal concentrations in Lake Alau, proper management of anthropogenic activities within the catchment, and continued assessment of the potential health risks associated with consumption of fish from the lake.

Conclusion

The study demonstrated that Clarias gariepinus inhabiting Lake Alau accumulates measurable quantities of Zn, Pb, Cu, Cd and Mn in its tissues, with the liver showing the highest accumulation. The observed concentrations indicate varying degrees of environmental contamination and suggest that anthropogenic activities within the catchment area contribute significantly to heavy metal inputs. Although essential metals such as Zn and Cu were predominant, the elevated levels of Pb and Cd raise concerns regarding ecological health and food safety. Continuous monitoring of heavy metals in water, sediments and fish tissues is therefore necessary to ensure sustainable utilization of the lake resources and protection of public health.

Recommendations

Based on the findings of this study, regular monitoring of heavy metals in the water, sediments, and fish tissues of Lake Alau is recommended to ensure early detection of pollution and safeguard aquatic resources. Anthropogenic activities such as indiscriminate waste disposal, excessive use of agrochemicals, and sand mining around the lake should be properly regulated to minimize heavy metal contamination. Public health authorities should periodically assess the safety of fish consumed from the lake, particularly because the concentrations of lead (Pb) and cadmium (Cd) exceeded the recommended permissible limits in some tissues. Furthermore, future studies should investigate heavy metal accumulation in other fish species and aquatic organisms and conduct ecological and human health risk assessments to provide a more comprehensive understanding of the environmental impacts of metal pollution in Lake Alau.

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