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Research Article

Histopathological Alterations in *Clarias gariepinus* from Biu Dam, Borno State, Nigeria as Indicators of Aquatic Pollution

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ABSTRACT

This study assessed heavy metal concentrations and associated histopathological alterations in *Clarias gariepinus* (African catfish) from Biu Dam, Borno State, Nigeria. Water and fish tissue samples were collected monthly from three sites (Main Dam Area, Dam Slope Area, and Gwalam Area) over six months (March–August 2024). Heavy metal concentrations (Arsenic, Cadmium, Chromium, Copper, Lead) in water and fish tissues (gill, liver, kidney, heart) were determined using Atomic Absorption Spectrophotometry, while histopathological examination was conducted using standard light microscopy with Haematoxylin and Eosin staining. Results revealed alarmingly high metal concentrations in water, with Arsenic (0.31±0.02 mg/L) and Lead (0.13±0.02 mg/L) exceeding WHO/FAO permissible limits by 31-fold and 130-fold, respectively. Correspondingly, catfish tissues showed significant bioaccumulation, with the liver accumulating the highest Arsenic concentration (0.045±0.005 mg/kg) and the heart showing elevated Cadmium (0.038±0.005 mg/kg) and Lead (0.028±0.004 mg/kg). Histopathological examination revealed severe tissue alterations including gill filament necrosis, extensive hepatocyte necrosis with vascular congestion, renal tubular necrosis, and cardiac inflammation. Seasonal analysis showed significantly higher Arsenic ($p=0.024$) during wet season and higher Copper ($p=0.014$) during dry season. The study concludes that *C. gariepinus* from Biu Dam is exposed to hazardous levels of heavy metals, resulting in severe histopathological damage across vital organs, posing significant ecological and public health risks to dependent communities.

Keywords: Bioaccumulation; Biu Dam; *Clarias gariepinus*; Heavy metals; Histopathology; Nigeria

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INTRODUCTION

Aquatic ecosystems are increasingly threatened by environmental pollution arising from anthropogenic activities such as industrial discharge, agricultural runoff, and domestic waste disposal. These pollutants introduce toxic substances into water bodies, particularly heavy metals, which accumulate in aquatic organisms and disrupt biological functions (Tchounwou *et al.,* 2012).

Fish are considered reliable bioindicators of environmental contamination because they occupy higher trophic levels in aquatic ecosystems and readily accumulate pollutants in their tissues (Authman *et al.,* 2015). Histopathological analysis of fish organs is an effective biomonitoring tool that allows detection of sub-lethal toxic effects caused by environmental pollutants (Bernet *et al.,* 1999).

Among freshwater fish species, the African catfish (*Clarias gariepinus*) is widely distributed across Africa and is commonly used in ecological and toxicological studies due to its economic importance and adaptability to diverse environmental conditions (Owolabi *et al.,* 2019). Because of its benthic feeding habits and frequent contact with sediments, this species is particularly vulnerable to pollutant accumulation.

Fish organs such as the gills, liver, kidney, and heart are sensitive to toxic insults and therefore serve as important targets for histopathological investigations. The gills function in respiration and osmoregulation and are directly exposed to waterborne pollutants (Mallatt, 1985). The liver is the primary organ responsible for detoxification and metabolism of xenobiotics, making it highly susceptible to toxic damage (Roberts, 2012). The kidney plays a critical role in excretion and osmoregulation and is also a major target organ for toxic substances (Camargo and Martinez, 2007). Cardiac tissues may exhibit pathological alterations resulting from systemic stress, hypoxia, or toxic exposure.

Although Biu Dam serves as an important freshwater resource for surrounding communities, limited information exists regarding the biological impacts of environmental contamination on aquatic organisms inhabiting this reservoir. Therefore, evaluating histopathological alterations in *Clarias gariepinus* provides valuable insights into the ecological health of the dam.

Measurement of physicochemical concentrations and histopathological changes in fish species of Biu Dam, Biu, Borno State, is an important task for determining environmental health and ecosystem sustainability. Fish species like *Oreochromis niloticus* (Tilapia) and *Clarias gariepinus* (Catfish) are sentinel animals, providing an early warning of environmental stressors through anatomical and physiological changes. Histopathological analyses, microscopic examination of the organization of tissue, provides a valid and sensitive technique for detection of sub-lethal and long-term effects of environmental pollutants considerably earlier than such significant changes are perceivable at the population level. Perturbations in functional organs such as gills, liver, and kidneys can reveal some toxicological effects due to contaminant exposure, particularly heavy metals. As such, tissue pathology studies on such fish species provide an invaluable diagnostic tool to assess the health of the aquatic ecosystem.

Lead, cadmium, and arsenic are heavy metals known for their persistence, bioaccumulative potential, and toxicity. Elevated levels of the metals are very ecologically dangerous and can instigate histopathological injuries that compromise the health of fish, interfere with body functions, and reduce survival. Biu Dam is of great socioeconomic importance to communities surrounding it that depend on fishing, agriculture, and tourism year-round. Histopathological changes and heavy metal accumulation in the tissue of fish must be observed not only for maintaining ecological balance but also for the protection of public health since fish form a major protein part of the food of the indigenous people. Toxic metal accumulation beyond protective limits or pathological tissue alterations in edible parts of fish can be extremely dangerous to human health. In addition, the study closes a vital knowledge gap as scant information exists in the literature regarding Biu Dam environment status, particularly regarding the synergistic interaction between tissue response and chemical contamination. The presence of baseline data on histopathological effects and heavy metal content will facilitate effective environmental monitoring, pollution control, and fisheries resource management in a sustainable way. In the international context, assessment of physicochemical and histopathological indices is among efforts to understand the impacts of urbanization, human activity, and climate change on freshwater ecosystems. For Borno State beset by socio-political and environmental issues, this research presents timely evidence for conservation planning guide, pollution risk reduction, and environmental resilience.

The impact of heavy metal contamination on aquatic ecosystems, particularly on fish species, has been widely studied due to its implications for biodiversity and food safety.

Heavy metals are a general term which applies to the group of metals and metalloids and it has an atomic density more prominent than 4000 kg/m^3 (Edelstein & Ben-Hur 2018). Almost all heavy metals are toxic to humans even at low metal ion concentrations (Sherlala *et al.* 2018; Bibaj *et al.* 2019; Hemavathy *et al.* 2019; Lei *et al.* 2019; Li *et al.* 2019; Suganya & Kumar 2019).

The contamination of aquatic environments by heavy metals in Borno State, Nigeria, has become a serious environmental and public health concern, particularly due to the increasing anthropogenic pressures and climatic vulnerabilities of the region. Studies by Yuguda *et al.* (2022) confirmed the bioaccumulation of these metals in fish species such as *Clarias gariepinus*, demonstrating how toxic elements in water bodies can transfer through the food chain and pose health risks to consumers.

Additionally, the findings of Akan *et al* (2013) emphasize how the reduction in water volumes due to seasonal climatic stress and increased evaporation in Maiduguri's irrigation systems results in elevated concentrations of heavy metals in both water and soils, thereby intensifying ecological toxicity. The accumulation of these metals not only threatens aquatic biodiversity but also undermines the sustainability of local livelihoods, particularly those reliant on fishing and irrigation-based agriculture. Overall, the literature emphasizes that metal pollution in Borno's aquatic systems is a multidimensional issue linked to poor waste management, climate variability, and urban expansion, underscoring the need for ongoing monitoring and environmental education efforts in the region.

This study aimed to investigate histopathological alterations in selected organs of *Clarias gariepinus* and heavy metal concentration of selected metals from Biu Dam and evaluate their potential as biomarkers of environmental pollution.

MATERIALS AND METHODS

Study Area

Biu is one of the twenty-seven local government areas of Borno State, located in the southern part of the state. It shares common boundaries with Chibok, Askira, Hawul, Damboa, kwaya-kusar and Bayo Local Government Areas, as well as Buni Gari Local Government Area of Yobe State. Biu lies generally at an altitude of about 762.32m above sea level, even though some areas might be lower. Biu is located between longitude 12°11'42" E and 10^{o} 36 40". It covers an area of approximately. 3,165 km² in size.

Biu Dam is a key water infrastructure project located in Biu, the dam plays a crucial role in water resource management, providing irrigation for farmlands, supporting fisheries, domestic water supply, opportunities for recreational activities and more. Biu Dam is situated on the Hawul River, a tributary of the Gongola River, now the River Benue. The coordinates for the dam are approximately 10° 35'0" N, 12°3'0 E. The construction of Biu Dam was started in 1979 by the second republic administration of Borno State Governor, Mohammed Goni, to address the perennial and acute water shortage in the area.

Site A (Main dam area) This site covers the main body of Biu Dam, which is extensive and supports a wide range of human activities. Common activities include fishing, water collection by residents, boating, and recreational use. The surrounding landscape has agricultural land, with farms encircling the dam. Human impact at this site is considered moderate. Site B (Dam slope area) Located along the large, engineered slope extending from the main dam, Site B is known for its beautiful scenery and is a hub for recreational activities such as picnicking, fishing, irrigation, washing and bathing. Like Site A, this site is also bordered by high agricultural lands. Human activities here are high considering it has a large space called slope high, which accommodates much human activity and the water level here is not that much, so people are not afraid of the water body like site A. Site C (Gwalam area). This site, situated near the Gwalam Dam, is comparatively more isolated and experiences minimal human disturbance. The primary activities observed are fishing and farming. The surrounding area is mainly agricultural land. Site C thus represents a low human activity zone.

Three sampling sites were selected, site A: Main dam region site B: Dam slope area site C Gwalam region. These locations represent areas with varying levels of anthropogenic activities.

Determination of Heavy Metals in organs of fish Sample

The standard method of atomic absorption spectrophotometer (AAS) was employed for analyzing the heavy metals in organs of the fish. The major underlined principle of AAS involves the atomization of samples by thermal sources and the absorption of a specific wavelength by the atomic source as it is excited. (APHA, 2012) The radiation used is a hollow cathode lamp containing the same element under analysis. The quantity of the same element absorbed by the atomic vapor is proportional to the concentration of the atoms in the ground state. (APHA, 2012)

Sample Analysis

All samples were analyzed in the Biochemistry laboratory of Gombe State University. An atomic absorption spectrophotometer (Bulk Scientific, model 205) was used for the analysis. Calibration of the instrument was performed by first analyzing two standard solutions for each metal, followed by the blank analysis, before the sample analysis. For quality assurance, all samples were analyzed in triplicate. The metals analyzed were Cadmium, Copper, Chromium, Arsenic, and Lead (APHA, 2012).

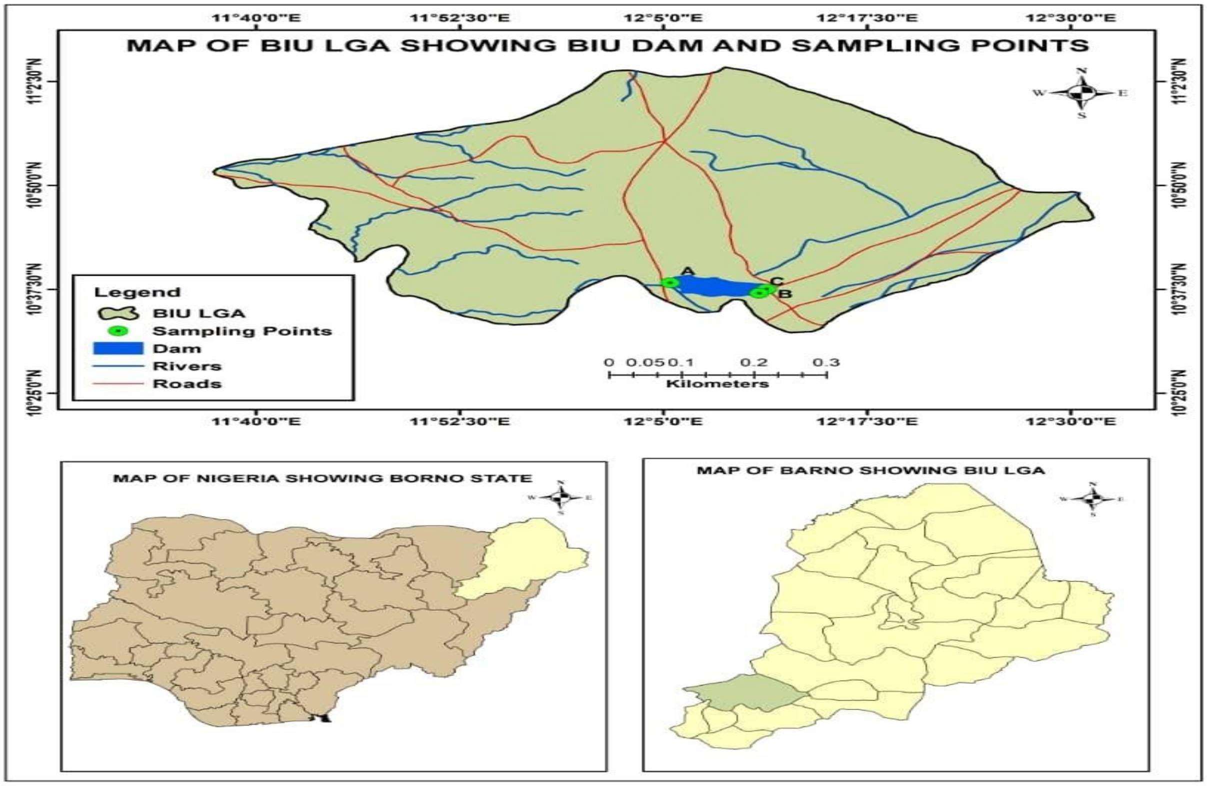

Figure 1: Map of the Study Area
Source: GIS Laboratory, Environmental Management and Toxicology, Federal University Dutse

Fish Collection and Identification

The sample was collected between the hours of 7:00 am and 09:00 am. With the help of fishermen using different fishing gears according to the regulations of the fishermen on site (gill nets, cast nets) were used for the collection of the fish sample. Fish were identified using guides/handbooks by Gartside (2010) and Idodo-Umeh (2003). iNaturalist and Specialist/professional from the Department of Biological Sciences of Nigerian Army University Biu, Borno state. For the analysis, three individuals of the fish sample were collected from each of the three dam sites (site A, site B, and site C) for histopathological examination (making a total of 9 fish sample across sites), and same size population were collected monthly for heavy metal analysis. Fish were collected at three locations of the study area considering the different activities and features each site of the dam has, from March 2024 to August 2024. The sex ratio of the specimen sample was not considered; sampling was carried out in both dry and rainy seasons. The collected fish were transported to the Nigerian Army University Biu, Borno State Biology laboratory in an aerated container for further process The fish samples were rinsed with distilled water to remove dirt and impurities. The fish samples were dissected with a clean stainless-steel knife to remove the liver, gills, kidney and heart separately. Organs of the fish sample were placed differently on a foil paper and put in an oven at a temperature of 105^0c for 24 hours to obtain a constant weight. After oven drying, the samples were then homogenized differently using porcelain mortar and pestle. The powdered samples were then put in a sterile sample bottle and labelled. (Nsofor, 2014).

Digestion Procedure of Fish Organ

All glass wares and sample bottles were thoroughly rinsed with deionized water and oven-dried before digestion. Powdered samples (0.5g of each sample) were weighed accurately with a weighing balance (Ohaus Model- AR 2130) and put into a round bottom flask. Concentrated acids of 1 ml of nitric acid (HNO_3), and 3 ml of hydrochloric acid (HCl) were prepared in a measuring cylinder and added to each sample and shaken. It was then placed on a hot plate to digest until a transparent or clear solution was attained. The solution was allowed to cool and then filtered with Whatman No.1 filter paper. The filtrate obtained was filled up to a mark of 100ml using deionized water.

The solution was then transferred into a labelled sample bottle for analysis. Sample blank was also prepared using the same digestion procedure but without the fish samples in it and transferred into sample bottles for analysis.

Table 1: Spatial Variation of Heavy Metals Concentration (Mg/Kg) in *Clarias gariepinus* (Catfish) Tissues from Biu Dam

Metal	Tissue	Site A	Site B	Site C	P-value	FAO/WHO 2018
As	Kidney	0.032 ± 0.005^{a}	0.041 ± 0.007^{b}	0.029 ± 0.005^{a}	0.021	0.01
	Gills	0.036 ± 0.004^{a}	0.011 ± 0.000^{a}	0.026 ± 0.004^{a}	0.000	
	Liver	0.045 ± 0.005^{a}	0.016 ± 0.001^{a}	0.036 ± 0.009^{a}	0.000	
	Heart	0.034 ± 0.005^{a}	0.032 ± 0.005^{b}	0.027 ± 0.007^{a}	0.110	
Cd	Kidney	0.032 ± 0.006^{b}	0.018 ± 0.003^{c}	0.011 ± 0.003^{b}	0.000	0.05
	Gills	0.004 ± 0.001^{b}	0.004 ± 0.001^{a}	0.000 ± 0.000^{a}	0.000	
	Liver	0.002 ± 0.000^{a}	0.005 ± 0.001^{b}	0.033 ± 0.004^{c}	0.000	
	Heart	0.003 ± 0.001^{a}	0.038 ± 0.005^{d}	0.026 ± 0.004^{c}	0.000	
Cr	Kidney	0.028 ± 0.005^{b}	0.013 ± 0.006^{b}	0.026 ± 0.006^{a}	0.007	0.05
	Gills	0.012 ± 0.002^{a}	0.010 ± 0.003^{a}	0.014 ± 0.000^{a}	0.102	
	Liver	0.010 ± 0.001^{a}	0.005 ± 0.001^{a}	0.020 ± 0.004^{a}	0.000	
	Heart	0.012± 0.001^{ab}	0.004 ± 0.001^{a}	0.015 ± 0.004^{a}	0.000	
Cu	Kidney	0.027 ± 0.006^{a}	0.030 ± 0.005^{b}	0.044 ± 0.010^{c}	0.004	2.0
	Gills	0.036 ± 0.006^{a}	0.038 ± 0.006^{b}	0.027 ± 0.005^{b}	0.029	
	Liver	0.024 ± 0.003^{a}	0.026 ± 0.005^{a}	0.002 ± 0.000^{a}	0.000	
	Heart	0.030 ± 0.003^{a}	0.039 ± 0.006^{a}	0.004 ± 0.000^{a}	0.000	
Pb	Kidney	0.005 ± 0.002^{b}	0.014 ± 0.006^{b}	0.006 ± 0.001^{b}	0.053	0.001
	Gills	0.002 ± 0.001^{b}	0.001 ± 0.000^{ab}	0.000 ± 0.000^{a}	0.001	
	Liver	0.000 ± 0.000^{a}	0.000 ± 0.000^{a}	0.030 ± 0.005^{b}	0.000	
	Heart	0.001 ± 0.000^{a}	0.001 ± 0.000^{a}	0.028 ± 0.004^{b}	0.000	

Table 2: Seasonal Variation of Mean Heavy Metals Concentration (Mg/Kg) in *Clarias gariepinus* Catfish Tissue

Metal	Dry Season	Wet Season	t-value	p-value
As	0.0281 ± 0.0011	0.0331 ± 0.0009	–3.586	0.024
Cd	0.0121 ± 0.0075	0.0138 ± 0.0009	–0.225	0.843
Cr	0.0207 ± 0.0076	0.0301 ± 0.0008	–1.245	0.336
Cu	0.0337 ± 0.0021	0.0208 ± 0.0009	5.599	0.014
Pb	0.0047 ± 0.0041	0.0102 ± 0.0008	–1.332	0.307

The tissues were excised and rinsed with deionized water. Care was taken to preserve the shape, structure and chemical constituents of the cells and tissue even after death. Preservation was carried out using 10% neutral buffered formalin as the compound fixative for histological processing (Ochei and Kolhatkar, 2008).

Gill samples were first removed to prevent possible postmortem changes. The innermost left gill arch of each fish was removed and placed into 10% neutral buffered formalin for fixation. After the surgical opening of the ventral abdominal wall, selected abdominal organs (liver, and kidney) were removed. Finally, the heart was removed through a ventral incision in the pericardial cavity. All tissue samples were placed immediately into 10% neutrally buffered formalin (NBF). Each respective organ was sampled immediately for histopathology after being removed. The hearts, gills, kidneys and livers of fish from all species were fixed as whole organs, grossing/tissue trimming was done at the National Veterinary Research Institute's Vom histopathology lab, and dehydrated through a graded series of ethanol concentrations (70%, 90% and 95%) manually (Avwioro, 2002).

After dehydration in graded ethanol and clearing in xylene, tissue samples were subjected to paraffin infiltration and embedding. The cleared tissues were transferred into molten paraffin wax maintained at 56–58°C in a paraffin oven. The tissues were infiltrated in molten paraffin for 1–2 hours to allow complete impregnation of the tissues with wax. Following infiltration, each tissue sample was carefully oriented in a labeled embedding mold filled with molten paraffin wax to ensure proper anatomical alignment during sectioning. The molds were then placed on a cold plate to allow rapid solidification of the paraffin and formation of tissue blocks. Once solidified, the paraffin blocks were trimmed and prepared for microtomy

Tissue Sectioning

The tissue blocks were sectioned using a microtome Thermos Scientific HM340E, and care was taken to ensure that the gauge controlling the thickness of sections was properly set. The thickness of the section was set at 15µm. The microtome was set to produce a cutting rhythm that formed a ribbon of about 1.5cm long. The sections were spread out in a water bath at 45^{0}C. The sections were successfully attached to the slide using bocine albumen adhesive. The slide was prepared and incubated at 50^{0}C to dry and fix the sections. The slides were ready for staining after three hours (Samson, 2015).

Staining of sections

The sectioned tissues were stained with Hematoxylin and Eosin (H and E) stains. The stained slides were examined for histopathological lesions using Leica DM 750 microscope and photomicrograph with LEICA ICE 50 HD camera as adopted by (Samson 2015) at the National Veterinary Research Institute Vom, Plateau State Nigeria. From each species of fish of each site, 3 sections of each tissue (gills, heart, kidney and liver) were examined. Microtome sections (3mm) Avwioro (2002).

Histopathological Analysis

The gills, liver, kidney, and heart were dissected from each fish specimen and fixed in 10% buffered formalin. The tissues were dehydrated through graded ethanol solutions (70–95%), cleared in xylene, and embedded in paraffin wax.

Sections approximately 15 µm thick were obtained using a microtome. The sections were stained with Hematoxylin and Eosin (H&E) and examined under a Leica DM750 light microscope equipped with a photomicrograph camera system for documentation.

RESULTS

Histopathological Alterations in Gills

Plate 1 (Gill, Site A Catfish) The gill tissue exhibits pronounced necrosis at high magnification (×400), characterized by the disintegration of lamellar epithelium and loss of structural integrity. The necrotic regions (indicated by black arrows) suggest acute damage, likely due to exposure to environmental toxins (e.g., heavy metals, ammonia) or parasitic infestation. The severity of necrosis implies significant respiratory compromise, which could lead to hypoxia and systemic stress in the affected fish.

Plate 2 (Gill, Site C Catfish) Necrosis of gill filaments (black arrows) is present, though less severe than site A. The damage is focal, implying intermittent or lower-intensity exposure to harmful agents.

Histopathological Alterations in Liver

Liver tissues showed extensive hepatocyte necrosis with structural degeneration of hepatic cells. In addition, parasitic cysts were observed in some specimens collected from Site C, suggesting the presence of parasitic infection. Liver histology showing hepatocyte necrosis and parasitic cyst. These lesions indicate severe hepatic stress and impairment of detoxification functions (Plate 3 and 4).

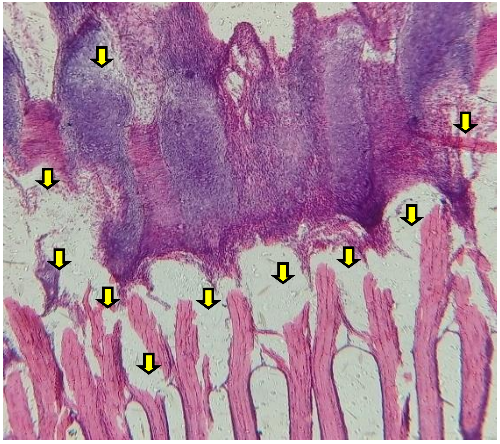

Plate1: Gill site A catfish: revealing necrosis. Hematoxylin and eosin stain (Magnification x400)

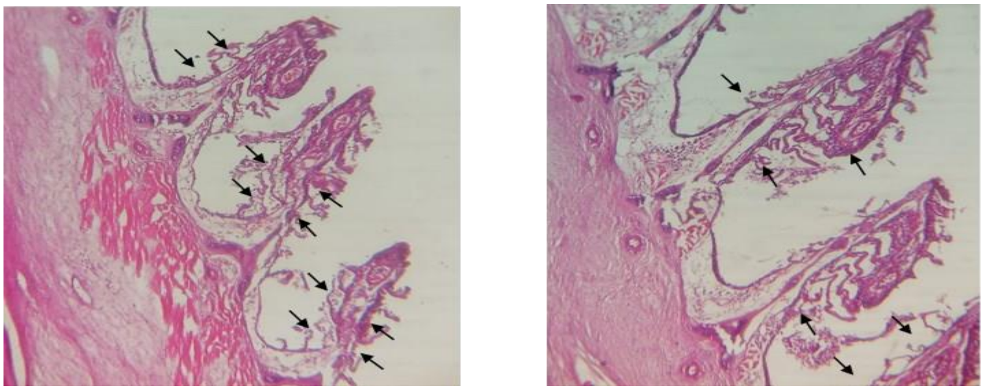

Plate 2: Gill site C Catfish: Necrosis of the gill filaments (black arrows). Hematoxylin and eosin stain (Magnification x100)

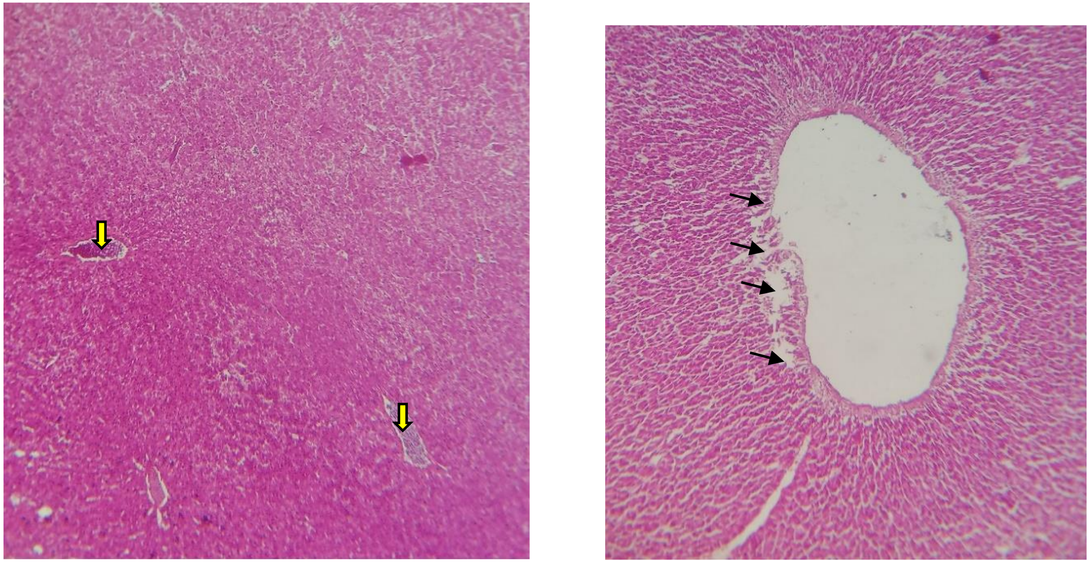

Plate 3: Liver site A catfish: congested veins (yellow arrows) and necrosis of the hepatocytes (black arrows) haematoxylin and eosin stain (Magnification x100)

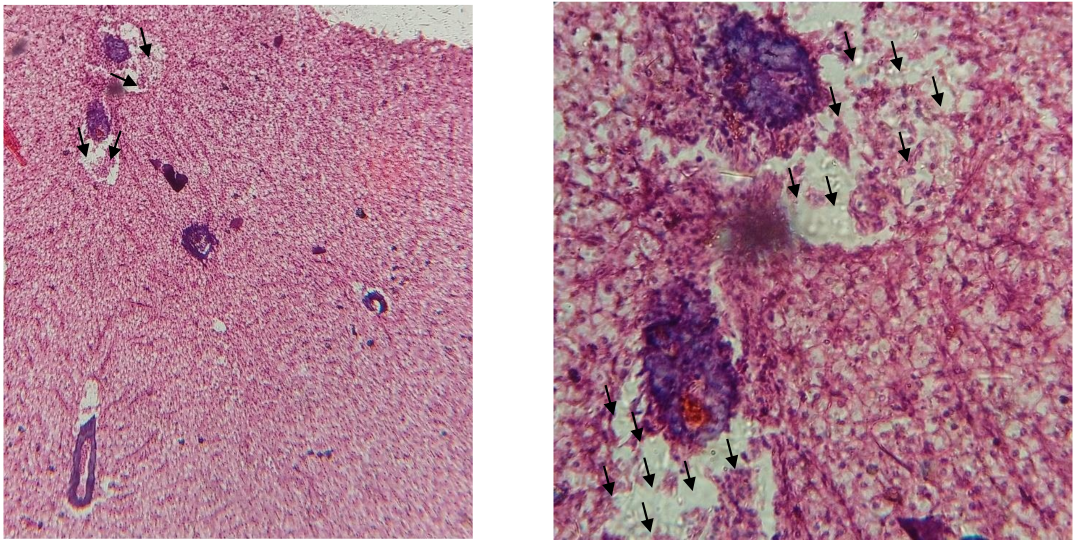

Plate 4: Liver site B catfish: revealing necrosis of the hepatocytes (black arrows). Hematoxylin and eosin stain (Magnification x50 and x400, respectively)

Plate 5 present the histopathology of liver; Site C Catfish A parasitic cyst (red arrow) is visible alongside necrotic hepatocytes (yellow arrows). The cyst's presence indicates a parasitic infection (e.g. Clinostomum), while the hepatocyte necrosis suggests concurrent toxic or hypoxic damage. The portal veins (blue arrows) appear normal, confirming that the primary pathology is localized to the parenchyma.

Histopathological Alterations in Kidney

The kidney tissue displays necrosis of the parenchyma (black arrows) at both low (×50) and high (×400) magnifications. The renal tubules appear disrupted, likely due to ischemic injury or nephrotoxic compounds. The absence of significant vascular congestion (compared to tilapia) suggests that the damage may be more localized, possibly linked to metabolic waste accumulation or direct toxin exposure (Plate: Kidney, Site A Catfish).

Congestion of renal vessels (yellow arrows) and necrosis of renal tubules (black arrows) are evident. The vascular congestion indicates impaired blood flow, while the tubular necrosis suggests direct toxic injury. The combined effects could lead to renal dysfunction, affecting osmoregulation and waste excretion in the fish (Plate 7: Kidney, Site B Catfish).

Plate 8 (Kidney, Site C Catfish) Congested blood vessels (yellow stars) and necrosis of the kidney parenchyma (green arrows) are observed. The vascular congestion implies circulatory stress, while the parenchymal necrosis indicates direct tissue injury. The combined effects could impair renal function, leading to metabolic disturbances.

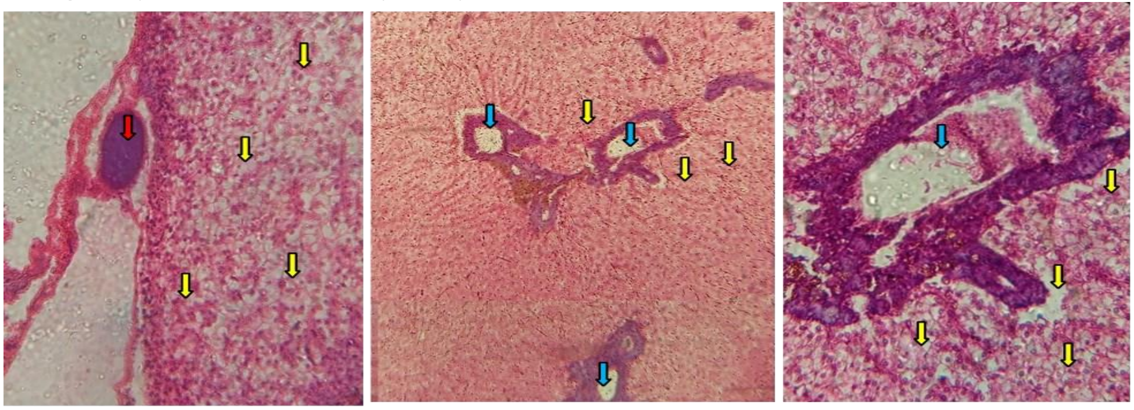

Plate 5: site C. parasite cyst (red arrow). Necrosis of the hepatocytes (yellow arrows).
The portal viens (blue arrows) reveal no pathology. Hematoylin and eosin stain. Magnification x100 and x400 respectively

Histopathological Alterations in Kidney

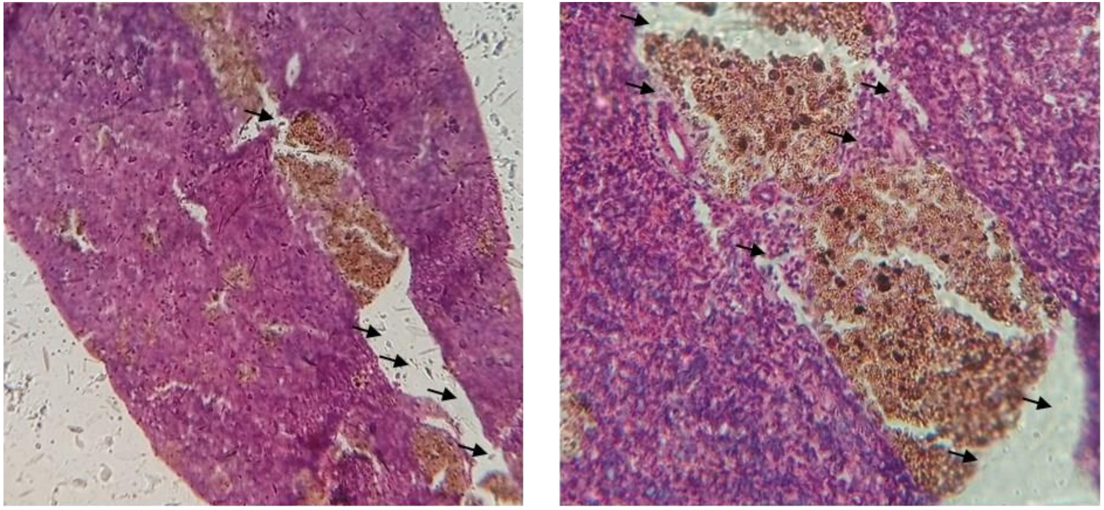

Plate 6: Kidney site A catfish: revealing necrosis of the kidney parenchyma (black arrows). Hematoxylin and eosin stain. Magnification x50 and x400 respectively

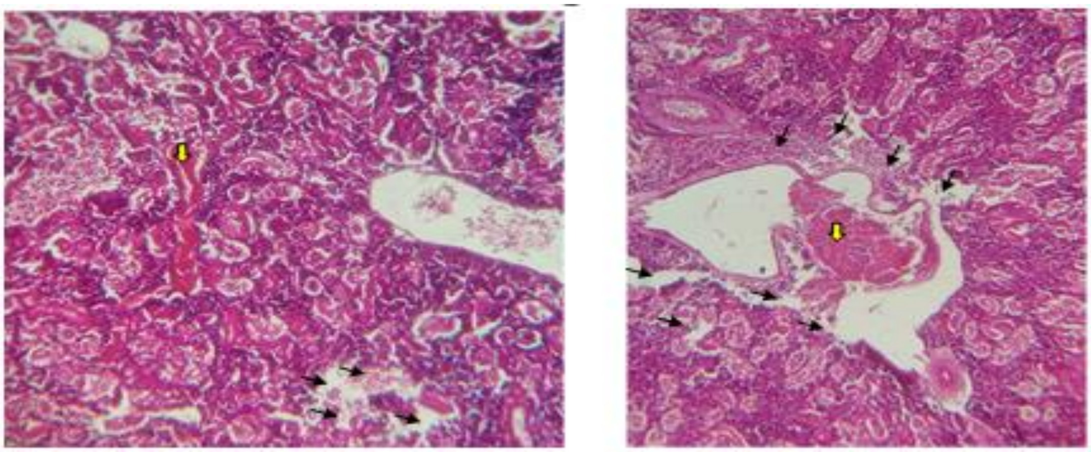

Plate 7: Kidney site B catfish: congestion of the renal vessels (yellow arrows) and necrosis of the renal tubules (black arrows). Hematoxylin and eosin stain. Magnification x100

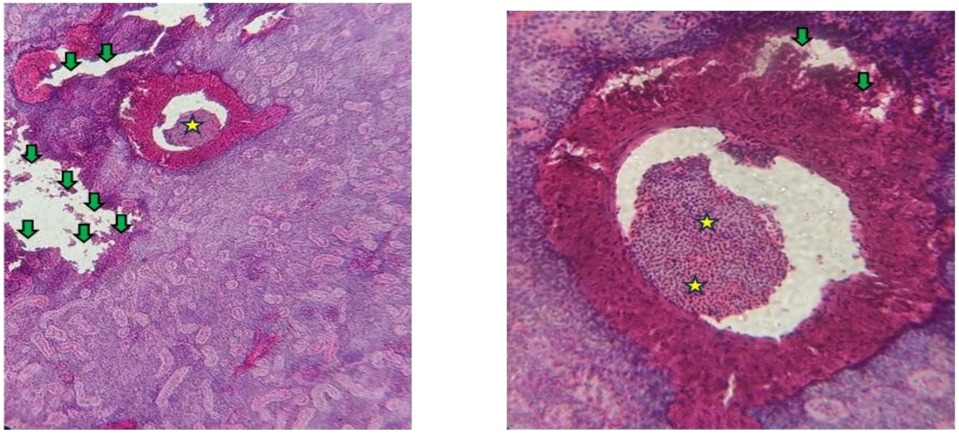

Plate 8: Kidney site C Catfish: revealing congested blood vessels (yellow stars) and necrosis of the kidney parenchyma (green arrows). Hematoyxlin and eosin stain. Magnification x50 and x400

Histopathological Alterations in Heart

Plate 9 (Heart, Site A Catfish) The cardiac muscle shows congestion of blood vessels (black arrows), indicating circulatory stress. While no overt necrosis is present, the vascular engorgement suggests impaired cardiac function, possibly secondary to gill damage (reducing oxygen supply) or systemic inflammation. Further investigation into potential infectious agents (e.g., bacteria, viruses) or environmental hypoxia is warranted.

Plate 10 (Heart, Site B Catfish) A notable aggregation of white blood cells (black arrows) is present within the cardiac muscle, suggesting an active inflammatory response. This finding points toward an infectious etiology, such as bacterial or viral myocarditis. The absence of necrosis in this plate contrasts with tilapia, implying that catfish may exhibit different pathological responses to cardiac stressors. These changes suggest systemic physiological stress possibly associated with infection or toxic exposure.

Control Samples

Control fish specimens showed normal histological architecture in all examined organs, confirming that the lesions observed in exposed fish were environmentally induced rather than spontaneous.

Plate 11 shows normal histoarchitecture of the gill, with intact secondary lamellae and no signs of necrosis, congestion, or inflammatory infiltration. This micrograph serves as a histological benchmark. The absence of pathology indicates that the gills are functioning optimally in respiration and osmoregulation under non-stress conditions.

Plate 12 Hepatocytes (blue arrows) and veins (yellow arrows) are structurally intact, with no signs of necrosis, congestion, or degenerative changes. The preserved liver parenchyma denotes a stable hepatic environment, free from toxic or infectious insult, confirming physiological metabolic activity.

Plate 13 (Control Catfish Heart), Cardiac muscle exhibits typical striations and no pathological changes histological integrity is preserved. The tissue is free from morphological distortion or cellular pathology, supporting its use as a control reference.

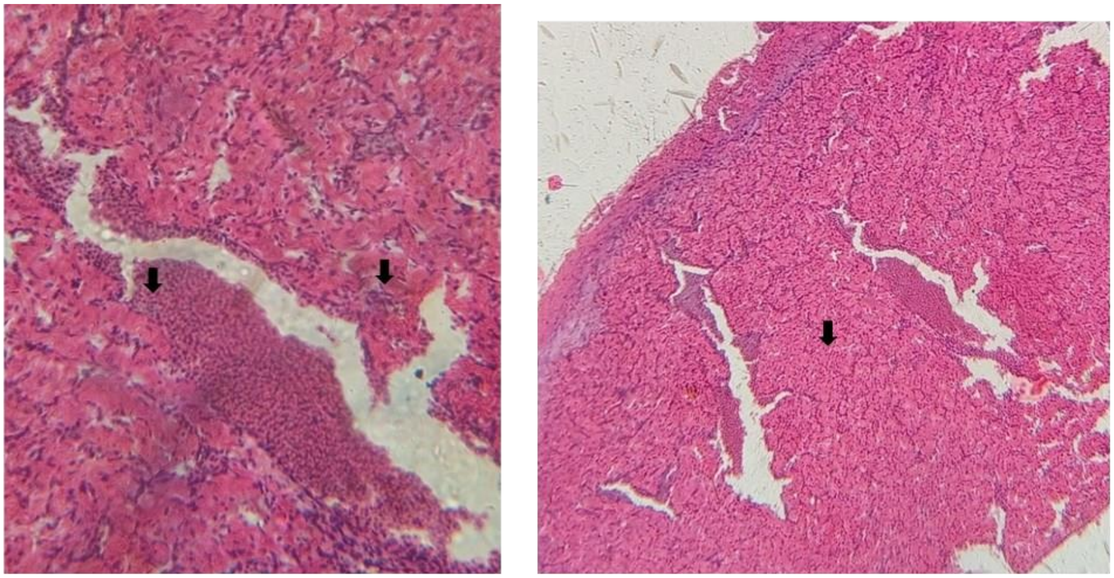

Plate 9: Heart (Cardiac muscle) site A catfish: revealing congestion of the heart vessel (black arrows) Haematoyxlin and eosin stain (Magnification x100 and x400 respectively)

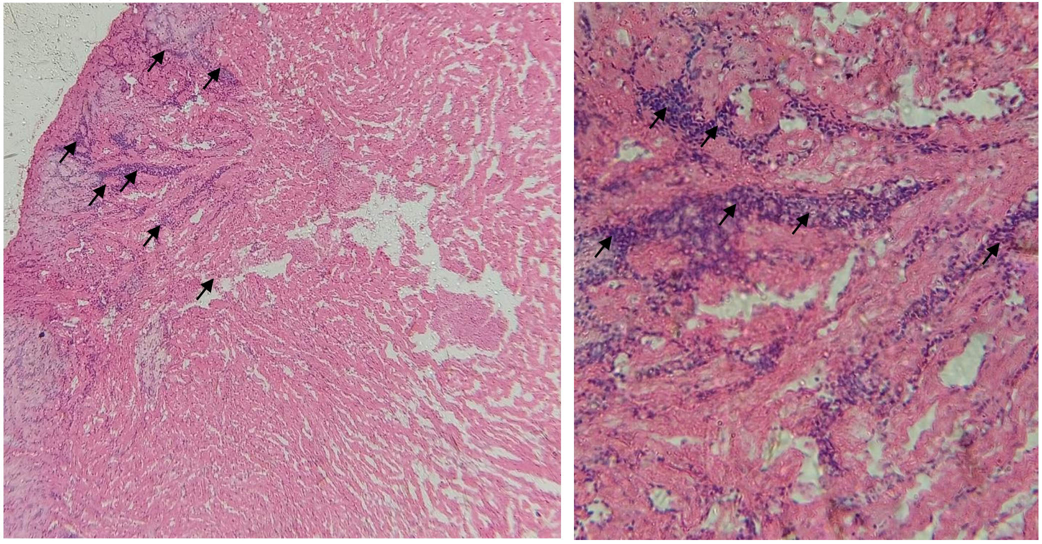

Plate 10: Heart (Cardiac muscle) site B: revealing white blood cell aggregation (black arrows)
This indicates some form of infection in the heart. Hematoxylin and eosin stain (Magnification x50 and x400 respectively)

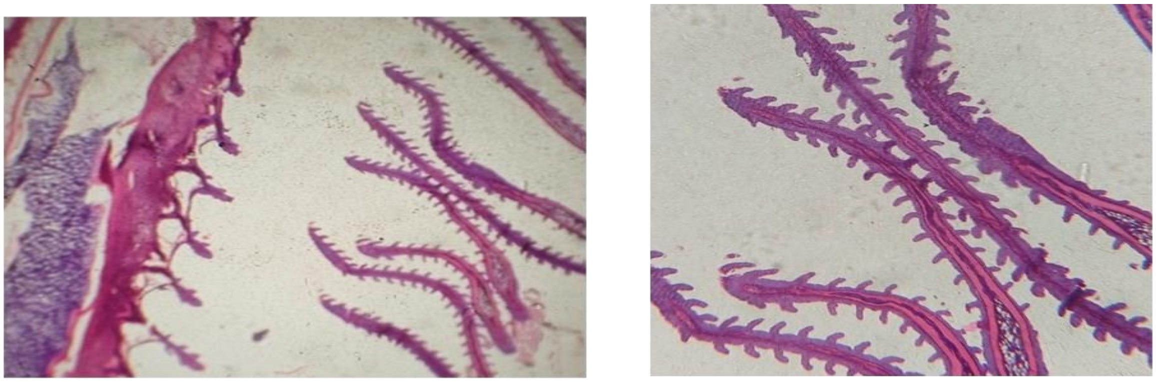

Plate 11: Histology of normal gills. No pathology observed. Hematoxylin and eosin stain (Magnification x100 and x400 respectively)

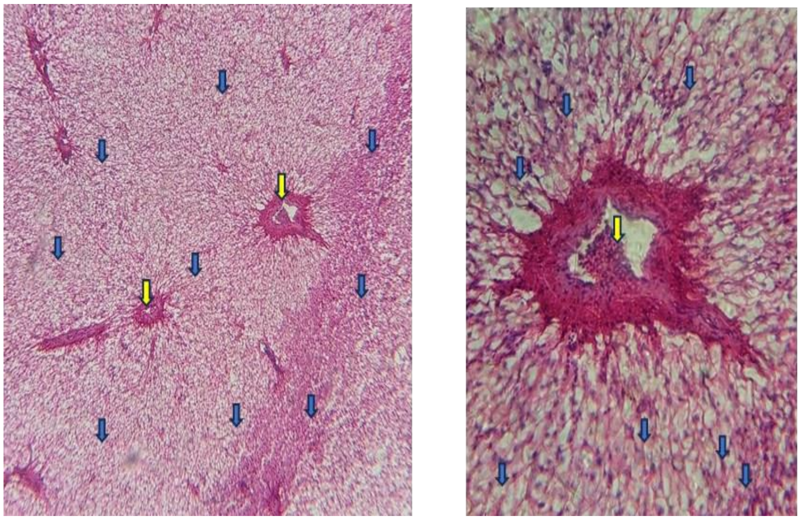

Plate 12: Control Catfish liver histology: no pathology observed
The veins represented by the yellow arrows are normal. The hepatocytes represented by blue arrows are normal
Haematoxylin and eosin stain (Magnification x100 and x400)

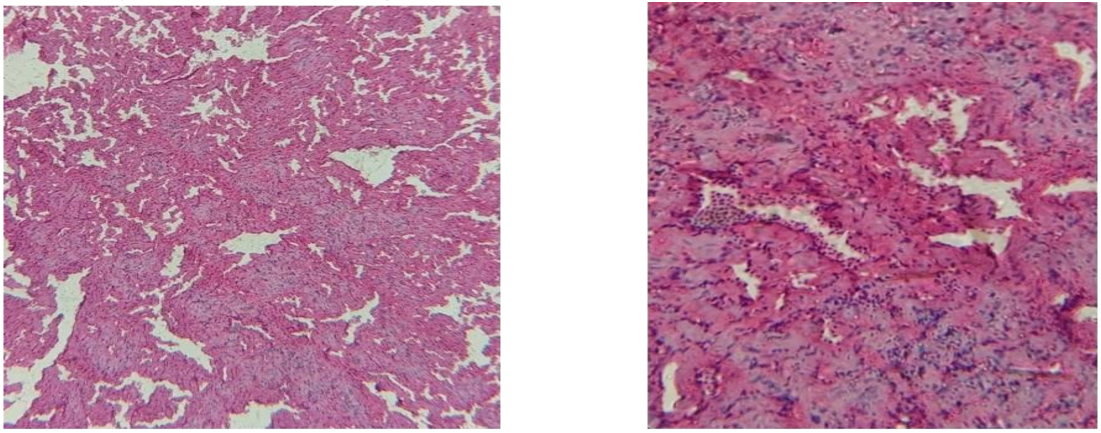

Plate 13: Control catfish histology: Cardiac muscle (Heart) with no pathology observed. Hematoxylin and eosin stain (Magnification x50 and x400 respectively)

DISCUSSION

The results of this study demonstrated significant bioaccumulation of heavy metals in various tissues of *Clarias gariepinus* from Biu Dam, with concentrations exceeding WHO/FAO (2018) permissible limits for several metals. The spatial analysis revealed site-specific contamination patterns, with Site C (Gwalam Area) showing the highest lead (Pb) concentrations in liver (0.030 ± 0.005 mg/kg) and heart (0.028 ± 0.004 mg/kg) tissues, representing 30-fold exceedances above the 0.001 mg/kg safety limit. This finding is particularly alarming as Pb is a non-essential heavy metal known for its neurotoxic, nephrotoxic, and cardiotoxic effects in both aquatic organisms and humans (Sfakianakis *et al.,* 2015; Tchounwou *et al.,* 2012).

The elevated Pb levels at Site C suggest localized contamination sources, potentially from historical use of leaded gasoline, hunting activities, or unidentified industrial inputs in the Gwalam catchment area. Similar findings have been reported by Bawuro *et al*. (2018) in Lake Geriyo, Adamawa State, where Pb accumulation in catfish tissues was attributed to anthropogenic activities including agricultural runoff and improper waste disposal. The bottom-dwelling nature of *C. gariepinus* makes it particularly vulnerable to sediment-bound contaminants, as it feeds on benthic organisms and detritus, thereby facilitating the trophic transfer of particle-associated heavy metals (Authman *et al.,* 2015).

Arsenic (As) accumulation was most pronounced in the liver tissue at Site A (0.045 ± 0.005 mg/kg), exceeding the WHO limit of 0.01 mg/kg by 4.5 times. The liver's role as the primary organ for detoxification and metal sequestration explains this accumulation pattern, as As is actively metabolized in hepatic tissues (Ahmed *et al.,* 2008). Kidney tissues at Site B also showed significantly elevated As concentrations (0.041 ± 0.007 mg/kg), indicating systemic distribution and potential renal impairment. These findings align with Suhendrayatna *et al*. (2002), who reported that arsenic accumulates preferentially in the liver and kidney of teleost fish, including Tilapia mossambica. The spatial variation in As accumulation (p = 0.021 for kidney, p = 0.000 for gills and liver) suggests differential inputs across the dam, likely from agricultural runoff containing arsenical pesticides or natural geological sources (Bhattacharya *et al.,* 2007).

Cadmium (Cd) presented a unique distribution pattern, with the heart tissue at Site B showing the highest concentration (0.038 ± 0.005 mg/kg), approaching the WHO limit of 0.05 mg/kg. Cardiac accumulation of Cd is particularly concerning, as this metal is known to disrupt cardiac electrophysiology and induce oxidative stress in myocardial tissue (Mathews *et al.,* 2014). The liver at Site C also showed elevated Cd (0.033 ± 0.004 mg/kg), suggesting multiple entry points and bioaccumulation pathways. These results corroborate the findings of Žikić *et al*. (2001), who observed Cd-induced cardiotoxicity in goldfish, and Thophon *et al*. (2003), who documented renal tubular damage in white sea bass exposed to sublethal Cd concentrations.

Chromium (Cr) concentrations remained below the 0.05 mg/kg safety limit across all tissues, though significant spatial variation was observed (p = 0.007 for kidney). The highest Cr levels were recorded in kidney tissue at Site A (0.028 ± 0.005 mg/kg) and Site C (0.026 ± 0.006 mg/kg). The presence of Cr in fish tissues from Biu Dam is noteworthy, as the region lacks major industrial activities typically associated with Cr pollution (e.g., tanneries, electroplating). This suggests alternative sources, including natural geochemical weathering of Cr-bearing parent materials or diffuse inputs from domestic waste and agricultural runoff (Kumar *et al.,* 2019).

Copper (Cu), an essential trace element, remained within the WHO permissible limit of 2.0 mg/kg across all tissues. However, significant spatial variation (p = 0.004 for kidney, p = 0.029 for gills) was observed, with Site C kidney showing the highest concentration (0.044 ± 0.010 mg/kg) and Site C liver showing the lowest (0.002 ± 0.000 mg/kg). This organ-specific distribution reflects the dual role of Cu as both a micronutrient (required for enzyme function and hemoglobin synthesis) and a potential toxicant at elevated concentrations (Kabata-Pendias, 2011). The elevated kidney Cu at Site C may indicate active excretion processes, as the kidney plays a crucial role in eliminating excess metals (Bost *et al.,* 2016).

Seasonal and Temporal Trends in Metal Accumulation

The seasonal analysis revealed that As concentrations in catfish tissues were significantly higher during the wet season (0.0331 ± 0.0009 mg/kg) compared to the dry season (0.0281 ± 0.0011 mg/kg; p = 0.024). This pattern is consistent with the hydrological mobilization of arsenic from contaminated soils and sediments during rainfall events, a phenomenon well-documented in floodplain and reservoir systems (Ahmed *et al.,* 2008; Rajeshkumar and Li, 2018). The wet season increase likely results from increased runoff carrying arsenical compounds from agricultural lands into the dam, combined with the reductive dissolution of iron oxides that releases bound As into the water column (Bhattacharya *et al.,* 2007).

Conversely, Cu exhibited significantly higher concentrations during the dry season (0.0337 ± 0.0021 mg/kg) compared to the wet season (0.0208 ± 0.0009 mg/kg; p = 0.014). This inverse seasonal pattern reflects evaporative concentration of dissolved ions during the dry period when water volumes are reduced, as well as reduced dilution from rainfall (Gossuin and Vuong, 2018). Additionally, the dry season corresponds to increased agricultural activities, including the application of Cu-based fungicides and fertilizers, which may contribute to elevated Cu inputs (Ibeanu *et al.,* 2017).

Cadmium, chromium, and lead did not show statistically significant seasonal variations ($p > 0.05$ for all), though mean concentrations were generally higher during the wet season for Cd and Pb, and during the dry season for Cr. The lack of statistical significance for these metals may reflect their complex biogeochemical cycling, including adsorption-desorption equilibria, redox transformations, and sediment-water partitioning that buffer against rapid seasonal fluctuations (Kumari *et al.,* 2022). However, the elevated standard deviations observed, particularly for Cd in the dry season (SD = 0.0075), suggest episodic contamination events that warrant further investigation.

Histopathological Alterations in *Clarias gariepinus*

The histopathological examination of *C. gariepinus* organs revealed severe, species-specific tissue alterations that directly correlate with the heavy metal concentrations measured in water and fish tissues. These findings provide morphological evidence of the toxicological impact of metal contamination on vital organ systems.

Gill Alterations: Catfish gills exhibited pronounced necrosis of gill filaments at all sampling sites, with Site A showing the most severe damage at high magnification (×400) characterized by disintegration of lamellar epithelium and loss of structural integrity (Plate 1). Site C also showed focal necrosis (Plate 2), though less severe than Site A, suggesting intermittent or lower-intensity exposure. The gill is the primary interface between fish and their aquatic environment, accounting for over 50% of the surface area for gas exchange, ion transport, and waste excretion (Yancheva *et al.,* 2016). The observed necrotic changes are consistent with direct toxic insult from waterborne heavy metals, particularly Pb and Cd, which bind to negatively charged sites on gill epithelium, disrupting osmoregulation and respiratory function (Playle, 1998; Mallatt, 1985). Similar gill pathologies have been reported in *C. gariepinus* exposed to lead (Olojo *et al.,* 2005) and in various fish species exposed to mixed metal contamination (Camargo and Martinez, 2007). The necrosis of gill filaments would inevitably compromise oxygen uptake, leading to systemic hypoxia, reduced metabolic capacity, and increased susceptibility to secondary stressors (Georgieva *et al.,* 2014).

Liver Alterations: The liver of *C. gariepinus* showed extensive histopathological changes across all sites, with Site B exhibiting the most severe damage. At Site A, congested hepatic veins and widespread necrosis of hepatocytes were observed (Plate 3), indicating impaired blood flow and direct chemical injury (Figueiredo-Fernandes *et al.,* 2007). Site B showed extensive necrosis of hepatocytes with complete cellular breakdown in some regions (Plate 4), suggesting prolonged or high-intensity exposure to hepatotoxic agents. Site C presented a unique finding: a parasitic cyst alongside necrotic hepatocytes, with normal portal veins (Plate 5), indicating concurrent parasitic infection (possibly Clinostomum spp.) and toxic insult.

The liver is the primary detoxification organ in fish, responsible for metabolizing xenobiotics, synthesizing plasma proteins, and maintaining metabolic homeostasis (Genten *et al.,* 2009). The observed hepatocyte necrosis and vascular congestion are consistent with metal-induced oxidative stress, where heavy metals such as As, Cd, and Pb generate reactive oxygen species (ROS) that damage cellular membranes, proteins, and DNA (Tchounwou *et al.,* 2012). The presence of a parasitic cyst at Site C suggests that metal-induced immunosuppression may have increased susceptibility to opportunistic infections, as heavy metals are known to suppress antibody production and compromise immune function in fish (Datta *et al.,* 2009; Nayak *et al.,* 2007). Similar hepatic lesions have been reported in *C. gariepinus* from polluted aquatic systems in South Africa (Marchand *et al.,* 2009) and in Oreochromis mossambicus exposed to Cd and Zn (van Dyk *et al.,* 2007).

Kidney Alterations: Renal tissue in catfish showed congestion of blood vessels and necrosis of the parenchyma across all sites. Site A exhibited pronounced necrosis of kidney parenchyma at both low (×50) and high (×400) magnifications (Plate 6), with disrupted renal tubules suggestive of ischemic injury or nephrotoxic compound exposure. Site B showed congestion of renal vessels and necrosis of renal tubules (Plate 7), indicating combined circulatory and direct toxic injury. Site C presented congested blood vessels and parenchymal necrosis (Plate 8), consistent with systemic toxicity.

The kidney is essential for osmoregulation, excretion of nitrogenous wastes, and maintenance of fluid and electrolyte balance (Ojeda *et al.,* 2003). In freshwater fish like *C. gariepinus*, the kidney produces copious dilute urine to eliminate excess water, making it particularly vulnerable to waterborne toxins (Mobjerg *et al.,* 2004). The observed tubular necrosis and vascular congestion are characteristic responses to heavy metal exposure, particularly Cd and Pb, which accumulate in renal tissues and impair filtration and reabsorption functions (Thophon *et al.,* 2003; Giari *et al.,* 2007). The absence of significant vascular congestion in catfish kidneys compared to tilapia may reflect species differences in susceptibility or adaptive responses, though the parenchymal necrosis indicates substantial functional impairment.

Heart Alterations: Cardiac tissue in catfish showed distinct pathological changes that varied by site. Site A exhibited congestion of heart vessels without overt necrosis (Plate 10), indicating circulatory stress possibly secondary to gill damage or systemic inflammation. Site B revealed notable aggregation of white blood cells within the cardiac muscle (Plate 11), suggesting an active inflammatory response and potential infectious etiology such as bacterial or viral myocarditis. The absence of necrosis in catfish heart contrasts with the severe myocardial necrosis observed in tilapia, implying that catfish may exhibit different pathological responses to cardiac stressors.

The heart is responsible for maintaining systemic circulation and oxygen delivery to tissues. Vascular congestion and inflammatory infiltration can impair cardiac output, leading to reduced tissue perfusion and exacerbating hypoxic conditions already established by gill damage (Marchand *et al.,* 2012). The inflammatory response observed at Site B may represent a compensatory mechanism attempting to contain tissue damage, though chronic inflammation can itself contribute to cardiac dysfunction. These findings align with those of Mathews *et al*. (2014), who documented Cd-induced cardiotoxicity in fish, and Yin *et al*. (2018), who reported Pb-induced cardiac inflammation in Carassius auratus.

The histopathological findings in *Clarias gariepinus* from Biu Dam revealed distinct patterns of organ susceptibility and severity of tissue damage that reflect the species' unique physiological and ecological characteristics. As a benthic-dwelling species, *C. gariepinus* exhibits particular vulnerability to sediment-associated contaminants, which has important implications for its use as a bioindicator of aquatic pollution.

Clarias gariepinus is a predominantly bottom-dwelling fish species that feeds on benthic invertebrates, detritus, and organic matter present in the sediment layer (Authman *et al.,* 2015). This feeding strategy exposes the species to significantly higher concentrations of particle-bound heavy metals compared to pelagic or surface-feeding fish. Sediments act as both sinks and sources of metal contaminants, often containing metal concentrations several orders of magnitude higher than overlying water (Kumar *et al.,* 2019). The present study confirmed this vulnerability, with catfish from all three sites showing substantial metal bioaccumulation, particularly in liver and kidney tissues.

The bottom-dwelling habit of *C. gariepinus* explains the elevated lead concentrations observed at Site C (Gwalam Area), where liver (0.030 mg/kg) and heart (0.028 mg/kg) tissues exceeded WHO limits by 30-fold. Sediment resuspension during periods of high human activity or rainfall events likely increases the bioavailability of sediment-bound metals, which are then ingested along with food items or absorbed through the gills (Rajeshkumar and Li, 2018).

The results demonstrated that the liver and kidney of *C. gariepinus* are the primary target organs for heavy metal accumulation and toxicity, followed by gills and heart. This organotropism reflects the physiological functions of these tissues and the routes of metal uptake and distribution.

Liver as Primary Detoxification Organ: The liver exhibited the most severe histopathological alterations among all organs examined, with extensive hepatocyte necrosis and vascular congestion observed at Sites A and B, and the additional finding of a parasitic cyst at Site C. The liver's central role in xenobiotic metabolism, including the biotransformation and excretion of heavy metals, makes it particularly susceptible to toxic injury (Genten *et al.,* 2009). Metals absorbed through the gills or gastrointestinal tract are transported via the hepatic portal system to the liver, where they are sequestered, metabolized, and excreted into bile (Figueiredo-Fernandes *et al.,* 2007). This continuous exposure and processing of metals place the liver at high risk for oxidative stress, cellular damage, and necrosis.

The severity of hepatic lesions in *C. gariepinus* from Biu Dam is consistent with the high metal concentrations measured in liver tissue, particularly As (0.045 mg/kg at Site A) and Pb (0.030 mg/kg at Site C). These metals are known hepatotoxicants that induce lipid peroxidation, protein carbonylation, and DNA damage through the generation of reactive oxygen species (Tchounwou *et al.,* 2012). Similar findings have been reported in *C. gariepinus* from polluted South African dams, where Marchand *et al*.

(2009) documented hepatic vacuolation, nuclear pyknosis, and fatty degeneration associated with metal contamination.

Kidney as Excretory and Filtration Organ: The kidney showed significant pathological changes across all sites, including vascular congestion and tubular necrosis. As the primary excretory organ responsible for filtering blood and eliminating metabolic wastes, the kidney receives a substantial proportion of postbranchial blood flow, making it vulnerable to bloodborne toxicants (Ojeda *et al.,* 2003). The observed tubular necrosis is particularly significant, as the proximal tubules are responsible for the reabsorption of filtered nutrients, ions, and water, and are highly sensitive to nephrotoxic agents including Cd and Pb (Thophon *et al.,* 2003).

The renal lesions in *C. gariepinus* from Biu Dam are consistent with the pattern of Cd accumulation observed in kidney tissue (0.032 mg/kg at Site A). Cadmium is well-documented to cause proximal tubular damage through disruption of mitochondrial function, inhibition of Na^+/K^+-ATPase activity, and induction of apoptosis (Žikić *et al.,* 2001). The presence of hyaline casts and cellular debris within tubular lumina, observed in the present study, indicates impaired filtration and reabsorption capacity that could lead to metabolic waste accumulation and osmoregulatory failure.

Gills as Primary Route of Metal Entry: The gill tissue of *C. gariepinus* exhibited necrosis of gill filaments at all sites, with Site A showing the most severe damage. The gill is the first organ to come into contact with waterborne contaminants, and its large surface area (accounting for over 50% of the fish's surface area) facilitates rapid metal uptake (Yancheva *et al.,* 2016). The observed necrosis and epithelial lifting are characteristic responses to metal toxicity, resulting from direct cytotoxic effects on gill epithelial cells and disruption of ion transport mechanisms (Mallatt, 1985).

The severity of gill lesions in *C. gariepinus* correlates with the high As concentrations in water (0.14-0.31 mg/L) and the positive correlation between Pb and turbidity ($r = 0.860$, $p < 0.05$), indicating that particle-bound metals contribute to gill damage. Similar gill pathologies have been reported in *C. gariepinus* exposed to lead, where Olojo *et al*. (2005) documented lamellar fusion, epithelial lifting, and chloride cell proliferation.

Heart as Secondary Target Organ: The cardiac tissue of *C. gariepinus* showed vascular congestion at Site A and inflammatory cell aggregation at Site B, indicating that the heart is affected by metal-induced systemic toxicity, though to a lesser extent than the liver and kidney. The heart receives a portion of the cardiac output and is perfused by blood that may contain dissolved metals and inflammatory mediators released from damaged tissues (Marchand *et al.,* 2012). The aggregation of white blood cells at Site B suggests an inflammatory response, possibly triggered by metal-induced oxidative stress or secondary infection.

The lower severity of cardiac lesions compared to hepatic and renal damage reflects the heart's position as a secondary rather than primary target organ for metal toxicity. However, the observed vascular congestion indicates compromised circulatory function that could exacerbate hypoxic conditions already established by gill damage.

Adaptive Responses and Tolerance Mechanisms

Despite the severe histopathological alterations observed, *C. gariepinus* demonstrates certain adaptive responses that may enhance its survival in contaminated environments compared to more sensitive species. These include:

Mucous Cell Proliferation: The thickening of the mucous layer on gill epithelium, observed as a compensatory response to metal exposure, may help reduce metal absorption by binding and sequestering metal ions before they reach epithelial cells (Van Heerden *et al.,* 2004). This response, while protective in the short term, can impair gas exchange if excessive.

Metallothionein Induction: Although not measured in this study, *C. gariepinus* is known to possess robust metallothionein systems that bind and detoxify essential and non-essential heavy metals (Hogstrand, 2011). The species' ability to survive and reproduce in moderately polluted waters, as observed in Biu Dam, suggests effective induction of these protective proteins.

Accessory Air-Breathing Capacity: The facultative air-breathing capability of *C. gariepinus* allows it to supplement branchial oxygen uptake with aerial respiration when gill function is compromised by pollution (Fagbenro *et al.,* 2020). This adaptation may explain why catfish were able to survive in Biu Dam despite severe gill necrosis, whereas more stenoxic species would likely perish.

Limitations of Tolerance and Threshold Effects

While *C. gariepinus* exhibits tolerance to moderate pollution, the present study demonstrates that this tolerance has limits. The extensive necrosis observed in liver, kidney, and gill tissues indicates that metal concentrations in Biu Dam exceed the species' adaptive capacity. Chronic exposure to metal mixtures, as occurs in the dam, may overwhelm detoxification mechanisms and lead to cumulative tissue damage (Kumari *et al.,* 2022).

The presence of a parasitic cyst at Site C, observed only in catfish liver, suggests that metal-induced immunosuppression may have compromised the fish's ability to resist opportunistic pathogens. This finding is particularly significant as it indicates that sublethal metal exposure can increase susceptibility to infectious diseases, potentially leading to population declines even when metal concentrations are not directly lethal (Datta *et al.,* 2009).

Comparison with Other Populations of *Clarias gariepinus*

The histopathological alterations observed in *C. gariepinus* from Biu Dam are consistent with findings from other polluted water bodies in Nigeria and internationally. Rabiu *et al*. (2022) reported similar hepatic and renal lesions in *C. gariepinus* from Watari Reservoir, Kano State, attributing the damage to agricultural runoff and domestic waste. Marchand *et al*. (2009) documented comparable histopathological changes in *C. gariepinus* from two polluted dams in South Africa, including hepatocyte vacuolation, nuclear alterations, and inflammatory infiltrates.

However, the severity of lesions in Biu Dam catfish appears greater than in some other Nigerian water bodies, possibly reflecting the cumulative impacts of multiple anthropogenic activities within the catchment area. The unique finding of a parasitic cyst at Site C distinguishes Biu Dam as a site where metal pollution and infectious disease co-occur, posing compounded health risks to fish populations.

Ecological and Management Implications

The species susceptibility patterns observed in *C. gariepinus* have important implications for fisheries management and conservation. As a commercially important species and a major protein source for local communities, the health of *C. gariepinus* populations directly affects food security and livelihoods in the Biu region.

The demonstrated sensitivity of *C. gariepinus* to heavy metal contamination, combined with its bottom-dwelling habit, makes it an excellent sentinel species for monitoring sediment quality and ecosystem health. Regular histopathological assessment of catfish populations could provide early warning of deteriorating water quality before population-level effects become apparent (Stentiford *et al.,* 2003).

The findings also highlight the need for species-specific water quality guidelines for *C. gariepinus* that account for its unique ecology and susceptibility patterns. Current WHO/FAO guidelines, which are based primarily on human health considerations, may not adequately protect this ecologically and economically valuable species.

Public Health Implications

The findings of this study have significant implications for public health, as *C. gariepinus* is a major protein source for local communities in Biu and surrounding areas. The consumption of catfish from Biu Dam poses potential health risks due to the bioaccumulation of toxic heavy metals, particularly Pb, As, and Cd, in edible tissues.

Lead contamination is of greatest concern, with liver and heart tissues at Site C exceeding safety limits by 30-fold. Chronic Pb exposure in humans is associated with neurological impairment, particularly in children, as well as renal dysfunction, hypertension, and reproductive disorders (Tchounwou *et al.,* 2012). The developing nervous system is especially vulnerable to Pb neurotoxicity, with effects observed even at low exposure levels (Sfakianakis *et al.,* 2015).

Arsenic, a Class I human carcinogen (IARC, 1980), was found at concentrations 4.5 times above safety limits in catfish liver. Chronic As exposure is associated with skin lesions, peripheral neuropathy, cardiovascular disease, and cancers of the skin, bladder, and lungs (IARC, 2012). The presence of As in edible tissues, particularly liver which is often consumed, represents a significant cancer risk for regular fish consumers.

Cadmium, though present at concentrations approaching but not exceeding safety limits, still poses risks for chronic exposure. Cd accumulates in the human body with a biological half-life of 10-30 years and is associated with renal tubular damage, bone demineralization (Itai-itai disease), and increased cancer risk (El-Kady and Abdel-Wahhab, 2018).

The spatial variation in contamination levels suggests that the risk is not uniform across the dam. Catfish from Site C (Gwalam Area) pose the highest risk for Pb exposure, while Site A fish pose higher risks for As exposure. This spatial heterogeneity should inform targeted public health advisories and risk communication strategies.

Comparison with National and International Studies

The heavy metal concentrations observed in *C. gariepinus* from Biu Dam are comparable to or higher than those reported in other Nigerian water bodies. Bawuro *et al*. (2018) reported Pb concentrations ranging from 0.002 to 0.015 mg/kg in catfish from Lake Geriyo, Adamawa State, which are lower than the 0.030 mg/kg observed at Site C in this study. Similarly, Rabiu *et al*. (2022) documented As concentrations of 0.012-0.028 mg/kg in *C. gariepinus* from Watari Reservoir, Kano State, which are generally lower than the 0.045 mg/kg recorded at Site A in this study.

Internationally, the levels observed in Biu Dam exceed those reported from many contaminated sites. For example, Demirak *et al*. (2006) reported Pb concentrations of 0.005-0.012 mg/kg in Leuciscus cephalus from a stream in southwestern Turkey, while Uysal *et al*. (2009) documented Cd concentrations of 0.002-0.008 mg/kg in various fish species from Enne Dam Lake in Turkey. The elevated levels in Biu Dam reflect the cumulative impacts of agricultural runoff, domestic waste disposal, and the absence of industrial effluent treatment in the region. However, the levels are lower than those reported from highly industrialized areas. For instance, Ali *et al*. (2016) documented Pb concentrations up to 0.45 mg/kg in fish from the Karnaphuli River, Bangladesh, which receives untreated industrial effluents. The intermediate contamination levels in Biu Dam suggest that the dam is moderately polluted but with potential for further deterioration if current practices continue.

Environmental and Ecological Implications

The heavy metal contamination documented in this study has broader implications for the ecological health of Biu Dam and its associated ecosystems. The observed histopathological alterations indicate that fish populations are experiencing sublethal stress that may affect their growth, reproduction, and survival. Chronic metal exposure is known to impair reproductive function in fish, reducing fecundity, altering sex ratios, and increasing larval deformities (Sfakianakis *et al.,* 2015). The gill damage observed in catfish would reduce respiratory efficiency, limiting aerobic capacity and potentially reducing foraging efficiency and predator avoidance (Mallatt, 1985).

The bioaccumulation of metals in fish tissues also facilitates trophic transfer to higher-level consumers, including piscivorous birds, mammals, and humans. Biomagnification of certain metals, particularly methylmercury (though not measured in this study) and Pb, can concentrate these toxins at higher trophic levels, amplifying ecological and health risks (Authman *et al.,* 2015).

The presence of a parasitic cyst in catfish liver at Site C, combined with metal-induced immunosuppression, suggests that contaminated fish may be more susceptible to infectious diseases. This could lead to increased mortality rates and population declines, with cascading effects on the dam's ecological balance.

Study Limitations and Future Research Directions

While this study provides valuable insights into heavy metal contamination and histopathological alterations in *C. gariepinus* from Biu Dam, several limitations should be acknowledged. First, the study duration of six months (March to August 2024) captured only part of the annual hydrological cycle. Longer-term monitoring over multiple years would better characterize inter-annual variability and long-term trends in contamination levels.

Second, the study did not measure all potentially toxic metals, including mercury (Hg), nickel (Ni), and zinc (Zn), which may also contribute to the observed histopathological changes. Future studies should include a broader panel of metals and metalloids.

Third, the study did not quantify metal concentrations in sediments, which serve as both a sink and source of contaminants in aquatic ecosystems. Sediment analysis would help identify contamination sources and predict future release of metals into the water column.

Fourth, while histopathological examination provides morphological evidence of toxicity, it does not elucidate the molecular mechanisms underlying the observed damage. Future studies should incorporate biochemical and molecular biomarkers, including oxidative stress markers (e.g., superoxide dismutase, catalase, glutathione), metallothionein expression, and genotoxicity assays (e.g., comet assay, micronucleus test), to provide a more comprehensive assessment of metal toxicity.

Fifth, the study did not assess the health status of human consumers or quantify the dietary intake of heavy metals through fish consumption. Future research should include human health risk assessments, including hazard quotient and carcinogenic risk calculations, to inform public health policy.

CONCLUSION

The findings of this study demonstrate that *Clarias gariepinus* from Biu Dam are exposed to significant heavy metal contamination, particularly lead, arsenic, and cadmium, with concentrations exceeding WHO/FAO permissible limits in several tissues. The spatial and seasonal variations in metal accumulation reflect the influence of anthropogenic activities, particularly agricultural runoff and domestic waste disposal, on water quality and fish health. The severe histopathological alterations observed in gills, liver, kidney, and heart tissues provide direct morphological evidence of metal-induced toxicity, confirming that Biu Dam is ecologically compromised.

The species-specific patterns of metal accumulation and tissue damage highlight the value of *C. gariepinus* as a bioindicator species for sediment-associated contaminants, given its benthic feeding habits. The correlation between heavy metal concentrations and histopathological lesions establishes a causal link between environmental contamination and biological damage, with implications for fish population health and human food safety.

The public health implications of these findings are substantial, as regular consumption of catfish from Biu Dam, particularly from Site C (Gwalam Area), may pose risks of chronic metal poisoning. Urgent interventions are needed, including source identification and remediation, continuous water quality monitoring, public health advisories, and promotion of alternative protein sources through sustainable aquaculture. These measures are essential to protect both the ecological integrity of Biu Dam and the health of the communities that depend on its resources.

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