Assessment of Heavy Metal Contamination in Fish Species and Water from Lake Kariba

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Abstract: Heavy metal contamination in freshwater ecosystems is a growing concern because of its long-term effects on aquatic organisms and human health, particularly in regions influenced by agriculture, aquaculture and mining and industrial activities such as those surrounding Lake Kariba. This study investigated the concentrations and spatial distribution of Lead (Pb), Cadmium (Cd), Mercury (Hg), Arsenic (As), and Zinc (Zn) in water and selected fish species; *Oreochromis niloticus* (Nile Tilapia), *Serranochromis thumbergi* (Largemouth Bream), and *Limnothrissa miodon* (Kapenta) from lake Kariba. The results were compared with World Health Organization (WHO) and Food and Agriculture Organization (FAO) thresholds to determine compliance with international safety standards. A total of twelve water samples and thirty fish samples were collected from four sampling sites. Analyses were conducted using Atomic Absorption Spectrometer (AAS) with quality assurance ensured through certified reference materials and replicate measurements. Water quality parameters pH, temperature, dissolved oxygen and conductivity were also measured to provide context for metal bioavailability. All analyzed heavy metals in fish and water were below the permissible limits. Zinc was the only metal detected in the fish samples with concentrations ranging from 11.99 ppm to 19.57ppm, well below recommended permissible limit. The study demonstrates that heavy metal contamination in the sampled areas of Lake Kariba is minimal. These findings provide a scientific baseline for environment monitoring in Lake Kariba, supporting sustainable fisheries management, public health protection and policy interventions aligned with Sustainable Development Goals (SDGs) 3, 6 and 14.

Keywords: *Lake Kariba; Heavy Metals; Fish Contamination; Atomic Absorbtion Spectroscopy; Zinc*

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I. INTRODUCTION

Lake Kariba one of the largest manmade lake stretches across the border between Zambia and Zimbabwe. Constructed in the late 1950s primarily for hydroelectric power generation, the lake extends 277 kilometers (km) in length, covers an area of 5364 km^2, and has a mean depth of 29 meters (m) [1]. Beyond energy production, lake Kariba is a critical ecological and socio-economic resource, supporting diverse aquatic life, including commercially important species such as *Oreochromis niloticus* (tilapia) and *Limnothrissa miodon* (kapenta), while also providing livelihoods through artisanal and commercial fisheries, aquaculture, and domestic water use [2].

However, anthropogenic activities within the lakes catchment including mining, agriculture, aquaculture, urbans settlements and industrial operations combined with inadequate waste management, pose significant risks of environmental contamination [3], [4]. These activities introduce heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As) and zinc (Zn) into the aquatic ecosystems, where they persistent, toxic and prone to bioaccumulation [5], [6]. While some metals, including iron (Fe), copper (Cu), and zinc (Zn), are essential for biological functions, they become toxic above certain thresholds, whereas non-essential metals such as aluminium (Al), mercury (Hg), and cadmium (Cd) are harmful even at low concentrations [7], [8], [9].

Heavy metals enter freshwater systems through both natural process, such as weathering and erosion, and human activities, including industrial effluents, agriculture runoff, and mining discharges [10], [11], [12]. Once in the aquatic environment, metals may remain dissolved, adsorb to sediments, or bioaccumulate in fish and the organisms. Fish, particularly the liver, are effective bioindicators of environmental contamination due to their capacity to accumulate pollutants, reflecting both ecosystem health and potential human exposure [13], [14]. Consumption of

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contaminated fish can pose significant health risks, including neurological disorders, kidney damage, and cancer [8].

Despite the ecological and socio-economic importance of Lake Kariba, data on heavy metal contamination in both water and fish species remain limited. Previous studies in similar freshwater ecosystems indicate that essential metals often predominate in farmed fish due to feed composition, whereas toxic metals are elevated in wild fish, particularly near pollution sources [10], [15]. Risk assessment using parameters such as estimated weekly intake (EWI), Target Hazard Quotient (THQ), and Hazard Index (HI) generally shows low risk; however, isolated cases of mercury concentrations exceeding safety thresholds highlight potential long term health concerns [16], [17].

This study aimed to investigate the levels of heavy metal contamination in water and key fish species *Oreochromis niloticus* (Nile Tilapia), *Serranochromis thumbergi* (Largemouth Bream), and *Limnothrissa miodon* (Kapenta) from Lake Kariba. The objectives of the study were as follows:

- To analyze heavy metal concentrations in fish species and water from Lake Kariba: lead, mercury, cadmium, arsenic and zinc.
- To examine the distribution of heavy metals across different fish species and location in Lake Kariba.
- To compare the results with International -World Health Organization (WHO) and Food Agriculture organization (FAO) and Local i.e. Zambian Bureau of Standards and Water Resources Management Agency.

II. METHODS AND MATERIALS

A. *Sampling Site and Study Area*

The study was conducted on the Zambian side of Lake Kariba (-17^0 S, 28^0 E), one of the world's largest manmade lakes. The lake spans 320km in length with an area of 5,400km^2 and an average of 29m depth. It supports capture fisheries, aquaculture, tourism, hydropower, and domestic water use.

Water and fish samples were collected from strategic locations on lake Kariba in Siavonga, Zambia, representing areas with aquaculture activities, effluent discharge points, settlement, and a reference open water site. Sites were selected based on proximity to potential pollution sources, accessibility, and representation of fish habitats. The sampling locations were georeferenced using GPS, and the coordinates of each site are provided in Table 1, along with site characteristics.

Table 1 Sampling Locations in Lake Kariba-Siavonga, Zambia

Site	Coordinates (°S, °E)	Site Description	Dominant Activities
Aquaculture (A)	16°30.724′S 28°37.878′E	Near fish farms	Aquaculture activities
Effluent Discharge (B)	16°29.028′S 28°38.885′E	Close to farms and effluent from aquaculture farm	Effluent discharge
Settlement Area (C)	16°32.231′S 28°42.438′E	Near local community	Domestic waste, fishing activities
Reference Open Water (D)	16°31.273′S 28°38.006′E	Open water, away from direct pollution	Minimal human activity

B. *Sample Collection*

A total of Thirty fish samples were collected, including Oreochromis niloticus (Nile Tilapia), Serranochromis thumbergi (Largemouth Bream), and Limnothrissa miodon (Kapenta). Farmed tilapia were collected alive from aquaculture cages, while largemouth tilapia and kapenta were purchased from local fishermen with fishing camps near the proximity of the sampling points.

Twelve water samples were collected from the same sites as fish sampling, three water samples per location. Samples were collected approximately 30cm below the water surface in pre cleaned 500mL Polyethylene bottles, rinsed three times with lake water prior to collection. Immediately after collection, samples were acidified with concentrated nitric acid ($HNO3$) and stored at 4°C until analysis.

Physiochemical parameters, including dissolved oxygen (DO), temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, ammonia and phosphate were measured in situ and compared with local thresholds for aquatic life.

C. *Sample Preparations*

Muscle tissue from tilapia and largemouth bream was dissected, while kapenta was prepared as a whole-body composite. Samples were oven-dried at 105°C until constant weight and ground into a fine powder. Approximately 1g of homogenized tissue was digested using 5ml nitric acid (HNO_3) and 5ml hydrochloric acid (HCl).

Water samples were filtered through Whatman® No. 42 filter paper to remove particulates. Digestion involved adding 5mL of HNO3 and 5mL of HCl to a 100 mL volumetric flask, followed by the filtered water sample. The volume was then topped up to 100mL with distilled water.

D. *Heavy Metal Analysis*

Concentrations of lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and zinc (Zn) were quantified using Atomic Absorption Spectroscopy (AAS). Calibration standards, regent blanks, and triplicate analyses were used to ensure accuracy and reproducibility. Only Zn was consistently detected in fish samples, while all other metals were below detection limits. The metals recorded negative values due to concentrations below instruments detection limit. Following

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standard practice, these values were reported as zero parts per million (0 ppm).

E. Quality Assurance and Quality Control (QA/QC)

Acid washed glassware and containers were used to avoid contamination. Blanks, duplicates and standard calibration curves were analyzed alongside the samples to ensure accuracy. Analytical-grade reagents and ultrapure deionized water were used throughout. All equipment was calibrated, and samples were analyzed in triplicate, with mean values recorded.

F. Sample Collection

Descriptive statistics were used to summarize heavy metal concentrations in fish and water samples. For each metal, the mean and range value were determined for replicate measurements. These values were presented in tables and graphs to illustrate Zn concentrations patterns across species and sampling locations. Concentrations were compared with international guidelines, including World Health Organization (WHO) and Food Agriculture Organization (FAO) values. No inferential statistics were applied because only Zn was consistently detected, while other metals were below detection limits.

III. RESULTS

The concentration of heavy metals in water and fish were generally low, with Zn being the only detectable metal in fish. Pb, Cd, Hg, and As were below detectable limits in all water and fish samples.

A. Physiochemical Parameters

The physiochemical parameters presented in Table 2 show water characteristics at the time of sampling from Site A to D, to determine environmental suitability for aquatic organisms. DO concentrations ranged from 6.29mg/l (Site B) to 7.71 mg/l (Site D), well above the minimum requirements of 5mg/l for sustaining healthy freshwater ecosystems. Water temperature remained stable across sites (22.2 - 23.3 °C), falling within the optimal range for growth, metabolic activity, and physiological performance in freshwater fish. pH values (6.43-7.93) were slightly alkaline and within the recommended limits for aquatic ecosystems, indicating a chemically stable environmental. EC (108-112 µS/cm) and TDS (54 -56 mg/l) were low across sites, suggesting minimal ionic inputs and limited influence from industrial or agricultural runoffs. Ammonia concentrations were low (0.02 – 0.09 mg/l), indicating negligible organic pollution and reduced risk of toxicity to aquatic fauna. Phosphate levels ranged from 0.20 to 0.47 mg/l, reflecting low enrichment and minimal likelihood of eutrophication. These parameters are consistent with the absence of detectable heavy metals, reinforcing that the lake currently poses no chemical risk to aquatic life.

A consolidated summary of the physiochemical parameters is presented in Table 2.

Table 2 Average Physiochemical Parameters

Parameter	Site A	Site B	Site C	Site D	Guideline/ Standard
Dissolved Oxygen (mg/l)	7.09	6.29	6.43	7.71	≥ 5
Temperature (°C)	22.7	22.5	22.7	23.3	20-28
pH	7.75	7.91	7.62	7.93	6.5-8.5
Electrical Conductivity (µS/cm)	112	112	112	108	1500
Total Dissolved Solids (mg/l)	56	56	56	54	1000
Ammonia (mg/l)	0.02	0.03	0.09	0.02	< 1
Phosphate (mg/l)	0.20	0.41	0.47	0.20	

[a.] WHO limit = WHO 2017 guideline for drinking water

B. Heavy Metal Concentration in Fish Species and Water

- *Heavy Metal Concentrations in Water*

All water samples recorded non-detectable concentrations (0.00 ppm) for Zn, Pb, Cd, Hg, and As, with concentrations at all four sampling points failing within WHO/FAO recommended limits, confirming the absence of metal contamination in the water column.

- *Heavy Metal Concentration in Fish Species*

Among the five metals analyzed in fish samples, only Zn was detected, with concentrations varying across species and sampling sites as shown in Table 3. *Oreochromis niloticus* (Farmed Tilapia) exhibited the highest Zn concentrations at 19.02 ppm, followed by *Serranochromis thumbergi* (Largemouth Bream), which ranged from 18.28-18.99 ppm across sites, and *Limnothrissa miodon* (Kapenta), which showed the lowest levels ranging from 12.19 -12.45 ppm across sites. All recorded concentrations were below the permissible limit of 100 ppm set by [18].

A consolidated summary of Zn concentrations is presented in Table 3.

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Table 3 Mean Concentration of Zinc (ppm) in Fish Species from Lake Kariba

Species	Site A (ppm)	Site B (ppm)	Site C (ppm)	Site D (ppm)	FAO/ WHO limit (ppm)
Oreochromis niloticus	19.02	NS	NS	NS	100
Serranochronis thunbergi	18.99	18.69	19.02	18.28	100
Limnothrissa miodon	12.38	12.25	12.45	12.19	100

[b.] NS = Not Sampled (species absent at this site)

C. Spatial Distribution of Zinc in Fish Species

All metals analyzed in this study, including lead, cadmium, mercury, and arsenic were below detectable limits in fish samples; therefore, only zinc was quantified. The mean Zn concentrations (ppm) differed across species, with the highest levels observed in *Oreochromis niloticus* (19.02 ppm), followed by *Serranochromis thumbergi* (18.99 ppm), and the lowest in *Limnothrissa miodon* (12.38 ppm). *Oreochromis niloticus* from the aquaculture site (Site A) consistently showed elevated Zn levels 19.02 ppm, while *Serranochromis thumbergi* displayed modest site-related variation, ranging from 18.69 ppm (Site B) to 19.02 ppm (Site C*)*. *Limnothrissa miodon* recorded the lowest concentrations overall ranging from 12.19 ppm to 12.45 ppm across all sites. Minor difference across sites indicate low external Zinc contamination in Lake Kariba as shown in Fig 1.

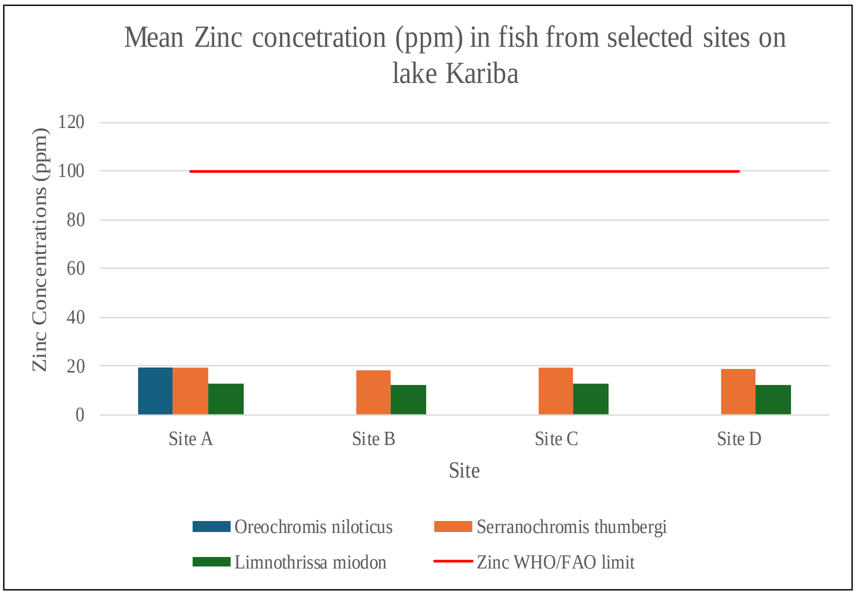

Fig 1 Spatial Distribution of Zinc (ppm) in Fish from Lake Kariba

D. Comparison of Heavy Metal Concentrations with WHO/FAO Limits

The heavy metal concentrations (ppm) in all the fish species and water samples were compared against international guidelines, as shown in Table 4. All water samples were below detection limits for Zn, Pb, Cd, Hg and As, demonstrating full compliance with both international and local drinking water standards. In fish, Pb, Cd, Hg and As were below detection limits, with only Zn detected. The mean concentration across all fish species analyzed was well below the permissible limit of 100 ppm by [18].

Table 4 Mean Heavy Metal Comparison with International and Local Standards

Metal	Zn	Pb	Cd	Hg	As
Oreochromis niloticus	19.02	ND	ND	ND	ND
Serranochronis thunbergi	18.75	ND	ND	ND	ND
Limnothrissa miodon	12.32	ND	ND	ND	ND
FAO/WHO limit	100	0.5	0.5	0.2	-

[c.] ND = Not detected (metal concentrations below the detection limit of the analytical method; FAO/WHO limit = permissible Zn concentration in fish according to [18])

IV. DISCUSSION

In the present study, all physiochemical water parameters were within acceptable range set by WHO. Additionally, water samples collected from sampling points on Lake Kariba in Siavonga showed no detectable concentrations of Pb, Cd, Hg, As, and Zn. Among fish species analyzed, only Zn was detected while the other four metals were not detected.

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Zn is an essential micronutrient for fish, supporting key physiological processes such as cell division and protein synthesis [19]. While necessary in small amounts, excessive Zn in water can be harmful. Elevated levels can damage gills, which are vital for breathing and waste elimination and interfere with reproductive processes [19]. Over time, Zn can accumulate in fish tissues and enter the food chain, potentially affecting human health. [16].

In this study, the mean Zn concentration in fish was 19.02 ppm for *Oreochromis niloticus*, 18.74 ppm for *Serranochromis thumbergi* and 12.30 ppm for *Limnothrissa miodon* across all four-sampling sites in lake Kariba, Siavonga District. All Zn concentration were below the permissible limit of 100 ppm set by FAO/WHO [18]. However, the levels recorded in this study were slightly higher than those reported in previous studies across the sub-Saharan Africa, where mean zinc concentration in fish ranged from 0.022 ppm to 9.4 ppm [2], [20], [21], [22]. These differences may be attributed to the species examined and specific tissue analyzed and the methods that was used in this study. Unlike previous studies that focused on isolated organs such as muscles, gills, and liver. The present study analyzed whole fish tissue of *Limnothrissa miodon* because of the size. This approach likely contributed to the higher Zn concentrations observed, as Zn tends to accumulate in organs such as liver, bones and gonads, consistent with findings by [23] and other studies reporting elevated Zn levels in whole fish or internal tissues [24].

The study further observed slightly elevated Zn concentration in fish sampled for Site A and Site C. This pattern may be linked to human activities such as aquaculture for site A and Human settlement for site C. Zn can enter aquatic systems through agriculture and industrial runoffs and effluent discharge [6]. Its mobility in water makes it more likely to spread from land based sources, including farm runoff, fertilizer leaching, and waste from surrounding communities. Runoffs from fish farms are likely contributing to higher Zn levels [19]. Similar patterns have been reported in other studies, where land based activities and surface runoffs increased chemical and nutrients concentrations in water, leading to higher metal accumulation in fish [10], [22], [25]. Additional potential sources include industrial activities, boating, tourism, all of which can introduce Zn into freshwater system and accumulate in fish [25].

Although Zn concentrations in *Oreochromis niloticus*, *Serranochromis thumbergi* and *Limnothrissa miodon* were below international permissible limit, [18], the findings align with previous studies from the same water body, where Zn was detected in these species [2], [21], [25]. Despite the generally low levels observed, the presence of Zn in fish from areas with high human activities highlights the need for ongoing environmental monitoring. Continuous metal accumulation may have ecological consequences and pose long-term health risks implications for health risks to communities that rely on these fish for food [21], [26].

This study had several limitations. First the number of sample collected may not fully represent the spatial and temporal variability of heavy metals concentrations across lake Kariba. Second, whole fish were analyzed rather than individual organs, which may have resulted in higher overall Zn concentrations compared to studies that analyzed muscle tissue only form the same water body. Thirdly, sampling was restricted to selected sites in Siavonga area, Zambian side of the lake; therefore, the findings may not fully represent heavy metal contamination across the entire lake Kariba. Additionally, the study was limited by the detection limits of the equipment used and samples were collected within a limited time frame, so seasonal variations were not captured.

Regular monitoring of Zn levels in Lake Kariba is recommended, particularly in areas with intensive agriculture and aquaculture. Future studies should examine seasonal variation and use a more advanced analytical instrument to improve detection accuracy.

Overall, the study shows that Lake Kariba currently has low heavy metal contamination, with zinc detected in fish at levels far below FAO/WHO limits, slightly higher concentrations at sites with more human activity highlight the need for continued monitoring.

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