Faculty of Natural and Applied Sciences Journal of Applied Chemical Science Research
Print ISSN: 3027-0359
www.fnasjournals.com
Volume 2; Issue 4; December 2025; Page No. 52-59.
DOI: https://doi.org/10.63561/jacsr.v2i4.1020

Bioaccumulation of Cadmium, Copper and Lead in Edible Tissues of *Clarias gariepinus* and *Oreochromis niloticus* from Anwai River, Nigeria

***[1]Onadje, F.O., [2]Chukwurah, A.I., [2]Olannye, D.U., [3]Efe-Eyefia, K., & [2]Oghene, U.J.**
1Department of Animal and Environmental Biology, Dennis Osadebay University, Asaba
[2]Department of Environmental Management and Toxicology, Dennis Osadebay University, Asaba
[3]Department of Biochemistry and Molecular Biology, Dennis Osadebay University, Asaba

***Corresponding author email**: festus.onadje@dou.edu.ng

Abstract
Environmental pollution is a continuous threat to the quality of aquatic habitats for plants and animals. This study aims to evaluate the concentrations of selected heavy metals (Cd, Cu, and Pb) in the flesh, liver, gills, and stomach *of Clarias gariepinus* and *Oreochromis niloticus* collected from the Anwai River, South-South Nigeria. Ten fish, each of both species measuring 17.25±1.70cm and 19.42±2.36cm respectively, were obtained and analysed using the Atomic Absorption Spectrophotometer. The collected data were subjected to one-way analysis of variance (ANOVA) at the 5% significance level. Results revealed that Lead concentrations were highest in all organs of the fish species, while the concentration of Cadmium was least. Heavy metals were lower in *Oreochromis niloticus* than in *Clarias gariepinus*. The concentrations of the metals investigated in both cases ranged from 0.09 mg/kg to 4.56 mg/kg and were far above regulatory permissible limits set by international standards, such as those of the World Health Organisation (WHO). The results of this study may indicate heavy metal pollution in the Anwai River and highlight the possible risk of eating fish from the river. Therefore, continuous evaluation of the Anwai River's pollution levels is necessary to reduce it through effective campaigns and sensitisation.

Keywords: Water Pollution, Heavy Metal, Aquatic habitat, Anwai River, Oreochromis niloticus, Clarias gariepinus

Introduction

Fish contains protein and necessaries for human nutrition and serves an important role for a healthy, well-balanced diet and the addition of meat to people's diets (Siddhnath et al., 2024; Segaran et al., 2023). Fish is a good source of protein, polyunsaturated fatty acids, especially omega-3 fatty acids, and minerals such as calcium, zinc, and iron (Izuchukwu et al., 2017). It is one of the most significant sources of the listed items among animal-origin food products due to its lower cost and greater nutritional value. Fish should be consumed at least twice a week for good health (Yilmaz et al., 2007). It is well known for its high protein and low fat content, making it a common choice among health-conscious consumers (Segaran et al., 2023; Inderhaug, 2020). In addition to being an important source of protein, fish typically have rich levels of essential minerals, vitamins, and unsaturated fatty acids (Tekade, 2025).Studies showed that people who include fish in their diets have a lower risk of coronary heart disease, hypertension, and cancer (Ejike & Liman, 2017; Nwude et al., 2020; Mustapha et al., 2021). However, fish can be a source of contamination and, under some conditions, can contain levels of heavy metals that are highly poisonous.

However, the increasing levels of environmental pollution, particularly in aquatic ecosystems, have raised concerns about the accumulation of heavy metals in fish tissues (Chukwurah et al., 2023; Garai et al., 2021; Shahjahan et al., 2022). Heavy metals, like lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), are known to have harmful effects on human health, even at low concentrations (Rahman & Singh, 2019). Heavy metals are metallic chemical elements characterised by restricted allowable quantities and significant toxicity even at minimal levels. They occur naturally as trace elements in the aquatic environment and the earth's crust, and their levels have increased due to industrial and agricultural activities (Li et al., 2017). Fish can easily accumulate heavy metals from sediment, water, or food by their position in the aquatic food chain (Takla et al., 2022; Sonone et al., 2020; Taiwo et al., 2018). Human activities contribute to heavy metal contamination in waterways (Vareda et al., 2019; Odesa & Olannye, 2024). Farming practices, wastewater runoff from manufacturing areas, sewage discharges from industrial operations (Mokarram et al., 2020), and mining activities (Sun et al., 2018) elevate heavy metal concentrations in aquatic environments. Furthermore, inappropriate waste management and disposal are the primary sources of heavy metal pollution (Vareda et al., 2019). The concentrations of heavy metals in fish are influenced by factors such as species, age, size, and feeding habits, as well as environmental factors and pollution levels in their habitats (Shahjahan et al., 2022; Salem, 2021; Ayanda et al., 2019). Given the evident bioaccumulation and biomagnification of heavy metals in fish, which serve as conduits for pollution across trophic levels, biomonitoring of hazardous compounds in fish is essential (Onadje et al., 2025; Rehman et al., 2017). Fish are used as bioindicators to monitor heavy metal levels in aquatic ecosystems (Hamada et al., 2024; Lee et al., 2023; Mahamood et al., 2023). The purpose of this study is to determine the levels of selected heavy metals (Cadmium, Copper and Lead) in the Flesh, liver, gills and stomach of two popular edible freshwater species of fish: African catfish (*Clarias gariepinus*) and Tilapia fish (*Orechromis niloticus*) from the Anwai River, Nigeria.

Materials and Methods

***Site of Study Area*:** The Anwai River, often referred to as 'Mmili Anwai', is situated in Asaba, the capital city of Delta State, Nigeria, between latitudes 6° 14′ and 6° 42′, at an elevation of 37 meters. The river originates in Otulu and discharges into the Niger River near Asaba, passing via the communities of Isele-Azagba and Okpanam (Iloba & Ada-mu, 2020). The river is an essential, recognised, and indispensable source of potable water, home supplies, agriculture, and fisheries for the adjacent communities (Edojarievwen et al., 2025). It receives floodwater from the adjacent landscape, abattoir effluents, and sacrificial waste from point and non-point abattoirs. A rainforest drains it. The river's flow is sustained by subterranean water sources and substantial rainfall in the rainforest region.

Collection of Fish species and Identification

Forty (10) fish, two different species (*Clarias gariepinus* and *Oreochromis niloticus*) were used for the study. The fishermen from the area collected the fish by using gill nets. The fish were rinsed with deionised water and taken to the laboratory in an ice box to avoid decomposition. The fish samples in the laboratory were identified with taxonomic keys established by Olaosebikan and Raji (1998) and Adesulu and Sydenham (2007). The fish species identified were *Clarias gariepinus* (Burchell, 1822), n=10, and *Oreochromis niloticus* (Linnaeus, 1758), n=10. The fish were dissected, and their essential organs, including the liver, gills, stomach, and flesh, were extracted. The Atomic Absorption Spectrophotometer was used to determine the levels of heavy metals in each sample. The samples were stored at -20 ^{0}C until analysis.

Preparatory Procedures

The fish samples were dissected, and the vital organs (flesh, liver, gills, and stomach) were removed for analysis. The components were dehydrated in a ventilated drying oven at 100°C until a constant weight was achieved, then pulverised into ash. This serves to improve the surface area of the fish samples during digestion.

Sample Treatment

The fish samples were desiccated in an oven at 75 °C for 48 hours. The tissue was excised using a stainless steel knife and pulverised to a fine powder using a porcelain mortar. 2 g of each homogenised fish sample were measured into individual beakers. Concentrated HNO_3 and H_2O_2 were introduced into the beakers in a 3:1 ratio and permitted to digest on a hot plate behind a fume hood at 120 °C for 20 minutes (Tawari-Fufeyin, 1998). The digested samples were permitted to cool to ambient temperature, filtered using Whatman filter paper, and each solution was adjusted to a final volume of 25 ml with deionised water, thereafter tested for the presence of trace metals.

Heavy metal analysis

Samples were analysed for Cadmium (Cd), Copper (Cu), and Lead (Pb) using an atomic absorption spectrophotometer (Perkin Elmer, Analyst 100). The element standard solution from Perkin Elmer was made by diluting stock solutions of 100 mg/mL for each element. The precision of the analytical method was validated using certified reference material (DORM-3). Results were expressed as mg/kg of dried weight of fish. All reagents utilised were of analytical grade and possessed 99% purity.

Cite this article as:
Onadje, F.O., Chukwurah, A.I., Olannye, D.U., Efe-Eyefia, K., & Oghene, U.J. (2025). Bioaccumulation of cadmium, copper and lead in edible tissues of clarias gariepinus and oreochromis niloticus from anwai River, Nigeria. *FNAS Journal of Applied Chemical Science Research, 2*(4), 52-59. https://doi.org/10.63561/jacsr.v2i4.1020

Statistical analysis

Mean values from three measures were analysed using analysis of variance (ANOVA) with GraphPad Prism software to ascertain the significance of differences. The Duncan multiple-range test was employed to compare means. P-values greater than 0.05 were statistically significant.

Results

The result for the values of the different metals in the flesh, liver, gills and Stomach of the two fish species is presented in Table 1 and Figures 1, 2 and 3. Cadmium concentrations in all the tissues and organs of *Clarias gariepinus* and *O. niloticus* were not significantly different (P > 0.05), as shown in Table 1. The highest concentrations of Cd were seen in the liver (11.00 ± 2.00 mg/kg and 4.07 ± 0.04 mg/kg) of *Clarias gariepinus* and *O. niloticus*, respectively. In contrast, the least concentrations were observed in the flesh of both fish species (4.43 ± 0.51 mg/kg and 2.62 ± 0.46 mg/kg, respectively). The levels of Cd were significantly higher (P < 0.05) in the liver (11.00±2.00 mg/kg) than that observed in the gills (7.30±0.62 mg/kg); stomach (2.45±0.61 mg/kg) and flesh (4.43±0.51 mg/kg) for *C. gariepinus* and significantly higher in the liver (4.07±0.04 mg/kg) than in the gill (3.27±0.38 mg/kg); stomach (2.74±0.06 mg/kg) and flesh (2.62±0.46 mg/kg) for *O. niloticus.* On the other hand, the levels of copper (Cu) were significantly higher in the liver (1.23±0.67 mg/kg) than that observed in the gill (0.69±0.19 mg/kg); stomach (0.46±0.30 mg/kg) and flesh (0.09±0.04 mg/kg) for *C. gariepinus* while it was higher in the liver (2.44±0.11 mg/kg) than in the gill (1.80±0.35 mg/kg); stomach (1.54±0.36 mg/kg) and flesh (0.51±0.38 mg/kg) for *O. niloticus*. The highest concentrations of Cu were observed in the liver (1.23±0.67 mg/kg) of *Clarias gariepinus* and the liver (2.44±0.11mg/kg) of *O. niloticu.* In contrast, the least concentrations were detected in the flesh (0.09±0.04 mg/kg) of *Clarias gariepinus,* as well as the flesh (0.51±0.38 mg/kg) of *O. niloticus*. The levels of Pb were highest in the liver (4.56±0.20 mg/kg) than in the other organs: gills (4.45±0.46 mg/kg, stomach (3.56±0.49 mg/kg) and flesh (2.44±0.11 mg/kg) for *Clarias gariepinus*. A similar trend was observed in *O. niloticus,* with the highest levels in the liver (3.80±0.29 mg/kg) than in the gill (3.49±0.45 mg/kg), stomach (2.40±0.40 mg/kg), and flesh (1.64±0.28 mg/kg).

Table 1: Heavy Metal Concentrations (mg/kg) in *Clarias gariepinus* and *Oreochromis niloticus*

Fish Species /Fish Organs	**Heavy Metals (mg/kg)**		
Clarias gariepinus	**Cadmium**	**Copper**	**Lead**
Flesh	4.43±0.51^{b}	0.09±0.04^{a}	2.44±0.11^{a}
Stomach	2.45±0.61^{b}	0.46±0.30^{a}	3.56±0.49^{ab}
Gill	7.30±0.62^{a}	0.69±0.19^{a}	4.45±0.46^{a}
Liver	11.0±2.00^{a}	1.23±0.67^{a}	4.56±0.20^{a}
Oreochromis niloticus			
Flesh	2.62±0.46^{a}	0.51±0.38^{a}	1.64±0.28^{a}
Stomach	2.74±0.06^{a}	1.54±0.36^{a}	2.40±0.40^{a}
Gill	3.27±0.38^{a}	1.80±0.35^{a}	3.49±0.45^{a}
Liver	4.07±0.04^{a}	2.44±0.11^{a}	3.80±0.29^{b}

Mean values (±Standard Error): no significant difference (P > 0.05) for fish species in the same column for each fish species with the same superscript.

Table 2: World Health Organization (WHO) recommended heavy metal levels in fish in (mg/kg)

Cadmium	**Copper**	**Lead**	**Reference**
0.010	2.250	0.010	WHO 2003

Cite this article as:
Onadje, F.O., Chukwurah, A.I., Olannye, D.U., Efe-Eyefia, K., & Oghene, U.J. (2025). Bioaccumulation of cadmium, copper and lead in edible tissues of clarias gariepinus and oreochromis niloticus from anwai River, Nigeria. *FNAS Journal of Applied Chemical Science Research, 2*(4), 52-59. https://doi.org/10.63561/jacsr.v2i4.1020

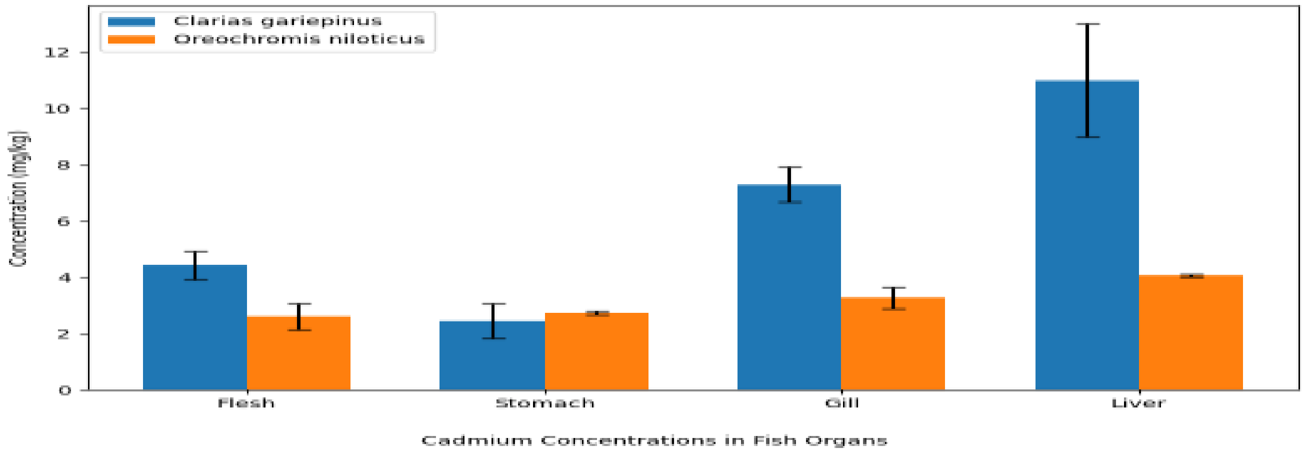


Figure 1: Cadmium concentrations (mean ± SD, mg/kg) in the flesh, stomach, gill, and liver of *Clarias gariepinus* and *Oreochromis niloticus*.

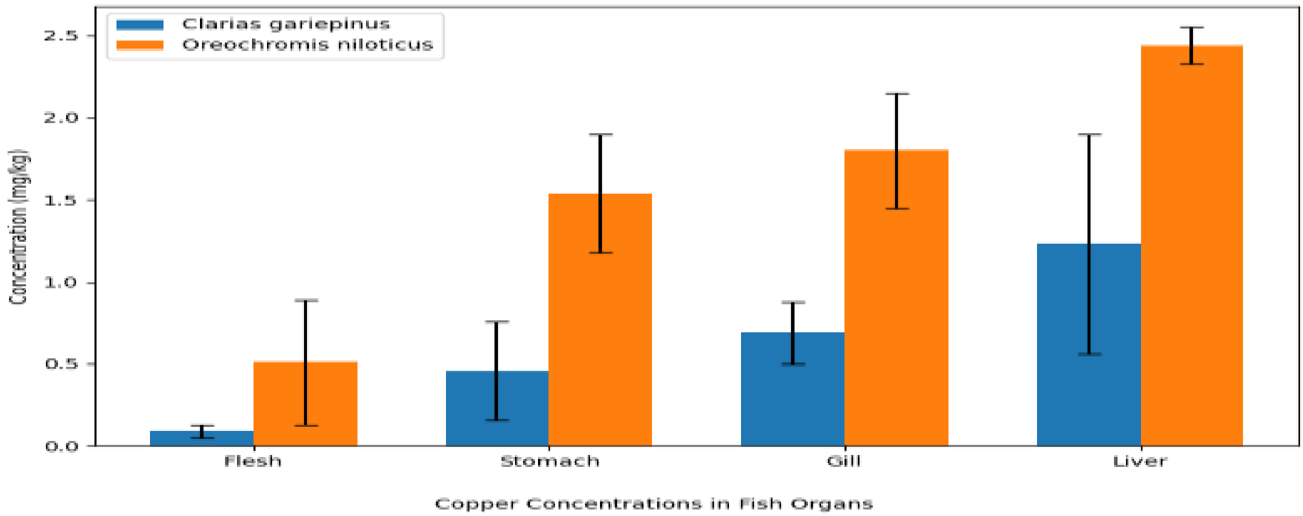
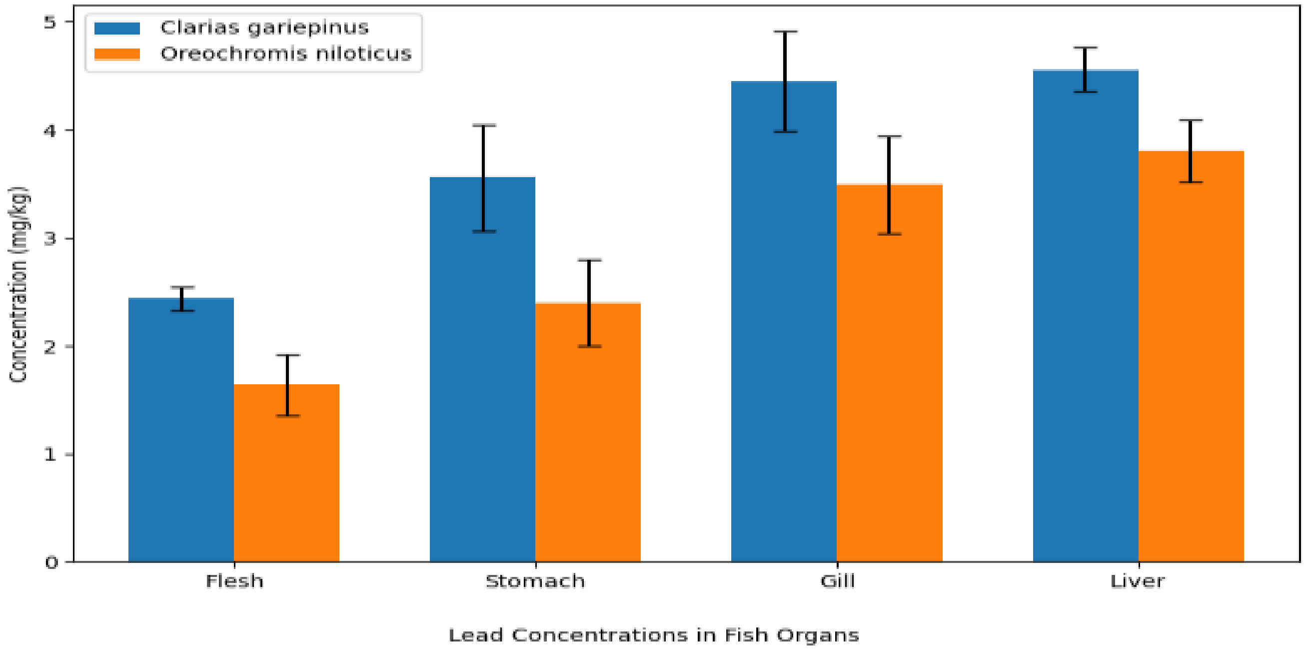


Figure 2: Copper concentrations (mean ± SD, mg/kg) in the flesh, stomach, gill, and liver of *Clarias gariepinus* and *Oreochromis niloticus*.



Cite this article as:
Onadje, F.O., Chukwurah, A.I., Olannye, D.U., Efe-Eyefia, K., & Oghene, U.J. (2025). Bioaccumulation of cadmium, copper and lead in edible tissues of clarias gariepinus and oreochromis niloticus from anwai River, Nigeria. *FNAS Journal of Applied Chemical Science Research, 2*(4), 52-59. https://doi.org/10.63561/jacsr.v2i4.1020

Figure 3: Lead concentrations (mean ± SD, mg/kg) in the flesh, stomach, gill, and liver of *Clarias gariepinus* and *Oreochromis niloticus*.

1.0. Discussion

Heavy metal pollution has been documented to ultimately infiltrate the aquatic ecology (Rama, 2021). Fish serve as effective biomonitors for assessing heavy metal pollution in aquatic ecosystems (Chukwurah et al., 2023). In the present study, the levels of metal accumulation differ between the two species. This disparity can result from differences in metabolic rates. Organisms vary in their metabolic rates, the amount of food they consume, and their food requirements (Ayande et al., 2019). Any of these could have played a role in the differences observed in metal accumulation by the fish species.

The study's findings indicate that the concentrations of lead (Pb), copper (Cu), and cadmium (Cd) varied significantly between the tissues of *Oreochromis niloticus* and *Clarias gariepinus*. The sequence of metal accumulation in both species was liver > gills > flesh, with liver always exhibiting the highest concentrations. For instance, Cd reached 11.0 mg/kg in the liver of *C. gariepinus* compared to 4.43 mg/kg in its flesh, while *O. niloticus* recorded 4.07 mg/kg and 2.62 mg/kg in the same tissues, respectively. These results are consistent with previous studies showing that the primary organs for fish metal uptake, storage, and detoxification are the liver and gills (Lee et al., 2024; Moussa et al., 2022). The liver serves as a significant site of metal absorption via metallothionein binding, while the gills act as the primary interface for direct waterborne absorption.

Cadmium is a non-essential trace metal capable of causing harm to fish and other aquatic species (Onadje & Akalusi, 2024; Ramesh Chandra, 2024). Concentrations of cadmium exceeding 0.1 mg/kg have been classified as toxic to fish and their predators (FAO, 1983). The findings of the study indicate that cadmium concentrations were elevated in the liver relative to other organs. Oladunjoye et al. (2017) previously reported similar results. The elevated levels of Cd observed in this study were consistent with those documented by Hussein et al. (2023) and Winiarska-Mieczan et al. (2017). Acute exposure to cadmium results in hypertension, renal impairment, testicular tissue destruction, and haemolysis (Wanjari & Gopalakrishnan, 2024; Wang et al., 2024). Cadmium sources in the human body originate from dietary intake. Severe toxic symptoms from cadmium consumption are observed between 19 and 26 mg/kg, whereas lethal ingestion leads to shock and acute renal failure at levels surpassing 350 mg/kg (Sivaperumal et al., 2007). The elevated levels of Cd observed in the liver of both species may stem from Cd's capacity to displace metallothioneins linked to essential metals in the liver (Nordberg & Nordberg, 2022) and potentially due to the challenges in excreting Cd once it has been accumulated (Bawuro et al., 2018).

The higher levels in *Clarias* are possibly a result of the species' benthic feeding lifestyle and sediment exposure, which enhance contact with contaminated particles (Odesa & Olannye, 2024; Egun et al., 2023; Adegbola et al., 2021; Olayinka-Olagunju et al., 2021). The Cd levels in the flesh of both species are significantly above the WHO maximum limits of 0.05–0.1 mg/kg for edible muscle tissue (WHO, 2023). There are serious health hazards associated with elevated Cd levels in fish tissues, including nephrotoxicity, osteomalacia, and an increased risk of cancer (Bautista et al., 2024; Zhuzzhassarova et al., 2024).

The pattern of organ accumulation of lead concentrations was similar to that of Cd, with higher values in the liver and gills than in the flesh. This pattern highlights Pb's strong preference for soft tissues, particularly those engaged in respiratory and metabolic processes (Moussa et al., 2022). Habitat preference and feeding style are examples of ecological and behavioural characteristics that can explain species differences (Egun et al., 2023; **Adegbola et al., 2021**). The Pb concentrations in the flesh are significantly higher than the WHO-recommended maximum limit of 0.010 mg/kg (WHO, 2023). Chronic exposure to lead has been associated with renal damage, cardiovascular illness, and neurological impairment in humans (Zhuzzhassarova et al., 2024). Therefore, elevated Pb concentrations in edible tissues raise serious concerns about food safety, particularly for populations that depend heavily on local fish. To minimise the dangers of Pb exposure, identifying and reducing the sources of contamination—such as industrial discharge, agricultural runoff, and urban effluents—should be a top management priority.

Copper concentrations were noticeably lesser than Cd and Pb but still showed clear organ-specific differences. In *C. gariepinus*, Cu levels were 1.23 ± 0.67 mg/kg in the liver, 0.69 ± 0.19 mg/kg in the gills, and 0.09 ± 0.04 mg/kg in the flesh, whereas *O. niloticus* showed 2.44 ± 0.11, 1.80 ± 0.35 and 0.51 ± 0.38 mg/kg, respectively. These results are consistent with research showing that, although necessary, copper is preferentially retained in tissues involved in metabolism, such as the liver (Mebane et al., 2023). Because critical metals are physiologically regulated, muscle usually retains the lowest levels, whereas gills typically reflect recent

Cite this article as:
Onadje, F.O., Chukwurah, A.I., Olannye, D.U., Efe-Eyefia, K., & Oghene, U.J. (2025). Bioaccumulation of cadmium, copper and lead in edible tissues of clarias gariepinus and oreochromis niloticus from anwai River, Nigeria. *FNAS Journal of Applied Chemical Science Research, 2*(4), 52-59. https://doi.org/10.63561/jacsr.v2i4.1020

exposure via water uptake (Lee et al., 2024). Increased copper levels in organs could still indicate localised pollution. According to Moussa et al. (2022), interactions between metals, including those between Cu and Cd, may also affect toxicity and absorption. Cu should be continuously monitored to make sure it stays within safe ranges, particularly in water bodies that receive discharges from industry or agriculture

Conclusion

According to this study, both Anwai River fish species had increased concentrations of heavy metals. As a result, it might be reasonable to infer that some of the fish species found in the Anwai River are unfit for consumption. Implementing laws that protect these aquatic ecosystems from pollution is essential to preventing health issues associated with these harmful metals. The findings collectively highlight the pressing necessity of risk assessment, environmental monitoring, and public health initiatives. To protect human health, reducing anthropogenic inputs and limiting consumption of fish from contaminated sites—especially organs such as liver and gills—should be given top priority.

Recommendations

1. Tracking pollution patterns over time should be conducted by implementing regular monitoring of heavy metals in water, sediments, and aquatic species to find pollution hotspots and direct focused responses. Multi-metal monitoring is especially crucial, as the kinetics of bioaccumulation may be influenced by interactions among cadmium, lead, and copper.
2. The increased concentrations of Cd and Pb found in fish tissues point to human-caused pollution from things like inefficient waste disposal, industrial discharge, agricultural runoff, and urban effluents. To reduce metal inputs into aquatic ecosystems, regulatory bodies should enforce stringent discharge regulations and carry out source-tracking studies.
3. It is essential to educate the public about the dangers of exposure to heavy metals through contaminated fish. Involving residents, fishermen, and legislators will promote compliance with safety protocols, encourage reporting of unlawful discharges, and support sustainable management of aquatic resources.
4. To reduce the accumulation of heavy metals in aquatic ecosystems, remediation techniques such as phytoremediation, enhanced wastewater treatment, erosion control, and sediment management should be implemented. By taking these steps, local fisheries will be protected, and the biological health of contaminated water bodies will be restored.
5. To estimate any risks to human health, thorough dietary exposure and health risk evaluations should be carried out utilising local fish consumption rates. The results should guide the development of evidence-based food safety and environmental regulations, such as regular inspection protocols and local permissible limits.

Acknowledgement

The authors appreciate the head of department and laboratory technologists for their assistance.

Statement Of Competing Interests

The authors have stated that there are no competing interests.

References

Adegbola, I. P., Aborisade, B. A., & Adetutu, A. (2021). *Health risk assessment and heavy metal accumulation in fish species (Clarias gariepinus and Sarotherodon melanotheron) from industrially polluted Ogun and Eleyele Rivers, Nigeria*. *Toxicology Reports*, 8, 1445–1460.

Ayanda, I. O., Ekhator, U. I., & Bello, O. A. (2019). Determination of selected heavy metals and proximate composition in some fish species from Ogun River, southwestern Nigeria. *Heliyon*, *5*(10), e02512. https://doi.org/10.1016/j.heliyon.2019.e02512

Bautista, C. J., Arango, N., Plata, C., Mitre-Aguilar, I. B., Trujillo, J., & Ramírez, V. (2024). Mechanism of cadmium-induced nephrotoxicity. *Toxicology, 502*, 153726. https://doi.org/10.1016/j.tox.2024.153726

Bawuro, A. A., Voegborlo, R. B., & Adimado, A. A. (2018). Bioaccumulation of heavy metals in some tissues of fish in Lake Geriyo, Adamawa State, Nigeria. *Journal of Environmental and Public Health, 2018*, 1854892. https://doi.org/10.1155/2018/1854892

Chukwurah A. I., Uruh K**.,** Olannye D. U., Emetulu V. C. and Enamuotor O. (2023). Effects of Water Pollution on Aquatic Life: A Case Study on River Ethiope. *Journal of Scientometrics and Innovations*. 1 (1): 210 – 220.

Edojarievwen, U. T., Chukwurah, A. I., Emetulu, V. C., Kesiena, U., & Onoriasakpobare, F. O. (2025). Assessment of water quality suitability for sustainable aquaculture using water pollution index: A case study of Anwai River, Southern Nigeria. *Current Research in Plant Science*, *1*(1), 18–23. https://doi.org/10.58613/crps113

Egun, N. K., Okotie, U. R., & Oboh, I. P. (2023). Distribution and toxicological risk assessment of metals in commercial fish species from a lentic ecosystem in Nigeria. *Journal of Trace Elements and Minerals, 6*, 100100. https://doi.org/10.1016/j.jtemin.2023.100100

Ejike, L. O., & Liman, M. G. (2017). Determination of heavy metals in selected fish species from Kwalkwalawa River, Sokoto State, Nigeria. *IOSR Journal of Applied Chemistry, 10*(1), 38–42. https://doi.org/10.9790/5736-1001023842

FAO. (1983). *Manual of methods in aquatic environmental research*. Food and Agriculture Organization of the United Nations.

Garai, P., Banerjee, P., Mondal, P., & Saha, N. C. (2021). Effect of heavy metals on fishes: Toxicity and bioaccumulation. *Journal of Clinical Toxicology, S*(18).

Hamada, N. H., Ali, R. A., El-Tabakh, M. A., & Bream, A. S. (2024). Environmental monitoring: Tobara fish as bioindicators of heavy metal pollution in a coastal ecosystem. *Regional Studies in Marine Science, 69*, 103335. https://doi.org/10.1016/j.rsma.2023.103335

Hussein, M. A., Morsy, N. S., Mahmoud, A. F., Darwish, W. S., Elabbasy, M. T., Zigo, F., Farkašová, Z., & Rehan, I. F. (2023). Risk assessment of toxic residues among freshwater and marine fish species. *Frontiers in Veterinary Science, 10*, 1185395. https://doi.org/10.3389/fvets.2023.1185395

Iloba, K. I., & Adamu, K. M. (2020). Ecological responses of macroinvertebrates to human impacts of a rural–urban flowing river in Delta State, Nigeria. *Journal of Biodiversity and Environmental Sciences, 16*(4), 10–18.

Inderhaug, T. (2020). Stockfish production, cultural and culinary values. *Food Ethics, 5*(1), 6. https://doi.org/10.1007/s41055-020-00069-5

Izuchukwu, I. U., Okeke, D. O., & Okpashi, V. E. (2017). Determination of heavy metals in fish tissues, water and sediment from River Niger, Nigeria. *Journal of Environmental & Analytical Toxicology, 7*(5), 1–3.

Lee, J. W., Park, J. S., & Choi, Y. J. (2024). Cadmium bioaccumulation and organ distribution in freshwater fish: A mechanistic review. *Toxics*, *12*(1), 34. https://doi.org/10.3390/toxics12010034

Lee, S., Mamun, M., Atique, U., & An, K. (2023). Fish tissue contamination with organic pollutants and heavy metals: Link between land use and ecological health. *Water, 15*(10), 1845. https://doi.org/10.3390/w15101845

Li, J., Sun, C., Zheng, L., Jiang, F., Wang, S., Zhuang, Z., & Wang, X. (2017). Determination of trace metals in tropical marine fishes from the Spratly Islands. *Marine Pollution Bulletin*, *122*(1–2), 464–469. https://doi.org/10.1016/j.marpolbul.2017.06.017

Mahamood, M., Khan, F. R., Zahir, F., Javed, M., & Alhewairini, S. S. (2023). Fish and aquatic plants as bioindicators of heavy metal pollution. *Scientific Reports, 13*, 28313. https://doi.org/10.1038/s41598-023-28313-9

Mebane, C. A., Schmidt, T. S., & DeForest, D. K. (2023). Copper bioavailability and toxicity in freshwater fish. *Environmental Toxicology and Chemistry, 42*(4), 1001–1015. https://doi.org/10.1002/etc.5589

Mokarram, M., Saber, A., & Sheykhi, V. (2020). Effects of industrial effluents on river water quality. *Journal of Cleaner Production, 277*, 123380. https://doi.org/10.1016/j.jclepro.2020.123380

Moussa, M. A., Okoye, B. C., & Afolabi, A. A. (2022). Heavy metal accumulation and DNA damage in *Oreochromis niloticus*. *Scientific Reports, 12*, 21104. https://doi.org/10.1038/s41598-022-25417-7

Nordberg, M., & Nordberg, G. F. (2022). Metallothionein and cadmium toxicology. *Biomolecules, 12*(3), 360. https://doi.org/10.3390/biom12030360

Nwude, D. O., Babayemi, J. O., & Ajibode, C. P. (2020). Heavy metal levels in freshwater fish from Ogun River, Nigeria. *Journal of Applied Sciences and Environmental Management, 24*(8), 1433–1440.

Odesa, G. E. & Olannye, D. U. (2024). Health Risk Assessment of PAHs and Heavy Metal Levels in Periwinkles (*Pachymelania fusca mutans*) and Crabs (*Scylla serrata*) Consumed in Crude Oil-Contaminated Coastal Regions of Southern Nigeria. *Toxicology Reports*. 14 : 101852. https://doi.org/10.1016/j.toxrep.2024.101852

Olayinka-Olagunju, J. O., Dosumu, A. A., & Olatunji-Ojo, A. M. (2021). *Bioaccumulation of heavy metals in pelagic and benthic fishes of Ogbese River, Ondo State, South-Western Nigeria.* Water, Air, and Soil Pollution, 232, 44**.** https://doi.org/10.1007/s11270-021-04987-7

Onadje, F.O., Chukwurah, A., I.& Agbeyi, E.A. (2025). Multiple Biomarkers Variability in Lead Exposed Fresh Water Fish (*Clarias gariepinus*). *Journal of Advances in Biology & Biotechnology 28 (4):5*13-20. https://doi.org/10.9734/jabb/2025/v28i42209.

Onadje, F. O., & Akalusi, K. E. (2024). Biochemical effects of lead exposure in *Clarias gariepinus*. *FNAS Journal of Applied Biological Sciences, 2*(1), 79–89.

Rahman, Z., & Singh, V. P. (2019). Impact of toxic heavy metals on the environment. *Environmental Monitoring and Assessment, 191*, 419. https://doi.org/10.1007/s10661-019-7528-7

Rama Jyothi, N. (2021). Heavy metal sources and their effects on human health. In *Heavy metals – Their environmental impacts and mitigation*. https://doi.org/10.5772/intechopen.95370

Salem, T. A. (2021). Changes in physicochemical and biological characteristics of Nile River waters. *Egyptian Journal of Aquatic Research, 47*, 21–27.

Segaran, T. C., Azra, M. N., Piah, R. M., Lananan, F., Téllez-Isaías, G., Gao, H., & Noordin, N. M. (2023). Catfishes: A global review. *Heliyon, 9*(9), e19135.

Shahjahan, M., Rahman, M. S., Islam, S. M., & Uddin, M. H. (2022). Heavy metal accumulation and health risks in freshwater fish. *Environmental Science and Pollution Research, 29,* 35612–35625.

Siddhnath, Sharma, S., & Singh, A. (2024). Dried fish and its role in the global economy. In *Dry fish: A global perspective on nutritional security and economic sustainability* (pp. 59–76). Springer Nature.

Sun, Z., Xie, X., Wang, P., Hu, Y., & Cheng, H. (2018). Heavy metal pollution from small-scale mining. *Science of the Total Environment*, *639*, 217–227. https://doi.org/10.1016/j.scitotenv.2018.05.235

Vareda, J. P., Valente, A. J., & Durães, L. (2019). Heavy metal pollution assessment and remediation strategies. *Journal of Environmental Management*, *246*, 101–118. https://doi.org/10.1016/j.jenvman.2019.05.126

Wanjari, U. R., & Gopalakrishnan, A. V. (2024). Cadmium as a male reproductive toxicant. *Environmental Science and Pollution Research*, *31*(12), 18340–18361. https://doi.org/10.1007/s11356-024-32210-7

WHO. (2003). *Codex alimentarius: Maximum levels of heavy metals in fish*. World Health Organization.

WHO. (2023). *Evaluation of certain contaminants in food*. World Health Organization.

Winiarska-Mieczan, A., Florek, M., Kwiecień, M., Kwiatkowska, K., & Krusiński, R. (2017). Cadmium and lead content in fishery products. *Biological Trace Element Research, 182*(2), 373–380. https://doi.org/10.1007/s12011-017-1104-1

Yilmaz, F., Ozdemir, N., Demirak, A., & Tuna, A. L. (2007). Heavy metal levels in two fish species. *Food Chemistry, 100*, 830–835.

Zhuzzhassarova, G., Sarsembayeva, N., & Duisenbekova, B. (2024). Fish and seafood safety: Human exposure to toxic metals. *Environmental Advances*, *16*, 100328. https://doi.org/10.1016/j.envadv.2024.100328