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Evaluation of Heavy Metals and Histopathology in *O. nioloticus* and *C. gariepinus* of Two Selected Corridors (Almakashi and Gwani) of River Gongola in Gombe State, Nigeria

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ABSTRACT

Agricultural runoff, industrial effluents, and domestic waste are examples of anthropogenic stressors that contaminate freshwater. This is particularly applicable to Nigeria's Gongola River. This study examined the accumulation of heavy metals and histopathological alterations in *Oreochromis niloticus* and *Clarias gariepinus* from Almakashi, Gwani, and the reference site Balanga Dam. We quantified the concentrations of copper (Cu), cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), arsenic (As), manganese (Mn), and iron (Fe) in the gills, liver, and kidneys. The gills of *C. gariepinus* from Almakashi exhibited the highest concentrations of Cu (17.20±1.17 µg/g), As (44.93±3.72 µg/g), and Ni (34.83±5.20 µg/g). The kidney tissues from Balanga exhibited the lowest concentrations of Fe (10.16±1.25 µg/g), Mn (1.10±0.20 µg/g), and Cu (4.23±0.30 µg/g) among O. niloticus tissues. Cadmium and lead concentrations were predominantly undetectable in kidney and liver tissues across all locations. Histopathological examination revealed that gill alterations (epithelial lifting, hyperplasia, fusion) were observed in *O. niloticus* from Almakashi in up to 100% of cases, while kidney necrosis was observed in C. gariepinus in up to 44.44% of cases. Steatosis (10–33.34%) and sinusoidal congestion (up to 14.29%) were among the hepatic lesions. Metal accumulation in Almakashi and Gwani was significantly greater than in Balanga Dam ($p < 0.05$). *C. gariepinus* typically exhibited elevated tissue concentrations, likely due to their consumption of benthic organisms. These findings validate that these species serve as effective bioindicators and underscore the need to rehabilitate the Gongola River and restore its ecosystems.

INTRODUCTION

Human activities, including urban development, domestic waste disposal, industrial discharges, and agriculture, are major contributors to environmental stress in freshwater ecosystems, leading to significant ecological and health challenges for aquatic life [1,2]. These ecosystems are increasingly subjected to a variety of natural and human-induced stressors that can interact in complex ways, sometimes resulting in unexpected negative outcomes [3,4]. Despite growing concern, the combined effects of multiple stressors on fish physiology and health are not well understood, making it difficult to predict their cumulative impact on fish populations [5,6]. In rivers affected by human activity, such as the Gongola River in Gombe State, Nigeria, industrial pollutants, agricultural runoff, and urban waste are key stressors that threaten aquatic organisms, particularly economically and

nutritionally important species like Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*) [7,8]. These species also serve as bioindicators of environmental contamination [9,0]. The interaction of multiple stressors can disrupt detoxification processes, increase pollutant accumulation, and trigger inflammatory and oxidative stress responses, leading to cellular damage and impaired fish growth and condition [11-13].

The Gongola River is vital for local communities, providing water for domestic use, agriculture, and fishing [14]. However, pollutants such as heavy metals from agriculture, domestic waste, and industry accumulate in the river, entering the food chain and causing reduced biodiversity, tissue damage, and functional impairments in aquatic fauna [7,10]. Farming introduces agrochemicals [15], while domestic and industrial activities further degrade water quality [8,16]. These combined impacts threaten fish health, population dynamics, and food safety, as pollutant bioaccumulation may render fish unsafe for human consumption [9,13].

Despite the importance of *O. niloticus* and *C. gariepinus* to the region's economy and nutrition, there is limited information on how heavy metals affect the histopathology of their organs in the Gongola River. This knowledge gap hampers effective management and pollution mitigation strategies. Therefore, this study aims to assess the influence of anthropogenic activities on the health of these fish species in two corridors of the Gongola River, using the Balanga Dam as a reference site. Specifically, the study will measure heavy metal concentrations in water, sediment, and fish samples from Almakashi, Gwani, and Balanga Dam. Moreover, the study examines the histopathology of key organs (gills, liver, and kidney) in *O. niloticus* and *C. gariepinus* from the study locations. This research will provide critical insights into the broader environmental and public health implications of pollution in the Gongola River, informing strategies for the sustainable management of its aquatic resources.

MATERIALS AND METHODS

Study Area

The Gongola River, situated in northeastern Nigeria, stands as the primary tributary of the Benue River. The upper course of the river and most of its tributaries are characterized by seasonal streams that swiftly fill up in August and September. It originates from the eastern slopes of the Jos Plateau, the Gongola flows into the Gongola Basin, following a northeast trajectory until it reaches Gombe Abba, then Nafada. It takes a southward turn from Nafada, passing through the corridors of the Almakashi landing site and proceeding to the Dadin Kowa Dam, after traversing the Gwani River corridor in the Yamaltu-Deba Local Government of Gombe State [17,18]. As it continues its southern course, the Gongola merges with its tributaries (Balanga dam and the Dogon Daji River), increasing its volume before ultimately joining the Benue River near the town of Numan.

The river exhibits a seasonal flow pattern, with high water levels during the rainy season (typically May to October) and significantly reduced flow during the dry season (November to April). Seasonal variations in flow are influenced by rainfall patterns across the Jos Plateau and surrounding regions. During the rainy season, the Gongola River often overflows its banks, creating extensive floodplains that support agriculture and diverse ecosystems.

These floodplains are crucial for local agriculture, providing fertile soil for crops [19]. The river and its floodplains are extensively utilized for irrigation and agriculture, supporting crops such as rice, maize, and vegetables. The fertile soils of the floodplains are crucial for local food production. Conversely, the Gongola River basin is home to a diverse array of flora and fauna, including aquatic species, riparian vegetation, and terrestrial wildlife. The seasonal floodplains provide critical habitats for many species [19]. The average annual rainfall in the sampled regions is 842.08 mm, with average temperatures ranging from 21.69 ºC to 34.47 ºC. The direct distance from Almakashi to Gwani is approximately 36 km [19].

Almakashi River Corridor of Gongola River Complex

Almakashi is a crucial catchment area of the Gongola River, situated beneath the Dadin Kowa Dam and recognized as one of the largest fish landing sites in Gombe State. The majority of its residents are artisanal fishermen who migrated from Benue State, settled, and established a small village named Almakashi. Their primary occupation is fishing, and as a result, they possess expertise in fishing activities [17]. Additionally, a significant portion of the population engages in peasant farming.

Almakashi's river corridor is perennial, consistently receiving water from the Ashaka river corridor. The Almakashi River proves highly productive, serving as a source of fish meat consumed not only in Bajoga and Kwami Local Government Areas but also in certain parts of Gombe town in Gombe State [19]. It is specifically located in the Bajoga Local Government Area of Gombe State, positioned at longitude 10º44' 38.15''N and latitude 11º30' 02.13''E (**Fig. 3**).

Gwani River Corridor of the River Gongola Complex

The water level in the Gwani corridor experiences significant increases due to the damming of the Dadin Kowa reservoir, leading to the displacement of numerous houses near the river. In response, residents who chose to remain, despite compensation offers, were compelled to relocate away from the river corridor. The Gongola River passes through the village of Gwani, dividing it into Gwanin Gabar (eastern Gwani) and Gwanin Yamma (western Gwani), establishing an essential sub-catchment corridor within the Gongola River complex [20]. Gwani, an ancient town inhabited by the Tera (Terawa tribe), is situated in the Yamaltu-Deba Local Government Area of Gombe State.

The primary occupation of Gwani's residents is farming, while fishing activities are predominantly carried out by the Hausawa, who migrated long ago from Jigawa, Sokoto, and Kano states. The practice of dry-season farming has led to the degradation of vegetation along the riparian forest, impacting the riverbanks due to the erosion and silting of particles into the water [19,20]. The residents of Gwani rely directly on the river water for various domestic activities such as drinking, bathing, cooking, and washing clothes. Gwani is positioned between longitude 10º23'7.035"N and 10º25'04.89"N, as well as latitude 11º31'32.013" and 11º26'40.24"E (**Fig. 1**).

Balanga Dam (Reference Dam)

The reference river of this study is the Balanga Dam, situated in the Balanga Local Government Area of Gombe State, is a notable dam characterized by water emerging from beneath the sedimentary rocks. The water flows westward from the dam until it meets River Dogon Daji, ultimately emptying into the lower reaches of the Gongola River, thereby playing a crucial role in replenishing the Gongola River. It is located at longitudes 9°35'0" and 10°0'0" N and latitudes 11°15'0" and 11°40'0" E (**Fig. 1**).

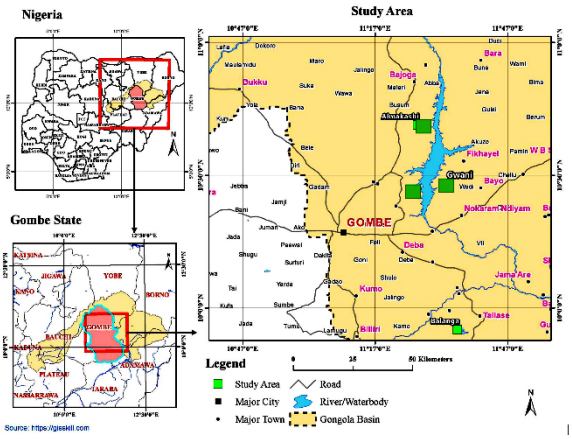

Fig. 1. Map of the study area indicating Sampling Locations of the Gongola River.

The Balanga Dam directly affects the hydrology, water resources management, and socio-economic dynamics of the Gongola River basin. It regulates the flow of water downstream, including into the Gongola River, by impounding water during periods of high flow and releasing it during dry periods. This regulation aids in managing floods and ensuring water availability for various purposes downstream [17, 21]. The dam is a key water resource for both domestic and agricultural/irrigational purposes for the communities residing along its coast. Balanga Dam's water is known for its high physical clarity, and it serves as a vital source of water for the surrounding communities [22]. The Balanga Dam was chosen as the reference reservoir due to its unique characteristic: the water source originates within the dam and flows into the River Gongola, meaning that water and waste materials are constantly being discharged from the dam into the river. This continuous outflow ensures that the physicochemical parameters of the dam's water remain relatively constant [22].

Sampling

Monthly sampling sessions took place between January 2020 and June 2021, focusing on collecting water, sediment, and fish samples from the landing sites within the Gongola River Corridors (Almakashi and Gwani) and Balanga (the reference) dam. The chosen sites were selected to provide a representative sample of the rivers, as they are among the major fish landing sites in Gombe, while ensuring ease of accessibility. Balanga Dam was chosen as a reference dam due to its low level of anthropogenic activities. Detailed records of sampling locations (**Fig. 1**), timing, and the total number of species during each sampling period were meticulously recorded. For consistency across the study areas, the water bodies were divided into three zones: Station I, Station II, and Station III, following the methodologies of [23] and [24].

Fish Sampling

In each sampling location and during every sampling round, *Clarias gariepinus* and *Oreochromis niloticus* were captured and identified using the standard reference identification manual [25]; [26]. The collected specimens were measured and dissected in situ. Fish were weighed in grams using a weighing balance (Adams PG 690), and their total and standard lengths were measured on the measuring board in centimeters using a centimeter ruler in which the total length (TL) was measured from the tip of the snout to the tip of the longer lobe of the tail fin in a straight line and standard length (SL) was measured from the tip of the snout to the posterior end of the last vertebra, excluding the length of the tail fin [27].

In the field, the liver, spleen, and gonads were removed, weighed, and stored for later analysis. In the laboratory, samples from the second pair of gills, a piece of liver, a piece of kidney from the mid-section were removed and placed in fixative (10% buffered formalin) for later processing. Heavy metal concentrations were determined in the selected fish organs (gills, liver, and kidney) using a flame atomic absorption spectrophotometer (Model Buck-205) following the guidelines of [28]. Each fish sample was digested and the digested samples were filtered, diluted, and labeled for analysis [28]. Standard reference material (Lake Superior fish 1946 NIST, National Institute of Standards and Technology, USA) and known concentration samples were used to check accuracy [29], with metal concentrations expressed as mg/kg dry weight in homogenized fish organ. The metal recovery range during analysis ranged between 95% and 110%.

Qualitative Histological Assessment

The slides of gill, liver, and kidney histology from *O. niloticus* and *Clarias gariepinus* were meticulously examined under light microscopy (Leica DM 750 shine me TV screen attached and Leica DM 500). Various structures within the different organs were identified, and photomicrographs were captured and measured using IM50 Image Manager Software.

Semi-Quantitative Histological Assessment

A standardized semi-quantitative histological assessment, based on the modified protocol established by [30] and further refined by [31], was employed to measure the histopathological alterations evident in gill, liver, and kidney histology slides. The evaluation, carried out by an expert histologist through multiple assessments (two to three times per slide) using a light microscope, ensures unbiased and precise results. The assessment initially considered five reaction patterns, as described by [30], and an additional pattern introduced by [32]. Each organ underwent scrutiny based on the reaction patterns (Circulatory Disturbances (CD), Regressive Changes (RC), Progressive Changes (PC), Tumour and intersex [33,34].

Importance factor (w)

[30] introduced an importance factor ranging from 1 to 3 for each alteration. The degree of a lesion is determined by its pathological importance, indicating how it affects organs and the fish's ability to survive. The three importance factors are classified as follows: (1) Minimal pathological importance, signifying that the lesion is easily reversible once exposure to the irritant ends; (2) Moderate pathological importance, indicating that the lesion is reversible in most cases if the stressor is neutralized; and (3) Marked pathological importance, implying that the lesion is generally irreversible, leading to partial or total loss of organ function.

Score value (a)

For each alteration, histologists assign a score value (a) from 0 to 6 to each alteration based on the degree and extent of the change. The scoring criteria are as follows: (0) unchanged; (2) mild occurrence or a focal alteration; (4) moderate occurrence or present in 50% of the tissue assessed; and (6) severe occurrence or an alteration present throughout (100%) the tissue assessed [34].

Organ index (Iorg)

This index measures the extent of damage to an organ, allowing for a comparison of the degrees of damage within the same organ across different individuals. The calculation is expressed as:

$$I_{org} = \Sigma_{rp} \Sigma_{alt} (a_{org\ rp\ alt} \times w_{org\ rp\ alt})$$

Where,
org = organ (constant); rp = reaction pattern; alt = alteration; a = score value; w = importance factor. This index is the summation of the multiplied importance factors and score values for all alterations identified within the assessed organ [33].

Fish index (Ifish)
The fish index serves as a metric for the overall health status of the fish, considering histological alterations observed in all organs. Calculated uniformly for each fish, this index allows for comparisons between individuals and is determined as follows:

$$I_{fish} = \Sigma_{org}\Sigma_{rp}\,\Sigma_{alt}\,(a_{\text{org rp alt}} \times w_{\text{org rp alt}}).$$

Where: org = organ; rp = reaction pattern; alt = alteration; a = score value; w = importance factor. This index is the summation of the multiplied importance factors and score values for all alterations identified within the assessed organ [32].

Percentage prevalence
The percentage prevalence of the recorded histological lesions in different tissues of *C. gariepinus* and *O. niloticus,* and in different locations was computed following the procedure of [35] and [36] viz:

$$\text{Prev. Fish Index (\%)} = \frac{\text{Number of specific alteration in a fish of a particular location}}{\text{Total number examined in the fish of that location}} \times 100$$

$$\text{Fish organ index (\%)} = \frac{\text{Number of lesions in a specicific organ of a particular fish}}{\text{Total number of thatorgan examined for such lesion}} \times 100$$

Statistical Analysis
The obtained data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 22 software. The Shapiro-wilk test was applied to test the normality of the obtained data. Descriptive statistics were used to calculate the means of all experimental groups, and the data were presented as the mean ± standard deviation (SD). These tests were used to assess whether there was a significant difference between independent and dependent variables in each of the following experimental groups: fish heavy metals and histopathology compared to location, seasons, and the sampled fish. In cases where differences were observed, *Duncan's post hoc* tests were conducted to examine the degree of variation. Values of $p < 0.05$ were considered significant.

RESULTS

Metal concentration in the organs of *C. gariepinus* and *O. niloticus*
Metal accumulation in the gills, kidney, and liver of *C. gariepinus* and *O. niloticus* was investigated in **Tables 1**, **2,** and **3**, respectively. A significant difference was observed between the Balanga dam and the two river corridors (Almakashi and Gwani) ($p < 0.05$).

Copper (Cu)
The analysis of copper accumulation in fish organs revealed a descending order of accumulation as gills > liver > kidney, except for the organs of *C. gariepinus* from the Gwani river, where no copper was detected in the liver (**Table 1**). In contrast, *O. niloticus* from Balanga dam showed the highest concentration in the liver (liver > gills > kidney) (**Table 2**). The gills of *C. gariepinus* from Almakashi had a mean concentration of 17.20±1.17 µg/g (**Table 1**), while the lowest mean concentration of 4.23±0.30 µg/g was recorded in the kidney of *O. niloticus* from the Balanga dam (**Table 2**).

Cadmium (Cd)
Both the gills and the liver of *O. niloticus* from Almakashi had the highest and lowest cadmium mean accumulation values of 2.33±4.04 µg/g and 01.00±0.17 µg/g, respectively (**Table 2**). No cadmium was detected in the kidney and liver, except in the liver samples obtained from *O. niloticus* of Almakashi (01.00±0.17 µg/g) and Gwani (0.16±0.28 µg/g), respectively (**Table 2**).

Table 1. Metal Accumulation in the Organs of *C. gariepinus* Obtained in 2020 and 2021 in Almakashi, Gwani and Balanga.

Organ	Loc.	Cu (µg/g)	Cd (µg/g)	Cr (µg/g)	Pb (µg/g)	Ni (µg/g)	As (µg/g)	Mn(µg/g)	Fe (µg/g)
Gills	Alm	17.20±1.17^{a}	0.43±0.75^{a}	7.53±0.40^{a}	0.06±0.11^{b}	34.83±5.20^{a}	37.86±5.01^{a}	8.33±5.23^{a}	22.53±0.90^{a}
	Gwn	14.96±2.13^{a}	0.36±0.63^{a}	7.16±0.32^{a}	0.1±0.17^{a}	35.66±10.88^{a}	44.93±3.72^{a}	7.7±9.78^{a}	25.4±1.08^{a}
	Blg	13.9±2.95^{a}	0.26±0.30^{a}	6.13±1.26^{a}	0.03±0.05^{b}	34.53±5.68^{a}	27.1±2.65^{a}	1.7±0.10^{b}	22.00±0.17^{a}
Kidney	Alm	12.43±0.30^{b}	0.00±0.00^{b}	5.33±0.15^{a}	0.00±0.00^{c}	27.13±0.20^{a}	24.66±4.57^{b}	5.33±0.25^{a}	12.8±0.3^{b}
	Gwn	0.00±0.00^{c}	0.00±0.00^{b}	5.3±0.45^{a}	0.06±0.11^{b}	26.5±0.20^{b}	22.83±2.81^{b}	5.2±0.5^{a}	12.13±0.30^{b}
	Blg	09.2±0.20^{b}	0.00±0.00^{b}	2.66±0.15^{c}	0.00±0.00^{c}	13.6±0.26^{c}	12.13±0.35^{c}	2.43±1.36^{b}	10.16±1.25^{c}
Liver	Alm	12.43±0.30^{b}	0.00±0.00^{b}	5.33±0.15^{a}	0.00±0.00^{c}	27.13±0.20^{a}	24.66±4.57^{b}	5.33±0.25^{a}	12.8±0.3^{b}
	Gwn	0.00±0.00^{c}	0.00±0.00^{b}	5.3±0.45^{a}	0.06±0.11^{b}	26.5±0.20^{b}	22.83±2.81^{b}	5.2±0.5^{a}	12.13±0.30^{b}
	Blg	10.46±0.60^{b}	0.00±0.00^{b}	4.66±0.20^{b}	0.00±0.00^{c}	7.53±3.33^{c}	17.66±3.23^{c}	1.6±0.3^{b}	11.83±0.30^{b}

Keywords: Loc= Location, Alm= Almakashi;Gwn=Gwani;Blg = Balanga; Cu= Copper; Cd= Cadmium; Pb = lead; Ni= Nickel; As= Arsenic; Mn= Manganese; Fe= Iron, 0.000= below detectable limit, NESREA = National Environmental Standard and Regulation Enforcement Agency. Same superscript in the same column indicates no significant difference while different values at the same column show significant difference.

Table 2. Heavy metals in the organs of *O. niloticus* obtained in 2020 and 2021.

Fish	Location	Cu (µg/g)	Cd (µg/g)	Cr ((µg/g)	Pb (µg/g)	Ni (µg/g)	As (µg/g)	Mn(µg/g)	Fe (µg/g)
Gills	Almakashi	6.36±0.49^{c}	2.33±4.04^{a}	4.6±0.26^{b}	0.66±0.76^{a}	37.73±6.53^{a}	40.66±1.92^{a}	5.5±0.20^{a}	23.8±0.09^{a}
	Gwani	5.4±1.22^{c}	1.06±1.84^{a}	3.86±0.70^{b}	0.00±0.00^{c}	33.96±8.56^{a}	24.7±0.19^{b}	5.63±0.30^{a}	24.60±6.84^{a}
	Balanga	4.4±0.81^{c}	0.36±0.63^{a}	2.46±0.40^{c}	0.00±0.00^{c}	17.97±13.06^{b}	25.46±4.67^{b}	5.00±2.00^{a}	23.8±0.09^{a}
Kidney	Almakashi	4.56±0.72^{c}	0.00±0.00^{b}	3.33±0.35^{b}	0.00±0.00^{c}	21.8±0.45^{b}	25.4±0.29^{b}	4.06±0.41^{b}	22.4±0.26^{a}
	Gwani	4.23±0.30^{c}	0.00±0.00^{b}	3.83±0.35^{b}	0.00±0.00^{c}	21.33±0.25^{b}	12.00±0.10^{c}	2.4±0.7^{b}	14.10±0.25^{b}
	Balanga	2.06±1.79^{c}	0.00±0.00^{b}	2.53±0.15^{c}	0.00±0.00^{c}	19.9±0.40^{b}	23.2±0.36^{b}	1.10±0.20^{b}	13.66±0.41^{b}
Liver	Almakashi	6.33±0.86^{c}	0.1±0.17^{b}	1.33±0.05^{c}	0.00±0.00^{c}	17.46±4.89^{b}	12.46±0.15^{c}	2.3±0.20^{b}	17.60±0.43^{a}
	Gwani	5.8±0.45^{c}	0.16±0.28^{a}	1.06±0.15^{c}	0.00±0.00^{c}	15.00±0.45^{c}	17.66±3.23^{c}	2.53±0.25^{b}	17.50±0.75^{a}
	Balanga	4.9±0.45^{c}	0.00±0.00^{b}	0.96±0.25^{c}	0.43±0.75^{a}	11.33±2.55^{c}	11.60±0.00^{c}	1.4±0.30^{b}	16.70±0.30^{b}

Keywords: Cu= Copper; Cd= Cadmium; Pb = lead; Ni= Nickel; As= Arsenic; Mn= Manganese; Fe= Iron, 0.000= below detectable limit, NESREA = National Environmental Standard and Regulation Enforcement Agency. Same superscript in the same column indicates no significant difference while different values in the same column show significant difference.

Table 3. Gill Index.

Gills	N=12	*Oreochromis niloticus* (N=7)	*Clarias griepinus* (N=5)	Total (N=12)	
	Circulatory	0(0%)	2 (26.8%)	2 (13.5%)	
	Regressive	1 (12.5%)	2 (26.8%)	3(20%)	
	Progressive	6 (75%)	1(14.3%)	7(46.7%)	
	Inflammation	0	0	0	
	Control	0(0%)	0(0%)	0(0%)	
	Fish Gill Index	7(58.33%)	5(41.67%)	12 (100%)	
	In terms of location	total = 07		total = 05	total= 12
Almakashi	*Oreochromis niloticus*	4(57.14%)	*Clarias gariepinus*	2(40%)	Total = 6(50%)
Gwani	*Oreochromis niloticus*	3(42.86%)	*Clarias gariepinus*	3(60%)	Total= 6(50%)
Fish Gill Index	Almakashi	6(50%)	Gwani	6(50%)	12(100%)
	In terms of species				
Oreochromis niloticus	Almakashi	4(57.14%)	Gwani	3(42.86%)	Total= 7(58.33%)
Clarias gariepinus	Almakashi	2(40%)	Gwani	3(60%)	Total=5(41.67%)
Fish Gill Index	*Oreochromis niloticus*	Total= 7(58.33%)	*Clarias gariepinus*	Total=5(41.67%)	12(100%)

The concentrations of Cd in the gills, kidney, and liver of Almakashi and Gwani did not significantly differ from the mean values obtained in Balanga dam ($p > 0.05$). Additionally, the gills, kidneys, and liver of C. gariepinus showed no significant difference compared to those of *O. niloticus*. Gill tissue did not differ significantly from the other analysed organs (liver and kidney).

Chromium (Cr)

The mean accumulation of chromium in the gills of *C. gariepinus* from Almakashi had the highest concentration of 7.53±0.40µg/g (**Table 1**), while the lowest mean accumulation of 0.96±0.25µg/g was observed in the liver of *O. niloticus* from Balanga dam (**Table 2**). The mean values obtained in the organs of samples from Almakashi and Gwani differed significantly from those obtained in Balanga dam ($p < 0.05$). Accumulation of chromium in the gills differed significantly from that in the liver and kidney. Additionally, the accumulations of chromium in the organs of *C. gariepinus* significantly differed from those of *O. niloticus* ($p < 0.05$).

Lead (Pb)

No accumulation of lead compound was recorded in the kidney of the sampled species. The liver organ *of O. niloticus* from the Balanga dam recorded a mean concentration of 0.43±0.05µg/g (**Table 2**). The highest lead accumulation was found in the gills of *O. niloticus* from the Almakashi river corridor (1.25±1.94µg/g) (**Table 2**), while the lowest mean concentration was 0.03±0.05 µg/g, recorded in the gills of *C. gariepinus* from Balanga dam (**Table 1**). There was no significant difference between the sampling organs (gills, liver, and kidney), and also Balanga dam did not differ significantly from Almakashi and Gwani in terms of lead concentrations ($p > 0.05$).

Nickle (Ni)

The Almakashi river corridor had the highest nickel accumulation of 37.73±6.53 µg/g in the gills of *O. niloticus* (**Table 2**), while the liver of *C. gariepinus* from Balanga (the reference) dam had the lowest mean concentration of 7.53±3.33 µg/g (**Table 1**). The nickel concentrations in Balanga (the reference) dam differed significantly from those in Almakashi and Gwani river corridors ($p < 0.05$), and the accumulation of nickel in gills differed significantly from that in the liver and kidney. There was no significant difference between the organs of *C. gariepinus* and *O. niloticus* samples in this research ($p > 0.05$).

Arsenic (As)

The accumulation of arsenic compound was examined, and the gills of *C. gariepinus* exhibited the highest accumulation of 44.93±3.72 µg/g (**Table 1**), while the liver of *O. niloticus* from Balanga dam had the lowest mean concentration of 11.33±2.55 µg/g (**Table 2**). Balanga dam significantly differed from the river corridors of Almakashi and Gwani ($p < 0.05$). Similarly, accumulations of arsenic in the gills significantly differed from those in the liver and kidney ($p < 0.05$). Conversely, the mean accumulation in the organs of *C. gariepinus* did not differ significantly from that of *O. niloticus* ($p > 0.05$).

Manganese (Mn)

The analysis of the gills, liver, and kidney of *C. gariepinus* and *O. niloticus* from Almakashi, Gwani, and Balanga dams revealed manganese concentrations. *C. gariepinus* from Almakashi had the highest mean concentration of 8.33±5.23 µg/g (**Table 1**), while the kidney of *O. niloticus* in the reference sampling location had the lowest mean value of manganese (1.10±0.20 µg/g) (**Table 2**). Significant differences were observed between the mean manganese concentrations of Balanga dam and those of the two sampling river corridors ($p < 0.05$). However, no significant difference existed between the sampling organs and sampling species in this research ($p > 0.05$).

Iron (Fe)

The organs of *C. gariepinus* collected from the Gwani river corridor exhibited the highest mean accumulation of 25.40±1.08 µg/g of iron, while the kidney of *C. gariepinus* from Balanga dam had the least mean concentration of 10.16±1.25 µg/g of mean iron (**Table 1**). There was a significant difference between the iron concentrations in organs of fish samples obtained in the Balanga dam compared to those found in Almakashi and Gwani ($p < 0.05$). Similarly, iron accumulation in the gills differed significantly from that in the liver and kidney. However, there was no significant difference between the sampling species (*C. gariepinus*

Histology and Histopathology

Gill tissue

The typical histological structure of the gills in *O. niloticus* and *C. gariepinus* specimens in this study exhibited a gill arch with associated striated muscles, from which primary lamellae extended. These primary lamellae were covered with secondary lamellae, and the capillary lumens of the secondary lamellae were supported by darkly stained (H and E) pillar cells and surrounded by a layer of epithelial cells. Parasites were identified in the gills of both *O. niloticus* and *C. gariepinus*, appearing encysted and commonly found in clusters of three or more cysts tightly packed together, encapsulated by a surrounding membrane. The histological analysis revealed normal tissue structure in **Fig. 2A**. However, in **Fig. 2B**, hyperplasia and intense epithelial lifting

were observed. **Fig. 2C** showed signs of partial fusion of secondary epithelial lamellae along with the presence of parasites. Additionally, **Fig. 2D** shows the fusion of epithelial layers as an alteration in the examined *Oreochromis niloticus*.

The histological analysis revealed normal tissue structure in **Fig. 2A**. However, in **Fig. 2B**, hyperplasia and intense epithelial lifting were observed. **Fig. 2C** showed signs of partial fusion of secondary epithelial lamellae along with the presence of parasites. Additionally, **Fig. 2D** shows the fusion of epithelial layers as an alteration in the examined *Oreochromis niloticus*.

The histological examination of the gills of *C. gariepinus* showed a normal structure in **Fig. 3A**, indicating secondary lamellae. However, **Fig. 3B** revealed congestion and aneurysm, **Fig. 3C** displayed aneurysm, and **Fig. 3D** exhibited signs of a parasite and fusion of epithelial lamellae. These observations indicate alterations in the gill tissues of *C. gariepinus*, including congestion, aneurysm, fusion of epithelial lamellae, and the presence of parasites.

Liver tissue

In the liver tissue of *O. niloticus*, hepatopancreatic tissue was identified, as shown in **Fig. 4A-B**. The hepatopancreatic tissue appeared dark purple-stained (H and E) and consisted of pancreatic acini with large nuclei (**Fig. 4A-B**) and pink-stained zymogen granules (**Fig. 4B**). Additionally, **Fig. 4C** indicates the presence of periportal and pericentric lymphocyte aggregates in the liver tissue. **Fig. 4**(A and B) indicates normal hepatocytes along with the pancreas, referred to as hepatopancreas, when observed through Leica DM750 and Leica DM500 microscopes. Lymphocyte aggregates were observed in **Fig. 4C**.

Images in **Fig. 4D** reveal indications of inflammation. The normal histological structure of the liver in the sampled *C. gariepinus* specimen showed hepatocytes arranged in hepatic cords. The hepatocytes, depicted in **Fig. 7A**, were hexagonal to oval-shaped cells with a central nucleus and a distinct cell membrane. The hepatic cords exhibited a "flower-like" arrangement of hepatocytes surrounding a blood sinusoid, as seen in **Fig. 5B**. The sinusoids were lined with elongated endothelial cells, and unstained areas between the hepatocytes indicated the presence of red blood cells, which were frequently found within the sinusoids (**Fig. 5B**).

Kidney tissue

The normal histological structure of the kidney in *O. niloticus* is shown in **Fig. 6A**, while that of *C. gariepinus* is presented in **Fig. 7A**. The kidney sections comprised nephrons surrounded by haematopoietic tissue. Each nephron consisted of renal corpuscles and renal tubules (**Fig. 7A**). The renal corpuscle included a glomerulus surrounded by Bowman's capsule, where the glomerulus appeared as a cluster of blood capillaries filled with red blood cells and mesangial cells providing structural support (**Fig. 7A**). Bowman's capsule was lined by an inner visceral epithelium of podocytes and an outer parietal layer of squamous epithelium supported by a basement membrane, enclosing a lumen referred to as Bowman's space (**Fig. 7A–B**). In *C. gariepinus*, an expansion of Bowman's space and inflammatory cell infiltration were evident (**Fig. 7B**). Necrotic renal tissue, characterized by darkly stained eosinophilic cytoplasm and pyknotic nuclei, was observed in **Fig. 7C**. Melanomacrophage centres were also present within the haematopoietic tissue, appearing as dark-brown pigmented deposits (**Fig. 7D**).

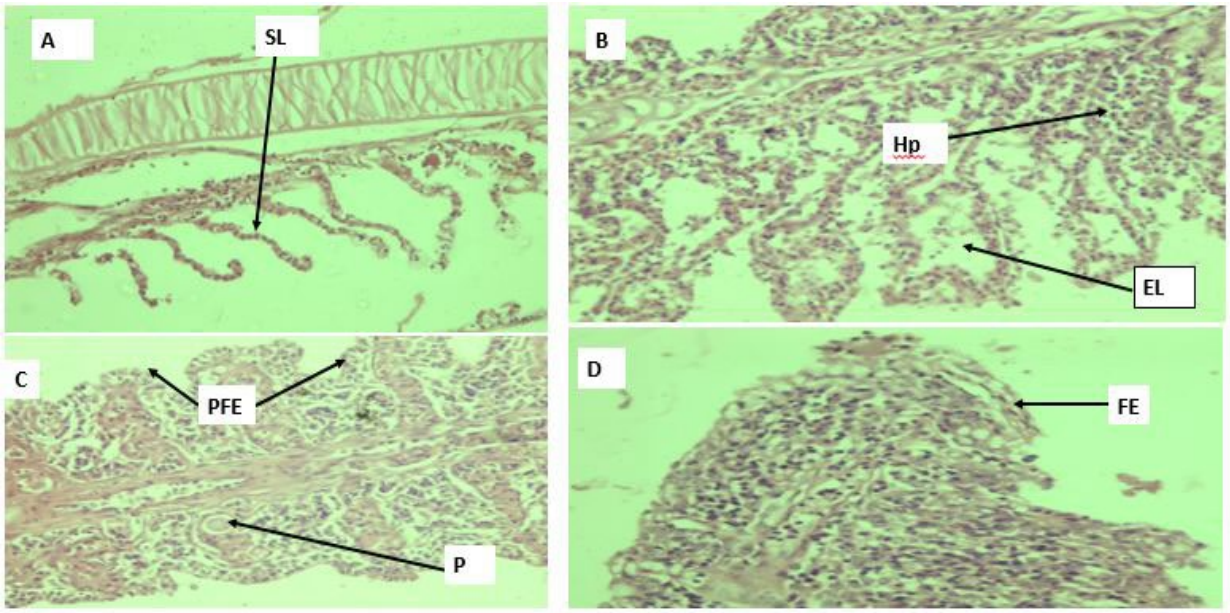

Fig. 2. Photomicrograph of *Oreochromis niloticus* gills (A) normal histology indicating secondary lamellar, (B) epithelial lifting (EL) and hyperplasia (HP). (C) Signs of partial fusion (PFE) and the presence of parasites (P), (D) Fusion of epithelia (FE) H and E stains x 40, x 100 magnification.

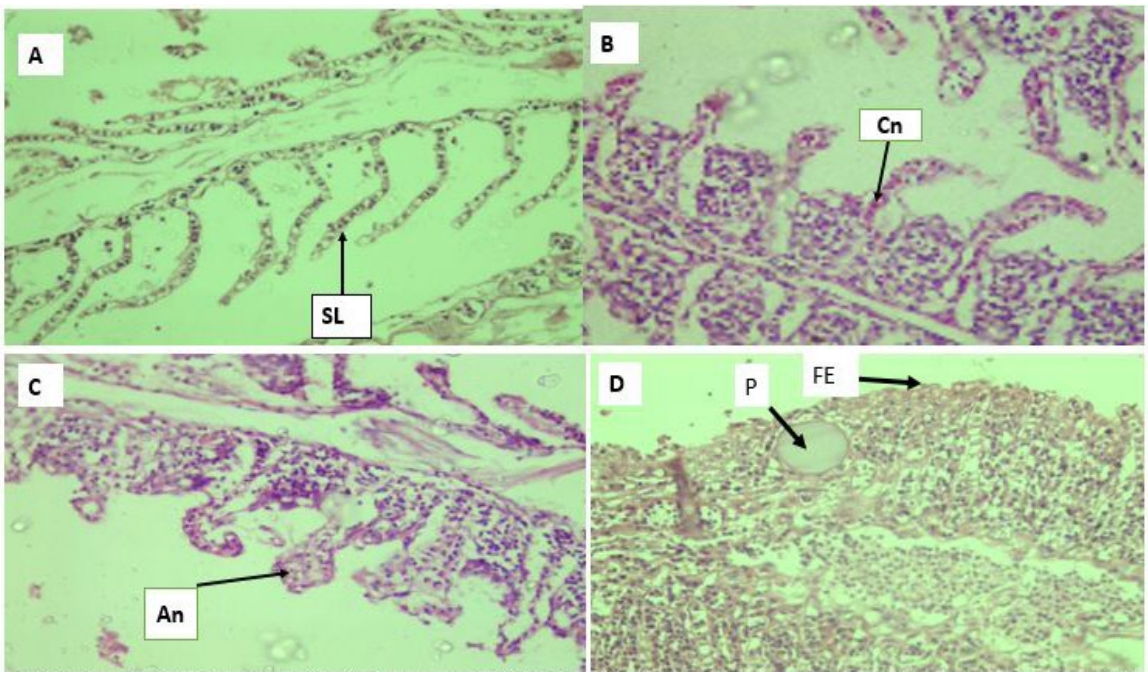

Fig. 3. Photomicrograph of the histological examination of the gills of *C. gariepinus* (A) normal, indicating secondary lamellae. (B) congestion, (C) aneurysm, and (D) signs of a parasite and fusion of epithelial lamellae. H and E stains x40, x100 magnification.

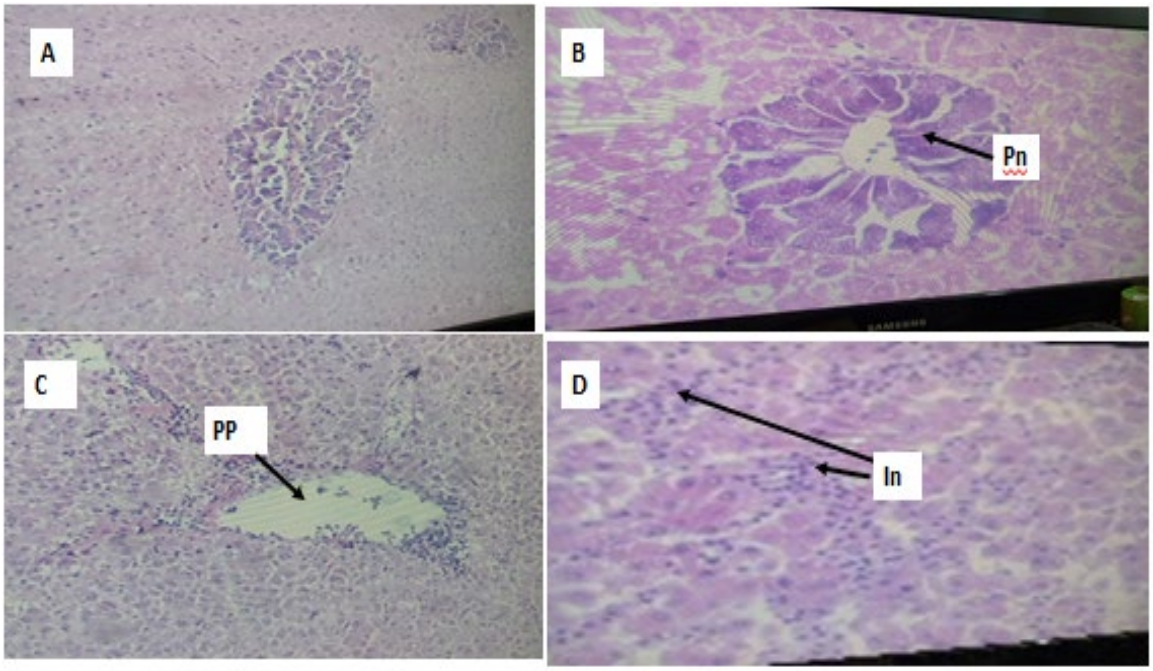

Fig. 4. Photomicrograph of hepatopancreas of Oreochromis niloticus (A) normal hepatocytes, (B) normal hepatocyte (C) peri-portal and pericentric lymphocyte aggregates, and (D) liver inflammation. H and E stains x40, x100 magnification.

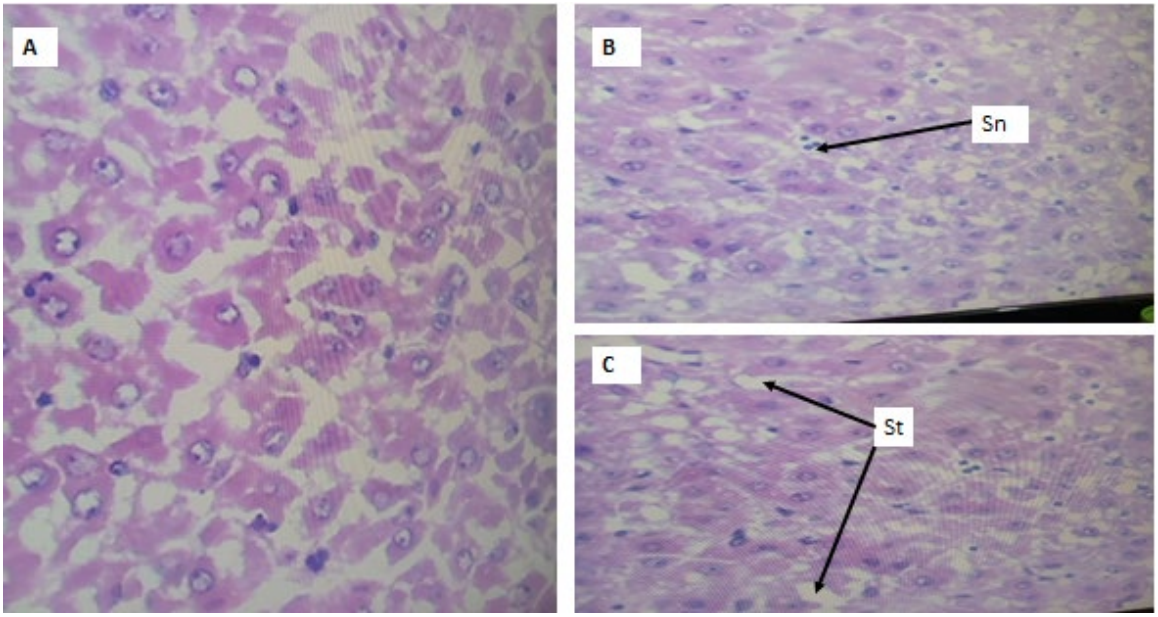

Fig. 5. Photomicrograph of the histological examination of the gills of *Clarias gariepinus* (A) normal hepatocytes, (B) congested sinusoids (C) focal steatosis. H and E stains x40, x100 magnifications.

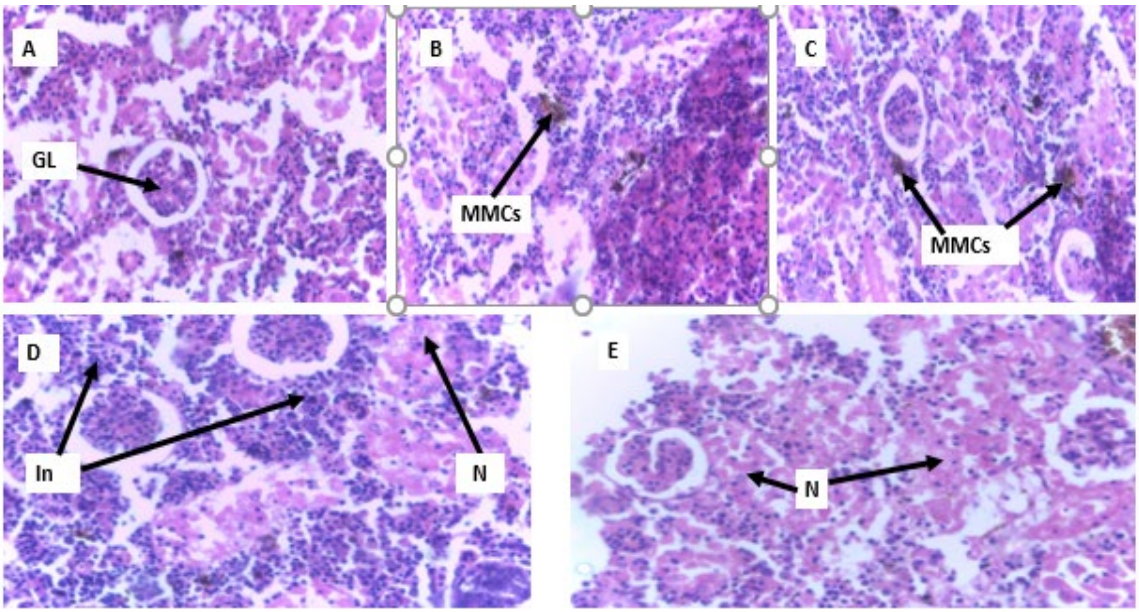

Fig. 6. Photomicrograph of the kidney Oreochromis niloticus (A) normal with glomerulus. (B) Melanomacrophages centres, (C) melanomacrophages centres, (D) Inflammation and necrosis sign and (D) necrosis. H and E stains x40, x 100 magnifications.

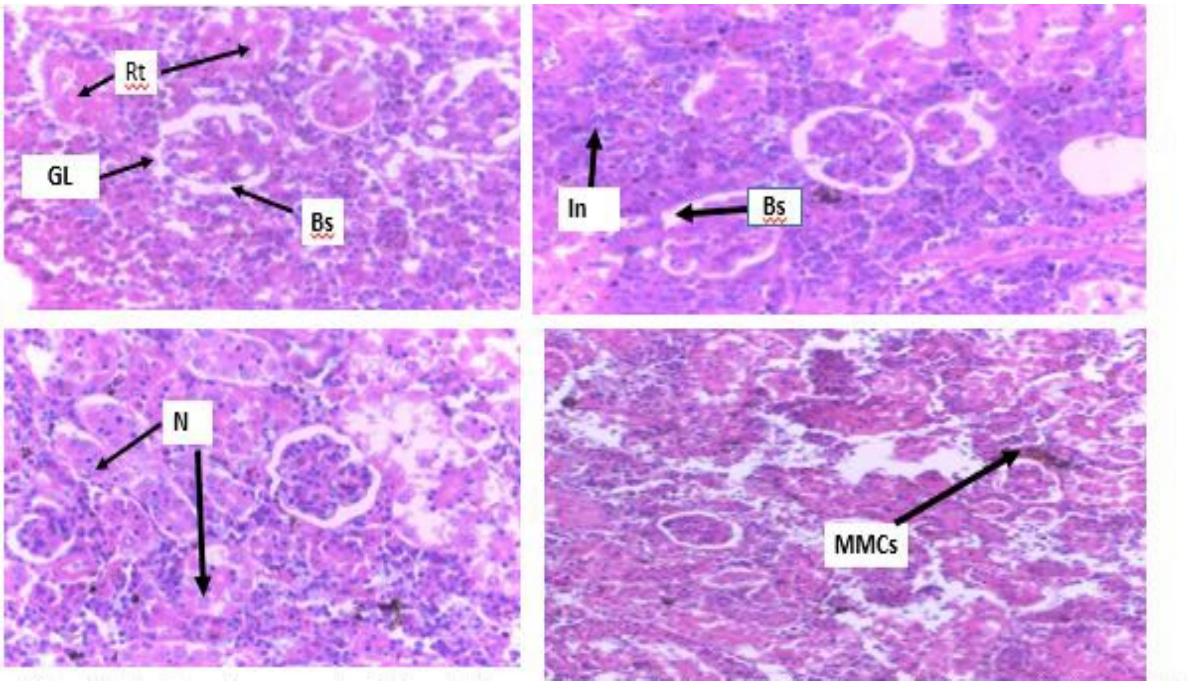

Fig. 7. Photomicrograph of the kidney Oreochromis niloticus (A) Kidney with Bowman's space and renal tubule. (B) an expansion in Bowman's space, inflammation, and (C) necrosis, and (D) melanomacrophages centres. H and E stains x40, x100 magnifications.

Prevalence of Histopathological Alterations in the Organs

The prevalence of histological alterations in the gills, liver, and kidneys of the fish specimens collected from different sampling locations was assessed, and alterations were found in all the examined gills, kidneys, and livers

Prevalence of histological alterations in the kidney

The prevalence of histological alterations in the kidneys of *O. niloticus* and *C. gariepinus* collected from different sampling sites indicated that kidney alterations were more frequent in *C. gariepinus* (71.43%) than in *O. niloticus* (28.57%). In *O. niloticus*, all alterations occurred in samples from Gwani, with 100% of specimens showing circulatory lesions characterized by congestion and widening of Bowman's space. In contrast, *C. gariepinus* exhibited 80% of total alterations in Almakashi and 20% in Gwani. The lesions in *C. gariepinus* were predominantly regressive changes (60%) and inflammatory reactions (40%), including tubular necrosis and interstitial infiltrates. Overall, the total prevalence of kidney alterations was 57.14% in Almakashi and 42.86% in Gwani, with no visible histopathological changes observed in specimens from the reference (Balanga) dam (**Table 5**).

Prevalence of histological alterations in the gills

In the gills, various histological alterations were identified in the fish specimens collected. These alterations include circulatory (congestion and aneurysm), progressive (fusion, epithelial lifting, and necrosis), as well as disturbances such as hyperplasia, which were identified in the presence study. The prevalence rates recorded in *O. niloticus* of Almakashi were 20% fusion of secondary lamellae, 40% partial and complete epithelial lifting, 26.67% proliferation of secondary lamellae, and 13.33% hyperplasia. Similarly, *C. gariepinus* in Almakashi showed 7.14% congestion and aneurysm, 14.29% fusion of secondary lamellae, 9.09% epithelial lifting, and 7.14% proliferation of secondary lamellae.

On the other hand, Gwani had 9.09% prevalence of the fusion of secondary lamellae and epithelial lifting in *O. niloticus,* while *C. gariepinus* in Gwani showed 8.33% congestion, 16.67% necrosis, and 9.09% prevalence of the fusion of secondary lamellae. No alterations were found in the gills of *O. niloticus* and *C. gariepinus* from Balanga dam (**Table 3**).

Prevalence of histological alterations in the liver

The liver of fish from Almakashi showed histological alterations in 33.33% of *O. niloticus* and 33.33% of *C. gariepinus*, accounting for a total prevalence of 33.33%. The alterations observed included circulatory (congested sinusoids) and regressive changes (mild steatosis). In contrast, the prevalence of liver alterations was higher in samples from Gwani, where 66.67% of both *O. niloticus* and *C. gariepinus* were affected, giving a total prevalence of 66.67%. The predominant lesions in Gwani were regressive (fatty degeneration) and inflammatory changes. Overall, *O. niloticus* and *C. gariepinus* each contributed equally to the total liver alteration index of 50% per species, representing 100% of the total fish examined (n=6). No histological alterations were observed in liver samples from the control site (reference dam) (**Table 4**).

Prevalence of histological alterations in the kidney

The prevalence of histological alterations in the kidneys of *O. niloticus* and *C. gariepinus* collected from different sampling sites indicated that kidney alterations were more frequent in *C. gariepinus* (71.43%) than in *O. niloticus* (28.57%). In *O. niloticus*, all alterations occurred in samples from Gwani, with 100% of specimens showing circulatory lesions characterized by congestion and widening of Bowman's space. In contrast, *C. gariepinus* exhibited 80% of total alterations in Almakashi and 20% in Gwani. The lesions in *C. gariepinus* were predominantly regressive changes (60%) and inflammatory reactions (40%), including tubular necrosis and interstitial infiltrates.

Overall, the total prevalence of kidney alterations was 57.14% in Almakashi and 42.86% in Gwani, with no visible histopathological changes observed in specimens from the reference (Balanga) dam (**Table 5**). There was no significant difference in the percentage prevalence of histological alterations between *O. niloticus* and *C. gariepinus* ($p > 0.05$). No major alterations were recorded in fish from Balanga Dam during the study period, except for mild hemosiderin deposits in the liver, which may indicate early melanomacrophage centre (MMC) formation. Among the sampling sites, the highest prevalence of gill alterations was recorded in Almakashi, followed by Gwani. In the liver, Gwani exhibited a higher prevalence rate than Almakashi, whereas in the kidney, Almakashi showed the highest prevalence, followed by Gwani. No histopathological changes were detected in any organs from the Balanga control site (**Table 6**).

Table 4. Liver Index.

Liver	N=06	*Oreochromis niloticus* (n=3)	*Clarias gariepinus* (n=3)	Total (n=6)	
	Circulatory	0(0%)	1(33.33%)	1(16.67%)	
	Regressive	1(33.33%)	2(66.67%)	3(50%)	
	Progressive	0(0%)	0(0%)	0(0%)	
	Inflammation	2(66.67%)	0(0%)	2(33.33%)	
	Fish Index	3(50%)	3(50%)	6(100)	
	Control	1(100%)	0(0%)	100(0%)	
	In terms of location				total = 6(100%)
Almakashi	*Oreochromis niloticus*	01(33.33%)	*Clarias gariepinus*	01(33.33%)	02(33.33%)
Gwani	*Oreochromis niloticus*	02(66.67%)	*Clarias gariepinus*	02(66.67%)	04(66.67%)
Fish Liver Index	Almakashi	02(33.33%)	Gwani	04(66.67%)	06(100%)
	In terms of species				
Oreochromis niloticus	Almakashi	01(33.33%)	Gwani	02(66.67%)	Total= 3(50%)
Clarias gariepinus	Almakashi	01(33.33)	Gwani	2(66.67%)	Total=3(50%)
Fish liver Index	*Oreochromis niloticus*	3(50%)	*Clarias gariepinus*	3(50%)	6(100%)

Table 5. Kidney Index.

Kidney	N=07	*Oreochromis niloticus* (N=2)	*Clarias gariepinus* (N=5)	Total (N=7)	
	Circulatory	2(100%)	0(0%)	2(28.57%)	
	Regressive	0(0%)	3(60%)	3(42.86%)	
	Progressive	0(0%)	0(0%)	0(0%)	
	Inflammation	0(0.0%)	2(40%)	2(28.57%)	
	Reference	0	0		
	Fish Index	2(28.57%)	5(71.43%)	7(100%)	
	In terms of location				
Almakashi	*Oreochromis niloticus*	0	*Clarias gariepinus*	4(80%)	Total = 4(57.14%)
Gwani	*Oreochromis niloticus*	2(100%)	*Clarias gariepinus*	1(20%)	Total= 3(42.86%)
Fish kidney Index	Almakashi	4(57.14%)	Gwani	3(42.86%)	11(100%)
	In terms of species				
Oreochromis niloticus	Almakashi	0(%)	Gwani	2(100%)	2(28.57%)
Clarias gariepinus	Almakashi	4(80%)	Gwani	1(20%)	5(71.43%)
Fish kidney Index	*Oreochromis niloticus*	2(28.57%)	*Clarias gariepinus*	5(71.43%)	7(100%)

Table 6. Percentage Prevalence of Alterations in *O. niloticus* and *C. gariepinus*.

Histological Alteration				
Location	Fish Sample	Gills (%)	Liver (%)	Kidney (%)
Almakashi	*O. niloticus*	100	0	37.5
	C. gariepinus	44.8	20	44.44
Gwani	*O. niloticus*	18.18	28.58	28.58
	C. gariepinus	25	33.34	18.18
Balanga	*O. niloticus*	0	0	0
	C. gariepinus	0	0	0

DISCUSSION

Heavy metals are one of the aquatic pollutants that persist in water bodies and can accumulate into various tissues and organs of fish [37]. Thus, they can accumulate directly into the body of *O. niloticus*, *C. gariepinus*, and other fishes through the contact of gills and skin with the outside environment or via the absorption of food particles contaminated with metal [38]. The toxicological impacts of metals on different tissues are expected to increase [39] if the ingestion and accumulation rates of metals exceed their excretion and detoxification rates.

Studies conducted on fish that habitually dwell in contaminated habitats are more feasible than those performed in controlled laboratory conditions [40]. Similarly, [41] and [37] affirmed that the data collected in the field have important ecological relevance and enhance understanding of the real interactions between metals and their effects on wild fish. Likewise, it is quite challenging to determine fish health using routine chemical analysis since aquatic organisms can react differently to the same contaminant. Consequently, fish are often used as bioindicators in many toxicological studies [42]. The widespread presence of Nile tilapia (*O. niloticus*) and African catfish (*C. gariepinus*) in African water bodies, their bioaccumulation characteristics, economic importance, and suitability as bioindicators make them valuable subjects for studying the impacts of heavy metal pollution in aquatic environments in Africa [43]; [44].

Accordingly, using integrated biomarkers to monitor environmental stressors and their impacts on aquatic biota has become a valuable and reliable tool [37]. In-view of the aforementioned, the result of the effect of metals on selected

organs of *O. niloticus* and *C. gariepinus* species in relation to sample locations was examined. According to the study, Almakashi is predominantly polluted, with more metals accumulating in the fish samples than in Gwani, while Balanga Dam had the least heavy metal accumulation. The high incidence of metal pollution observed in Almakashi may be attributed to the high rate of human activities, such as runoff from nearby farmlands containing synthetic fertilizers and pesticides. Furthermore, runoff water/ wastewater released from the Cement Company in the neighbouring town of Ashaka might be discharged into the Almakashi water. The average metal levels in different tissues of both species were higher at Almakashi than at Gwani and Balanga (the reference) dam. On the other hand, *C. gariepinus* revealed higher accumulations of most studied metals in various tissues than *O. niloticus*. This may be because of variation in habit preference and feeding habits. *C. gariepinus* is an omnivorous species feeding on both plants and animals at different micro-habitats, such as pelagic, bentho-pelagic, benthic, and sediments [45]. The finding is related to the similar studies conducted by [46] and [47].

Furthermore, *C. gariepinus* showed higher Copper (Cu) content in all the tissues examined in all the sampling sites. The gills of *C. gariepinus* in Almakashi had the highest Cu concentration of 17.20±1.17µg/g compared to the mean of kidney and liver tissues of all specimens examined in all the sampling stations of this research. This is likely because all materials pass through the gills before accumulating in the internal organs of both O. niloticus and C. gariepinus; therefore, they have direct contact with the external environment [48]. Moreover, the Cu content in C. gariepinus was significantly elevated in all tissues examined in this study compared to *O. niloticus* ($p < 0.005$). The high accumulation of copper in the tissues of *C. gariepinus* can be attributed to the fact that all materials released into the water tend to settle at the bottom of rivers, which is the benthic zone where *C. gariepinus* resides.
The only recorded mean concentrations of Cd found in the liver were in O. niloticus from Gwani and Almakashi, respectively.

The liver is a site of metal binding [48], or high accumulation of cadmium (Cd) in the liver may be attributed to the active interaction of the liver with exposure to contaminated food, due to its functional nature of detoxification, which may cause direct contact with food containing this metal. The highest Cd concentration was found in the gills of O. niloticus from Almakashi; thus, Gill tissue was significantly increased in all studied species compared to liver and kidney. However, the presence of Cd in the gills and livers of both O. niloticus and C. gariepinus, in proportion to Cd concentrations in both water and sediments, may confirm the uptake of metal by individuals and suggest different levels of toxicity from each exposure concentration [49]. The direct exposure of gills to water may lead to higher accumulation of Cd in the gills compared to other tissues.

In this research, there was no evidence of Cd presence in the kidneys of the sampled specimens, which is consistent with the findings by [50] on Clarias gariepinus in Nigeria, who also found no detectable levels of Cd in kidney samples, suggesting a limited ability for metal accumulation in fish kidneys. This aligns with more recent research by [51], indicating that fish kidneys have a limited capacity to accumulate cadmium due to their physiological mechanisms for metal regulation. The accumulated Chromium (Cr) of *C. gariepinus* was highest in the gills at Almakashi, while the liver of *O. niloticus* of Balanga dam had the least value. This may be attributed to the direct contact of gills with the external environment or an opening for the intake of materials into the body of fish species [49].

The lead (Pb) content in the gills of *O. niloticus* at Almakashi was the highest, but not significantly elevated, compared to Gwani and Balanga dams. Meanwhile, the lowest lead (Pb) content was reported in the gills of C. gariepinus from Balanga dam. Pb contents were not found in the liver and kidney of the sampling species of Balanga dam. The accumulated nickel (Ni) in the organs of *C. gariepinus* was not significantly higher than that of *O. niloticus* ($p > 0.05$). The highest concentration of Ni was found in the gills of *O. niloticus* at Almakashi. This is because all materials pass through the gills before being accumulated into the internal organs of fish such as *O. niloticus* and *C. gariepinus* [52]. The accumulated arsenic (As) was found to be highest in the gills of *C. gariepinus* from Gwani and was not evidently elevated compared to the mean concentrations obtained in the organs of O. niloticus at all the study sites. The trace amount obtained may be attributed to the release of chemicals in farming within the riverine coast, the dumping of waste materials, and the dam construction that lowered the natural movement of water. If this long-term exposure to metals and pesticides continues, it might result in significant alterations in the organs of fish.

The accumulated manganese (Mn) mean concentration was found to be highest in the gills of *C. gariepinus* at Almakashi. There was no significant elevation between organs or at various sampling locations ($p > 0.05$). Similarly, the mean concentration of iron was still found to be highest in the gills of *C. gariepinus* at Gwani, while the lowest was obtained in the kidneys of C. gariepinus from Balanga dam. Iron concentrations in the tissues of *C. gariepinus* were slightly increased but not significantly so in the tissues, sampling specimens, and locations of this research. Generally, gills had the highest accumulation while the liver had the lowest. This may be attributed to the direct contact of the gills with the external environment.

In this study, *O. niloticus* exhibited lower concentrations of Copper, Arsenic, Manganese, and iron metals compared to *C. gariepinus*. This aligns with findings by [49], who also reported significantly higher ($p < 0.05$) heavy metal (Cu, As, Mn, and Fe) accumulation in various tissues of *C. gariepinus* than *in O. niloticus*. The variations in habitat and food preferences between the two species might explain this difference. *O. niloticus* typically inhabits the pelagic zones of water bodies, while heavy metals tend to settle in sediments at the bottom. On the other hand, *C. gariepinus* is a bentho-pelagic species, living and feeding in different zones, including benthic regions where metal concentrations are higher. These dietary and habitat behaviors increase the likelihood of *C. gariepinus* encountering and accumulating more heavy metals in sediments than *O. niloticus* [53]; [54]. Most of the time, C. gariepinus can be found close to the benthic zone but moves to the pelagic zone to hunt and feed on plankton. Moreover, C. gariepinus also feeds on bottom sediments and plants, or consumes organisms that have accumulated metals. Another reason may be that they are omnivorous species, feeding on a wide range of biota at different locations (bottom, littoral, and pelagic zones) of the Aquatic ecosystem.

Conversely, no significant difference was found in the accumulation of heavy metals between O. niloticus and C. gariepinus; however, the mean concentrations of cadmium, lead, and nickel were higher in *O. niloticus*. This is probably due to the higher trophic position [55], greater bioaccumulation from the water column [56], and potentially different physiological factors

[57], which allow pelagic fish species like *Oreochromis niloticus* to accumulate higher levels of certain heavy metals compared to benthic species like *Clarias gariepinus* in the same aquatic environment.

The adoption of organic farming should be encouraged to minimize environmental degradation. Meanwhile, stricter regulations on the use of agrochemicals and the disposal of waste in water bodies must be enforced through regular monitoring and penalties for non-compliance. Proper waste management policies should be developed and implemented to prevent dumping into critical waterways, with efficient waste collection and recycling systems established in both rural and urban areas. Regular health assessments of key fish species should be conducted, focusing on histopathological alterations in major organs to evaluate ecosystem health. Conservation efforts must be promoted to protect aquatic biodiversity through targeted programs for threatened species and by fostering community participation in environmental monitoring via citizen science initiatives. Additionally, genotoxicity studies using immunohistochemical techniques should be conducted to assess DNA damage and mutations in important commercial fish species, such as Oreochromis niloticus and Clarias gariepinus, along the River Gongola corridor. Further studies should also assess fish health using indices such as the Hepatosomatic Index, Gonadosomatic Index, and Packed Cell Volume to understand long-term environmental impacts. Ultimately, integrated water resource management strategies should be promoted to align agricultural practices with water quality and the conservation of aquatic ecosystems, emphasizing collaboration among farmers, local communities, and government agencies for sustainable resource management.

CONCLUSION

Conclusively, the effect of anthropogenic activities was found to cause stress conditions in C. gariepinus and O. niloticus in the Gongola River catchments of Gombe State. However, the stress condition could be reversed when the situation subsides. This stress condition alters certain physicochemical and biometric indices, as well as the haematobiochemistry and normal histology of organs. Heavy metal analysis reveals that the gills of *Clarias gariepinus* from Almakashi exhibit the highest copper concentrations. This study found significant differences in contamination levels between Balanga Dam and the river corridors, although all values are within acceptable limits. The gills, liver, and kidneys of *O. niloticus* and *C. gariepinus* in this study reveal some histopathological alterations. Gill is the most affected organ. The lesions identified in the gills of *O. niloticus* include epithelial lifting, partial and complete fusion, and the parasite sign. Congestion, aneurysms, and fusion of secondary epithelia, as well as parasite signs, were the alterations found in C. gariepinus from the Gongola River corridors of Almakashi. Furthermore, the liver lesions found include steatosis, periportal and pericentral lymphocyte aggregates, congestion of sinusoids (in the liver of C. gariepinus only), and liver inflammation. On the other hand, an increase in Bowman's space, melanomacrophages, centers, inflammation, and necrosis are the alterations found in the kidneys of O. niloticus and C. gariepinus from the sampling areas of this study. The prevalence of alterations found in the gills was more severe than in the kidney and liver. This study revealed that the fish in the study area are under stress due to contaminants resulting from uncontrolled anthropogenic activity, which causes alterations in different tissues of the sampled species. Furthermore, the heavy metals cause stress and reduced antioxidant enzyme activities in the gills, liver, and kidneys of *O. niloticus* and *C. gariepinus,* leading to dysfunction and altered tissue histology. However, these values were within the normal range. It is recommended that comprehensive awareness campaigns be initiated to educate the public on the harmful effects of agrochemical use and improper waste disposal, supported by workshops and training sessions for farmers on sustainable practices and safe agrochemical application.

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