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Research Article

Relationship Between Water Quality and Biological Indices of Nile Tilapia (*Oreochromis niloticus*) and African Catfish (*Clarias gariepinus*) from Alau and Biu Dams, Borno State, Nigeria

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ABSTRACT

Water quality plays a critical role in aquatic ecosystems, as water pollution can alter physicochemical conditions and negatively affect fish health, growth, reproduction, and survival. This study assessed the influence of physicochemical parameters on biological indices of *Oreochromis niloticus* and *Clarias gariepinus* from Biu and Alau Dams, Northeastern Nigeria. Both water and fish samples were collected bi-weekly from the study sites for 3 months. In each dam, a composite of sample from 4 different sampling sites were collected. A total of 48 (6 sampling visits x 4 landing sites per reservoir x 2 fish species per each visit) fish sample for each sampled species were collected. Temperature, EC and TDS were measured in-situ using a handheld device while NO^{3-} and SO^{4-} were analyzed at Public Health Engineering Laboratory, Abubakar Tafawa Balewa University, Bauchi. The result of the study indicates that Alau Dam recorded higher temperature (30.2±1.4 °C), EC (336±23.7 µS/cm), NO^{3-} (27.5±4.8 mg/L), SO^{4-} (12.1±4.3 mg/L), BOD (2.4±0.8 mg/L), and TDS (186.25±12.5 ppm) compared to Biu Dam (24.2±4.7 °C; 72.42±31.1 µS/cm; 13.1±3.6 mg/L; 8.7±4.2 mg/L; 1.1±0.5 mg/L; 111.87±1.2 ppm respectively). Female GSI of *O. niloticus* was higher in Alau (13.1±8.8%) than Biu (9.4±2.8%), while male GSI of *C. gariepinus* increased from 3.11±2.8% (Biu) to 4.29±2.1% (Alau). PCA showed 85.5% variance explained by PC1, separating dams spatially. CCA revealed strong associations between EC, NO^{3-}, SO^{4-}, TDS, and reproductive indices. Furthermore, the results also suggest that nutrient-driven environmental gradients were associated with reproductive and physiological indices.

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1.0 INTRODUCTION

Water quality is a fundamental determinant of fish health, growth performance, reproductive success, and overall aquaculture productivity. In freshwater ecosystems, variations in physicochemical parameters such as temperature, dissolved oxygen, pH, turbidity, ammonia, nitrate concentration, and heavy metal load directly influence metabolic processes and physiological stability in fish species. Among commercially important freshwater fish in tropical and subtropical regions, African catfish (*Clarias gariepinus*) and Nile tilapia (*Oreochromis niloticus*) are widely cultured due to their adaptability and tolerance to environmental fluctuations. However, even these resilient species exhibit measurable physiological and biochemical responses when exposed to suboptimal water quality conditions (Bwala et al 2026; Ekpo et al 2025).

Seasonal and spatial fluctuations in physicochemical parameters have been shown to significantly influence reproductive and physiological indices in both species. Variability in gonadosomatic index (GSI), hepatosomatic index (HSI), stomach repletion index (SRI), and condition factor (K) of *C. gariepinus* and *O. niloticus* from River Ngadda, Nigeria, demonstrated strong associations with changing water quality parameters (Bwala et al 2026). Similarly, seasonal shifts and climate variability in the Great Kwa River were reported to alter physicochemical properties and induce morphological adaptations in Nile tilapia, emphasizing the ecological sensitivity of these species to environmental dynamics (Ekpo et al 2025).

Anthropogenic activities have intensified freshwater pollution, thereby altering aquatic habitat quality. Heavy metal contamination remains a critical concern due to its toxicity and bioaccumulation potential in fish tissues. Assessment of heavy metals in sediments, water, and *C. gariepinus* from Alau Dam revealed environmental contamination patterns with implications for fish health (Bwala 2023). In addition, irrigation activities and nonpoint source pollutants have been reported to degrade water quality and reduce fish biodiversity in River Ngadda, Maiduguri, Nigeria (Bwala 2021a; Bwala 2021b). These findings underscore the vulnerability of freshwater systems to human-induced disturbances.

Physiological stress responses in fish serve as early indicators of deteriorating water quality. In Benue Cement Dam, variations in physicochemical parameters were linked to altered physiological stress biomarkers in selected fish species, demonstrating sublethal impacts of environmental stressors (Aende et al 2026). Furthermore, parasitic infestation in *C. gariepinus* has been identified as a reliable bioindicator of water quality status in Omi Dam, Kogi State, Nigeria (Olubiyo et al. 2024). Such biological responses reflect the integrated effects of environmental changes on fish health and ecosystem stability.

Aquaculture systems provide controlled environments to evaluate the interaction between water quality and fish performance. Stocking density has been shown to significantly influence growth performance and water quality in Nile tilapia and African catfish pond culture systems, where higher densities may reduce dissolved oxygen and increase metabolic waste accumulation (Omach et al. 2025). Dietary interventions interact with water quality to influence fish growth and health status. The inclusion of black soldier fly larvae meal in the diet of Nile tilapia was associated with changes in water quality parameters and corresponding effects on growth performance and physiological health indicators (Fayed et al. 2024). Emerging environmental pollutants further complicate water quality management in natural river systems. The distribution patterns and ecological associations of tire-derived pollutants in the Egyptian Nile River Bend suggest potential risks to aquatic organisms, including economically important fish species (Hassan et al. 2026). Such contaminants may indirectly affect fish health by altering habitat conditions and water chemistry. Water quality not only affects fish growth and reproduction but also influences the nutritive value of fish products. In Khartoum State, Sudan, variations in water quality parameters significantly affected the proximate composition and nutritive value of catfish, emphasizing the broader implications for food security and human nutrition (Idam and Degais 2025). This study therefore is aimed at assessing the effect of water quality on African catfish (*C.*

gariepinus) and Nile tilapia (*O. niloticus*) from Biu and Alau Dams, Borno State which is essential for sustainable fisheries management and freshwater ecosystem conservation.

Although previous studies have evaluated water quality and fish biology separately in northeastern Nigeria, comparative information on how physicochemical variations influence biological indices of fish species in Alau and Biu Dams remains limited. The present study therefore compares two important reservoirs to determine whether environmental differences are associated with reproductive and physiological responses in fish populations.

2.0 MATERIAL AND METHOD

2.1 Study Area

Biu Dam is situated in Biu town, Biu Local Government Area of Borno state, Nigeria. Its geographical coordinates are 10° 49' 0" North, 12° 2' 0" East. It is about 12 km away from Biu town, Gombe road, the catchment area of the dam is 147 km^2 and the area covered under reservoir at full storage capacity is 3.0 km^2 the approximate length of reservoir is 2.0 km and width 1.5 km. the maximum depth of the reservoir is 15.0 m the storage capacity of the reservoir is 11.1 million m^3 of water of which 9.6 million m^3 will be useful storage, and will ensure 22.730 m^3 of water supply daily, the water drain from East to West (Wakil et al 2025).

Alau Dam on the other hand is situated in Alau Community, Konduga Local Government Area, Borno State, Nigeria. Alau dam lies between Latitude 11° 39' 84" – 11° 40' 02" N and Longitude 13° 39' 92" – 13° 40' 12"E at the highest altitude of about 354m above sea level. The lake is the largest manmade lake in Borno State, Northeast Nigeria with a mean depth of 9.5 m and surface area of 56 km^2, with annual inflow calculated of 329,000 m^3 (Olanrewaju et al 2026). **Figure 1** shows the map of Borno State, highlighting the two water reservoirs (Biu and Alau Dams).

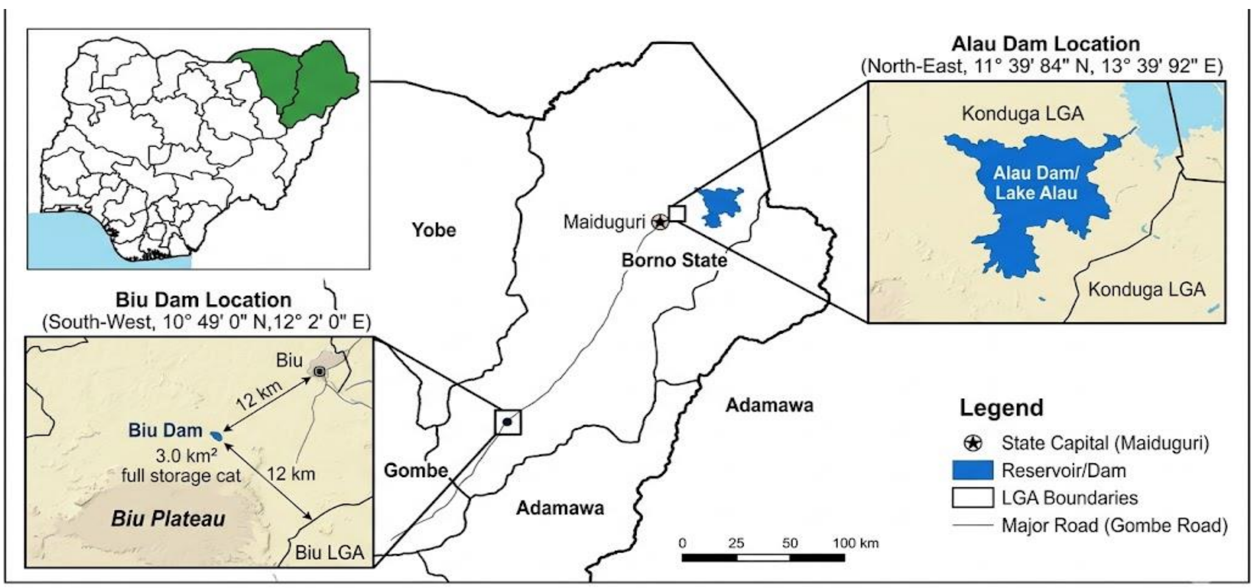

Figure 1: Map of Borno State showing Alau and Biu Dams. Prepared by the authors using ArcGIS 10.8 based on administrative boundary data obtained from the Office of the Surveyor General of Nigeria (2025).

2.2 Sample Collection and Analysis

Fish specimens were obtained from artisanal fishermen immediately after capture at the designated landing sites during each sampling visit. Only freshly caught fish originating from the respective reservoir were selected. Because fish were collected from landing sites rather than captured directly at individual water sampling stations, the biological responses reported represent reservoir-scale conditions rather than point-specific responses. Consequently, associations between water quality and biological indices should be interpreted at the reservoir level. Specimens of *O. niloticus* and *C.*

gariepinus were collected bi-weekly for three months at the landing sites from the two different reservoirs. At each site, four different samples of similar sizes were collected for each sampled specie. Forty-eight (6 sampling visits x 4 landing sites per reservoir x 2 fish species per each visit) fish samples were collected per specie. A total of 96 fish specimens comprising 48 *O. niloticus* and 48 *C. gariepinus* were collected from four landing sites in each reservoir between June – August 2025 and transported in ice to the laboratory and are identified and authenticated at Fisheries Department, University of Maiduguri, Borno State. The fish specimens' total length, body weight, gonad weight, liver weight, and stomach weight were measured immediately upon arrival at the laboratory on fresh specimens after being transported in ice prior to chemical preservation.
Similarly, Surface water samples were collected at approximately 20–30 cm depth were collected bi-weekly for three months at 4 different landing sites and a composite sample was used for the study from each of the two reservoirs for water quality assessment using the standard methods as explained by Bwala (2021a; 2021b). Water Quality was measured with a handheld water quality meter (HI9813-61 Portable pH/EC/TDS/Temperature Meter, Hanna Instruments, USA). Nitrate was determined using a colorimeter (DR/890 Colorimeter, Hach Company, USA) while sulphate was spectrophotometrically determined (752N Spectrophotometer, NADE, China) at Public Health Engineering Laboratory, Abubakar Tafawa Balewa University, Bauchi.

2.2.1 Water Quality Analysis

Four fixed sampling stations were established in each reservoir. These stations corresponded to the major fish landing sites routinely used by local fishermen and represented shoreline areas distributed around the reservoir to capture spatial variability. Surface water samples were collected biweekly from the sampling stations in Alau and Biu Dams during the study period. Water samples were collected approximately 20–30 cm below the water surface using pre-cleaned polyethylene bottles and transported immediately to the laboratory for analysis. All analyses were carried out according to standard procedures described by the American Public Health Association (APHA, 2017).

Temperature

Water temperature (°C) was measured in situ using a calibrated digital thermometer by immersing the probe directly into the water sample. The thermometer was allowed to stabilize before the readings were recorded.

potentia Hydrogenii (pH)

Hydrogen ion concentration (pH) was measured in situ using a portable digital pH meter previously calibrated with standard buffer solutions of pH 4.0, 7.0, and 9.0. The electrode was rinsed with distilled water between measurements to avoid contamination.

Electrical Conductivity (EC)

Electrical conductivity (µS/cm) was determined using a portable conductivity meter. The instrument was calibrated according to the manufacturer's instructions before use, and readings were recorded directly at each sampling station.

Total Dissolved Solids (TDS)

Total dissolved solids (mg/L) were measured using a digital TDS meter. The probe was immersed in the water sample until a stable reading was obtained.

Dissolved Oxygen (DO)

Dissolved oxygen concentrations (mg/L) were determined using a portable dissolved oxygen meter calibrated before each field sampling exercise. The probe was immersed directly into the water sample and allowed to stabilize before readings were recorded.

Biochemical Oxygen Demand (BOD)

Biochemical oxygen demand (BOD_5) was determined using the five-day incubation method. Initial dissolved oxygen concentrations were measured immediately after sample collection. The samples were subsequently incubated in airtight BOD bottles at 20°C for five days in the dark, after which the final dissolved oxygen concentrations were measured. BOD was calculated as the difference between the initial and final dissolved oxygen concentrations and expressed in mg/L.

Chemical Oxygen Demand (COD)

Chemical oxygen demand (COD) was determined using the dichromate reflux method. Water samples were digested with potassium dichromate in the presence of sulfuric acid and a catalyst under reflux conditions. The amount of oxidizable organic matter present in the sample was then determined spectrophotometrically and expressed as mg/L.

Nitrate (NO_3^-)

Nitrate concentrations were determined using a portable colorimeter (DR/890 Colorimeter, Hach Company, USA) following the manufacturer's prescribed procedures. Water samples were first filtered to remove suspended particles, after which the appropriate nitrate reagent was added to develop the characteristic colour. The intensity

Sulphate (SO_4^{2-})

Sulphate (SO_4^{2-}) concentrations were determined using the turbidimetric method according to APHA (2017) using a 752N UV–Visible Spectrophotometer (NADE, China). Barium chloride crystals were added to the samples to produce a barium sulphate suspension, and the resulting turbidity was measured spectrophotometrically. Sulphate concentrations were obtained from calibration curves prepared using standard sulphate solutions and expressed in mg/L.

Dissolved Oxygen (DO)

Dissolved oxygen (DO) concentrations were determined in situ using a portable dissolved oxygen meter previously calibrated according to the manufacturer's instructions. The probe was immersed approximately 20–30 cm below the water surface and allowed to stabilize before readings were recorded. Measurements were taken at each sampling station in triplicate and expressed as mean ± standard deviation.

2.3 Ethical Approval

All experimental procedures involving the sampled fish species were conducted in accordance with internationally accepted guidelines for the care and use of experimental animals. The study protocol was reviewed and approved by the Departmental Health Research and Animal Ethics Committee of Abubakar Tafawa Balewa University, Department of Ecology. Additionally, handling, sampling, and euthanasia were performed using humane methods to minimize stress and suffering, and all efforts were made to reduce the number of animals used while ensuring scientific validity. The Departmental Ethics Committee did not assign formal approval numbers for observational fish studies conducted during the study period. Additionally, no formal approval number assigned to the study.

2.4 Data Analysis

The collected data were organized and tabulated using Microsoft Excel 2013 which was further used to estimate GSI, HSI, SRI, and K following the established statistical methodologies as described by Ghaffari et al (2011), Sudarshan and Kulkarni (2013), and more recent protocols by Aufy (2023); Muslim et al. (2023); Prakash (2022); and Rizzo and Bazzoli (2020). To evaluate how biological indices respond to water quality variations, the dataset underwent multivariate analysis—specifically Canonical Correspondence Analysis (CCA)—utilizing PAST (Paleontological Statistics Software). Six independent field sampling events constituted the environmental observations. Each sample was subjected to laboratory analyses where necessary and conducted in triplicate for quality assurance, and the average value from the triplicate analytical measurements was used as the observation for statistical analyses. Instrument readings therefore do not represent independent environmental samples and expressed as mean ± standard deviation.

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 29.0 (IBM Corp., Armonk, NY, USA) and PAST (Paleontological Statistics) Version 4.17 (University of Oslo, Norway). Data were tested for normality using the Shapiro-Wilk test and homogeneity of variance using Levene's test. Independent-samples t-tests were used to compare physicochemical parameters and biological indices between Biu and Alau Dams. Statistical significance was accepted at $p < 0.05$. Principal Component Analysis (PCA) and Canonical Correspondence Analysis (CCA) were performed using standardized variables to evaluate multivariate associations between environmental variables and biological indices. Prior to PCA, all variables were standardized using z-score transformation because the variables were measured using different units and scales.

2.4.1 Biological Indices

Fish were processed immediately upon arrival at the laboratory. Total length, body weight, liver weight, gonad weight and stomach weight were measured on fresh specimens transported in ice to the laboratory prior to chemical preservation. Total length was measured using an ichthyometer to the nearest 0.1 cm, while weights were measured using a digital analytical balance (OHAUS Pioneer PA214, readability 0.001 g). To assess environmental stress and its impact on the fitness, survival, and adaptive capacity of the fish species, several physiological indicators were determined: Gonadosomatic Index (GSI), Hepatosomatic Index (HSI), Stomach Repletion Index (SRI), and Condition Factor (K) (Aufy 2023; Ghaffari et al. 2011; Muslim et al. 2023; Prakash 2022; Rizzo and Bazzoli 2020; Sudarshan and Kulkarni 2013).

These biological indices were estimated using the formula below:

$$GSI = \frac{GW}{BW} X\ 100$$

$$HSI = \frac{LW}{BW} X\ 100$$

$$SRI = \frac{SW}{BW} X\ 100$$

$$K = \frac{BW}{TL^3}$$

Where **GW** – Gonadal Weight (g)
BW – Body Weight (g)
LW – Liver Weight (g)
SW – Stomach weight (g)
TL – Total Length (cm)

3.0 RESULTS

3.1 Water Quality

The results of the water quality assessment as shown in **Table 1**, **Figure 2a** and **Figure 2b** indicates that Alau Dam recorded higher temperature (30.2±1.4 °C), electrical conductivity (336±23.7 µS/cm), nitrate (27.5±4.8 mg/L), sulphate (12.1±4.3 mg/L), BOD (2.4±0.8 mg/L), and TDS (186.25±12.5 ppm) compared to Biu Dam (24.2±4.7 °C; 72.42±31.1 µS/cm; 13.1±3.6 mg/L; 8.7±4.2 mg/L; 1.1±0.5 mg/L; 111.87±1.2 ppm).

Independent-samples t-tests revealed significant differences in several physicochemical parameters between the two reservoirs. Temperature was significantly higher in Alau Dam than in Biu Dam, $t(22) = 4.19$, $p < .001$. Similarly, electrical conductivity, nitrate concentration, biochemical oxygen demand, and total dissolved solids were significantly higher in Alau Dam ($p < .001$). In contrast, pH, dissolved oxygen, sulphate, and chemical oxygen demand did not differ significantly between the reservoirs ($p > .05$).

Table 1: Physicochemical Characteristics (Mean ± SD) of Biu and Alau Dams, Borno State, Nigeria

Parameter	Biu Dam	Alau Dam	t	p
Temperature (°C)	24.2 ± 4.7	30.2 ± 1.4	4.19	< .001***
pH	7.5 ± 2.3	7.4 ± 4.2	0.07	.945
DO (mg/L)	23.21 ± 4.3	20.10 ± 4.8	1.36	.188
EC (µS/cm)	72.42 ± 31.10	336.00 ± 23.70	23.40	< .001***
NO_3^- (mg/L)	13.1 ± 3.6	27.5 ± 4.8	8.29	< .001***
SO_4^{2-} (mg/L)	8.7 ± 4.2	12.1 ± 4.3	1.96	.063
COD (mg/L)	49.9 ± 4.2	51.4 ± 6.2	0.69	.497
BOD (mg/L)	1.1 ± 0.5	2.4 ± 0.8	4.84	< .001***
TDS (ppm)	111.87 ± 1.20	186.25 ± 12.50	20.52	< .001***

Values are presented as mean ± standard deviation. Independent-samples t-tests were used to compare physicochemical parameters between Biu and Alau Dams. Significant differences are indicated by p < .05.

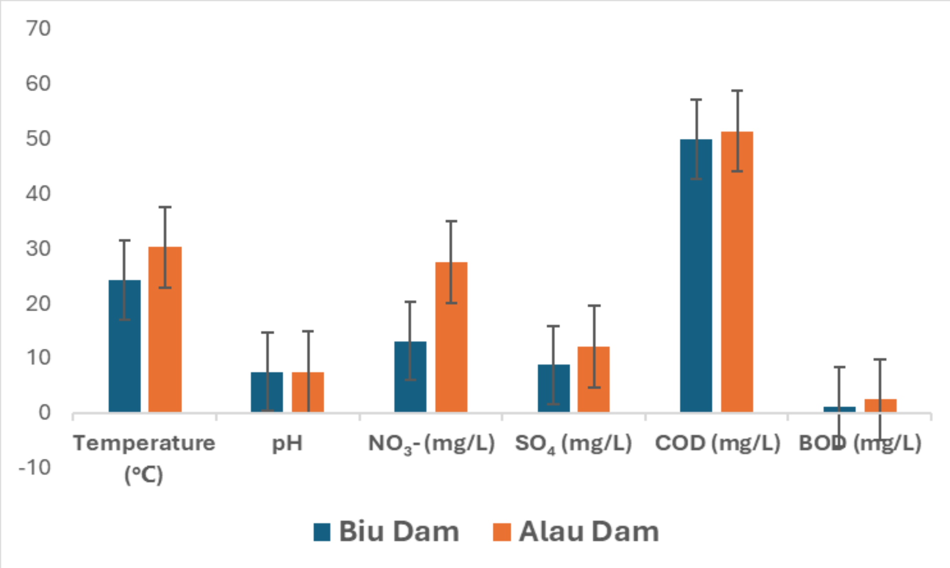

Figure 2a: Water Quality Parameters from the Study Area

The DO concentrations as shown in **Figure 2b** appeared relatively high (20.10±4.8 and 23.21± 4.3 mg/L in Alau and Biu Dams respectively) in both reservoirs. This may be attributed to wind-induced mixing, shallow sampling depth, photosynthetic activity of aquatic plants, and relatively low organic pollution during the sampling period.

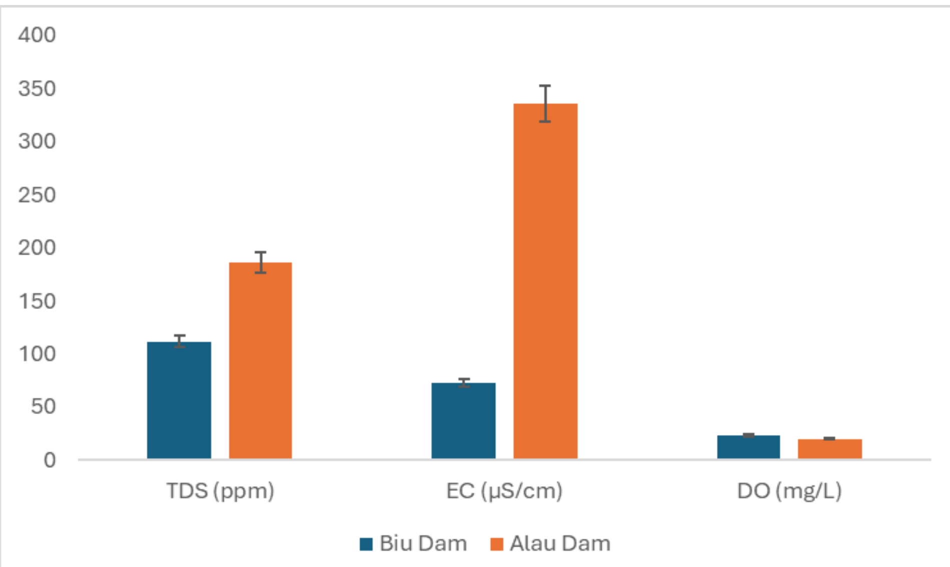

Figure 2b: Water Quality Parameters from the Study Area

3.2 Biological Indices

The biological indices of the fish species from the study area are presented in **Table 2** and **Figure 3**. Female GSI values of *O. niloticus* were higher in Alau Dam (13.10 ± 8.80%) than in Biu Dam (9.40 ± 2.80%). Similarly, male GSI values of *C. gariepinus* increased from 3.11 ± 2.80% in Biu Dam to 4.29 ± 2.10% in Alau Dam. The SRI values were generally similar between reservoirs. The condition factor values ranged from 1.05 to 1.45, indicating that both species maintained good physiological condition within the two reservoirs. The higher GSI values observed in Alau Dam may reflect differences in reproductive activity, nutritional status, maturity stage, or environmental conditions. However, because maturity stages and reproductive cycles were not investigated, the results should be interpreted cautiously.

Similarly, *O. niloticus* SRI was 7.32±2.3% and 8.54±4.1% (in Biu and Alau Dams respectively) while *C. gariepinus* SRI was 10.1±3.1% and 10.2±4.0% (in Alau and Biu Dams respectively). The Condition factor (K) in *O. niloticus* was 1.32±0.18 (Alau Dam) and 1.45±0.21 (Biu Dam) while K in *C. gariepinus* was 1.05±0.14 (Alau Dam) and 1.18±0.16 (Biu Dam).

Independent t-tests showed that most biological indices did not differ significantly between Biu and Alau Dams ($p > .05$). However, male hepatosomatic index of *O. niloticus* was significantly higher in Alau Dam ($t(22) = 2.48$, $p = .021$). Similarly, the condition factor of *C. gariepinus* differed significantly between the two reservoirs ($t(22) = 2.11$, $p = .046$), with higher values observed in Biu Dam.

Table 2: Biological Indices (Mean ± SD) of *O. niloticus* and *C. gariepinus* from Biu and Alau Dams, Borno State, Nigeria

Species	Biological Index	Biu Dam	Alau Dam	t	p
Oreochromis niloticus	Male GSI (%)	6.31 ± 2.10	7.23 ± 2.40	0.99	.333
	Female GSI (%)	9.40 ± 2.80	13.10 ± 8.80	1.38	.181
	Male HSI (%)	3.52 ± 1.40	5.32 ± 2.10	2.48	.021*
	Female HSI (%)	6.32 ± 2.50	4.56 ± 1.80	1.98	.060
	SRI (%)	7.32 ± 2.30	8.54 ± 4.10	0.88	.388
	Condition Factor (K)	1.45 ± 0.21	1.32 ± 0.18	1.63	.117
Clarias gariepinus	Male GSI (%)	3.11 ± 2.80	4.29 ± 2.10	1.17	.255
	Female GSI (%)	5.12 ± 2.20	5.72 ± 2.40	0.64	.530
	Male HSI (%)	1.58 ± 0.70	1.71 ± 0.60	0.49	.631
	Female HSI (%)	1.91 ± 0.80	1.92 ± 0.70	0.03	.977
	SRI (%)	10.20 ± 4.00	10.10 ± 3.10	0.07	.946
	Condition Factor (K)	1.18 ± 0.16	1.05 ± 0.14	2.11	.046*

Values are presented as mean ± standard deviation. Independent-samples t-tests were used to compare biological indices between Biu and Alau Dams. Significant differences are indicated by p < .05. GSI = Gonadosomatic Index; HSI = Hepatosomatic Index; SRI = Stomach Repletion Index; K = Condition Factor.

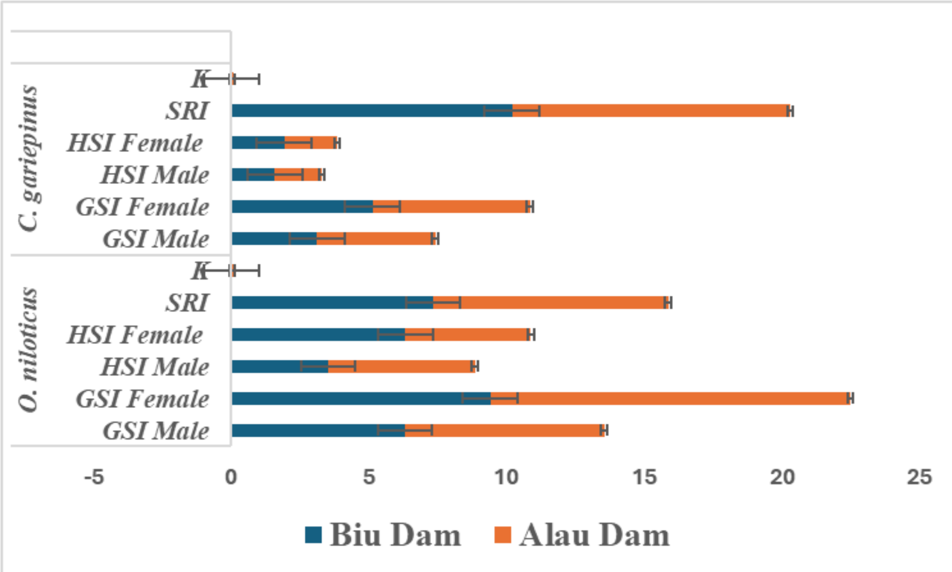

Figure 3: Biological Indices of the Fish Species from the Study Area

3

.3 Association between Water Quality and Biological Indices

The result of the Principal Component Analysis (PCA) as shown in **Figure 4** reveal the relationships between water quality parameters and physiological indices of male and female *O. niloticus* and *C. gariepinus* collected from Biu Dam and Alau Dam over three sampling months. PC1 and PC2 explain the majority of the total variance in the dataset, illustrating the influence of physicochemical variables on fish physiological responses.

Additionally, the results of the PCA Loading as shown in **Figure 5** and **Table 3** indicates that pH, DO, Female GSI (*O. niloticus*), Female GSI (*C. gariepinus*) and K (*C. gariepinus)* variables had strong positive loadings on PC1 included whereas temperature, EC, Nitrate, Sulphate, COD, BOD, TDS, HSI (male and female) and SRI variables had strong negative loadings. This suggests that nutrient enrichment and ionic concentration gradients are major drivers of biological variation.

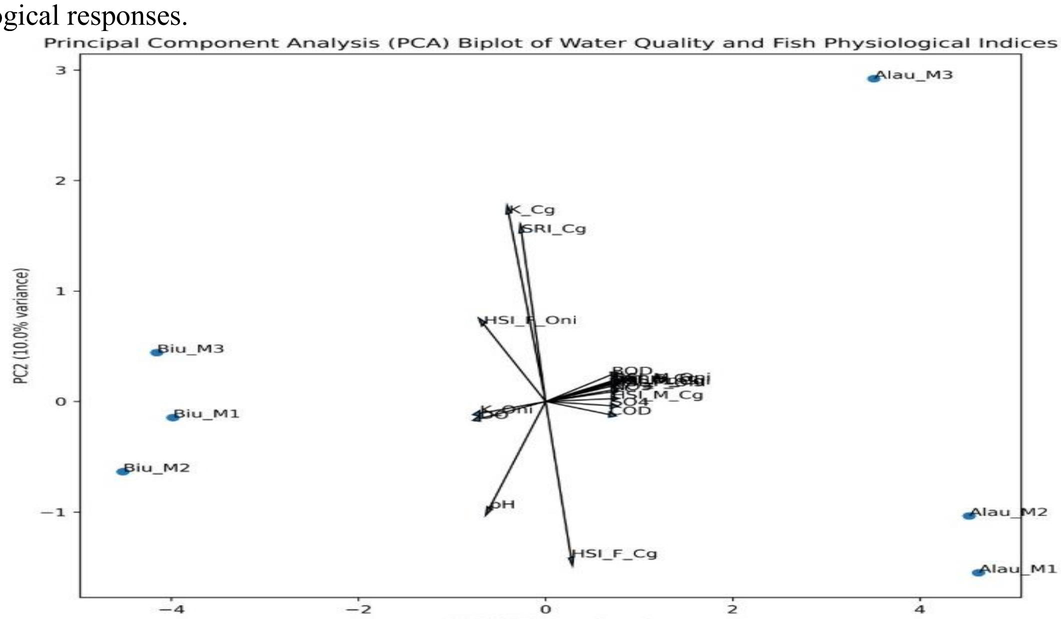

Figure 4: PCA Biplot of the Physicochemical Parameters and Biological Indices

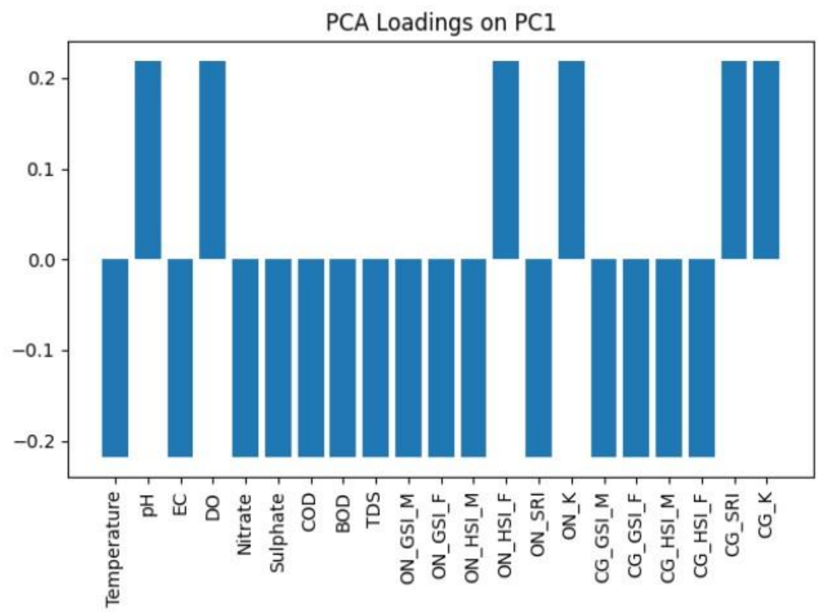

Figure 5: PCA Loading of the Physicochemical Parameters and Biological Indices

The result of the PCA Loadings of the combined environmental and biological parameter as shown in **Table 1** indicate that nutrient enrichment (nitrate, sulphate), ionic concentration (EC, TDS), and temperature were associated withfish physiological responses .

Table 3: PCA Loadings for Combined Environmental and Biological Variables

Variable	**PC1**	**PC2**
Temperature	0.92	0.11
pH	-0.38	0.74
EC	0.97	-0.08
DO	-0.93	0.14
Nitrate	0.95	-0.02
Sulphate	0.91	-0.26
COD	0.73	0.42
BOD	0.86	-0.19
TDS	0.96	-0.04
GSI Female (*O. niloticus*)	0.88	0.27
GSI Male (*O. niloticus*)	0.82	0.34
HSI Female (*O. niloticus*)	-0.45	0.71
HSI Male (*O. niloticus*)	0.74	0.46
SRI	0.63	-0.41
K	-0.69	0.52

The CCA was performed to evaluate the association between environmental variables (predictor matrix) and biological indices (response matrix). The result of the CCA as shown in **Figure 6** and **Table 4** indicates that the first canonical axis showed a strong positive association between EC, Nitrate, Sulphate, BOD, TDS and biological responses such as elevated female GSI in *O. niloticus,* Increased male GSI in *C. gariepinus, h*igher SRI values. Additionally, Biu Dam and Alau Dam were distinctly separated along the canonical gradient and the result further indicates that Alau Dam clustered positively along CCA1 (high nutrient and conductivity regime); while Biu Dam clustered negatively (lower nutrient loading and ionic concentration).

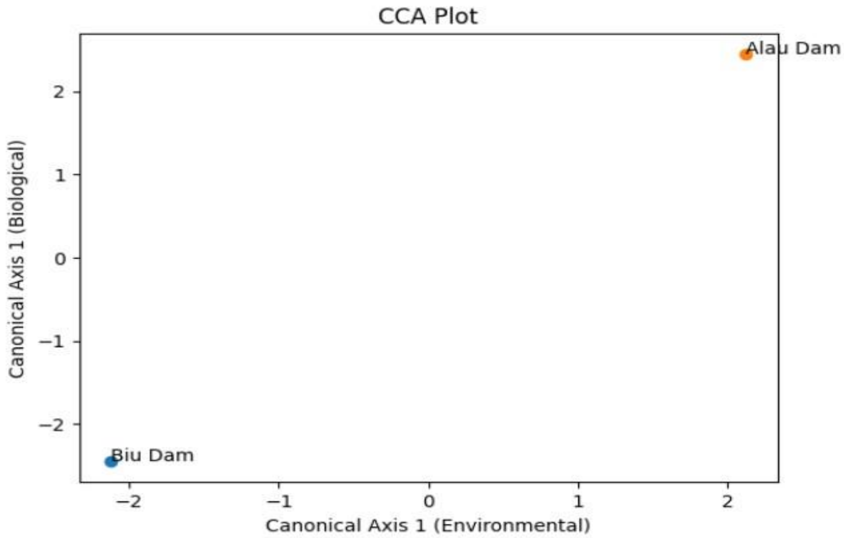

Figure 6: CCA Plot of the Environmental Parameters and Biological Indices

Table 4: CCA Loadings for Combined Environmental and Biological Variables

Axis	Eigenvalue	% Variance	P-value
CCA1	0.64	58.3	0.01
CCA2	0.28	24.6	0.03

4.0 DISCUSSION

The results of the multivariate analyses from this study suggests that water quality parameters exert significant effects on the reproductive and physiological indices of both *O. niloticus* and *C. gariepinus*. The high variance as explained by PC1 suggests that spatial environmental gradients between Biu Dam and Alau Dam are the primary determinants of biological variability. Spatial differences in water quality observed between Biu Dam and Alau Dam suggest varying levels of nutrient enrichment and anthropogenic influence. The higher conductivity, nitrate, and sulphate concentrations observed in Alau Dam indicate increased dissolved ions and nutrient inputs, which may arise from runoff and anthropogenic activities. Similar patterns of elevated nutrients affecting aquatic environments have been reported in Nigerian reservoirs and rivers (Bwala, 2021a; Wakil et al., 2025).

The significant differences observed in temperature, EC, NO_3^-, BOD, and TDS indicate that Alau Dam experiences greater nutrient enrichment and dissolved ionic concentrations than Biu Dam. Elevated conductivity and TDS may reflect increased runoff, anthropogenic activities, and nutrient loading within the watershed. The higher NO_3^- and BOD values further suggest increased organic inputs and microbial activity in Alau Dam. Conversely, the lack of significant differences in pH, DO, SO_4^{2-}, and COD indicates that both reservoirs maintain relatively similar acid-base conditions and oxygen availability despite variations in nutrient concentrations. These further suggest that local environmental conditions may contribute to differences in water quality between the reservoirs and may partly explain the variations observed in certain biological indices of the fish species although the statistical comparison of the biological indices between Biu and Alau Dams revealed that most of the measured parameters did not differ significantly between the two reservoirs ($p > .05$). This suggests that the overall physiological and reproductive conditions of *O. niloticus* and *C. gariepinus* were generally comparable across the study area. The absence of significant differences in GSI, SRI, and most HSI values indicates that both reservoirs provide relatively similar environmental conditions capable of supporting reproductive activities and energy allocation in the two species. However, the significantly higher male hepatosomatic index of *O. niloticus* in Alau Dam ($p < .05$) suggests possible differences in energy storage, metabolic activity, or nutritional status associated with local environmental conditions. Similarly, the significant variation in the condition factor of *C. gariepinus* between the two reservoirs indicates differences in fish well-being and growth performance, which may be related to variations in food availability, water quality, or habitat characteristics. These imply that although both reservoirs support similar biological performance, certain physiological responses may be influenced by local environmental conditions and resource availability within each location. The high levels of EC, nitrate, sulphate, and TDS in Alau Dam might had impacted on the reproductive capacity and general health of the fish, particularly in female *O. niloticus*. This aligns with findings that physicochemical variability strongly influences reproductive indices and condition factors in freshwater fish populations (Bwala et al. 2026). Similarly, nutrient enrichment and water chemistry fluctuations have been shown to affect population biology parameters of *O. niloticus* in North-East Nigeria (Olanrewaju et al. 2026). The strong association between EC, TDS, and reproductive indices may also reflect contaminant influence. Heavy metal contamination and sediment-water interactions have been documented in reservoirs within Borno State, including Biu Reservoir and Alau Dam (Bwala 2023; Wakil et al. 2025). Such contaminants can alter physiological responses, potentially influencing gonadal development and liver activity. Sampling was restricted to three months and therefore seasonal variations could not be fully assessed.

In this study, both the GSI and HSI were analyzed separately for male and female fish because these indices are closely linked to reproductive physiology and sex-specific metabolic processes. In contrast, both the analyzed SRI and K were estimated using pooled samples for each species. This approach is consistent with the ecological interpretation of these indices, as both SRI and K primarily reflect feeding intensity and general physiological condition rather than reproductive differentiation between sexes. The SRI provides an estimate of feeding activity and stomach fullness, which is influenced mainly by food availability, environmental productivity, and habitat conditions rather than gender-specific physiological processes (Prakash 2022; Sudarshan & Kulkarni 2013). Similarly, the K is widely used as an indicator of overall fish health and nutritional status, representing the balance between weight gain and body length growth (Aufy 2023; Ghaffari et al. 2011). The results of this study suggest that the SRI values in both *O. niloticus* and *C. gariepinus* remained relatively stable across sampling months, suggesting consistent feeding activity within the reservoirs. Slightly higher SRI values observed in *C. gariepinus* compared with *O. niloticus* may reflect species-specific feeding behaviour and trophic strategies, as African catfish are opportunistic feeders capable of exploiting a wider range of food resources (Aruho et al. 2026; Omach et al. 2025). Similarly, the K values recorded for both species indicate that the fish populations maintained relatively good physiological condition in both reservoirs. Previous studies have demonstrated that K values are influenced by environmental conditions, food availability, and water quality parameters, rather than strictly by sex differences (Sudarshan & Kulkarni, 2013; Muslim et al., 2023). Comparable findings have also been reported in freshwater fish populations where variations in feeding intensity and habitat quality were reflected in SRI and K values across seasons and locations (Bwala et al. 2026).

The reproductive indices observed in *O. niloticus* and *C. gariepinus* showed clear gender-specific variation. Female fish exhibited higher GSI values than males in both species, reflecting the larger gonadal development associated with egg production. This pattern is consistent with reproductive biology studies indicating that female fish typically invest more energy in gonad development than males (Ghaffari et al. 2011; Rizzo & Bazzoli 2020). Similar variations in GSI and HSI across aquatic systems have also been reported in other freshwater species where reproductive cycles and environmental conditions influence gonadal development (Aufy 2023; Prakash 2022).

Higher GSI values of male and female *O. niloticus* observed in Alau Dam may be related to the higher nutrient availability and productivity of the reservoir. Nutrient-rich waters can enhance food availability, thereby improving reproductive capacity in fish populations (Ekpo et al. 2025; Fayed et al. 2024). However, excessive nutrient enrichment may also introduce physiological stress, affecting metabolic processes and organ indices (Aende et al. 2026).

The hepatosomatic index values recorded in both species reflect variations in energy storage and metabolic activity. The liver plays a central role in metabolism, detoxification, and energy storage; therefore, variations in HSI may indicate environmental stress or changes in nutritional status (Sudarshan & Kulkarni 2013; Muslim et al. 2023). Previous studies on *C. gariepinus* and *O. niloticus* in Nigerian waters have similarly reported that water quality fluctuations can influence somatic indices and physiological responses in fish (Bwala et al. 2026; Olanrewaju et al. 2026).

The PCA results further highlight the strong association between water quality variables and physiological indices of fish. The clustering pattern observed in the PCA biplot indicates that variations in nutrient concentrations and dissolved solids contribute significantly to the physiological responses of both fish species. Similar relationships between water quality and fish physiological parameters have been documented in aquatic ecosystems where environmental conditions influence growth, feeding behavior, and reproductive performance (Idam & Degais 2025; Omach et al. 2025; Maulianawati et al. 2024).

The linkage observed in CCA between nutrient parameters and SRI supports evidence that feeding intensity and metabolic allocation respond to water quality dynamics (Bwala et al. 2026). Environmental stress markers are known to correlate with altered physiological indices in fish exposed to fluctuating water conditions (Aende et al. 2026). The influence of nutrient enrichment observed in the PCA and CCA is consistent with reports that water quality fluctuations alter physiological stress biomarkers in fish populations (Aende et al. 2026). Increased nutrient levels may enhance primary productivity but can also induce metabolic stress responses.

Furthermore, nutrient-driven productivity in aquatic systems has been shown to enhance fish growth performance under controlled aquaculture settings (Fayed et al. 2024; Omach et al., 2025). However, excessive nutrient accumulation may pose ecological risks, particularly in natural reservoirs. Emerging pollutants such as tire-derived contaminants may further complicate ecological interactions in river systems (Hassan et al. 2026). Nutrient-driven productivity effects observed here parallel findings in controlled aquaculture systems, where water quality significantly affects growth performance in both Nile tilapia and African catfish (Fayed et al. 2024; Omach et al., 2025). Bioindicator studies have demonstrated that parasitic loads in *C. gariepinus* reflect underlying water quality status (Olubiyo et al. 2024), reinforcing the biological sensitivity of this species to environmental change. Seasonal shifts and climatic variability also contribute to physicochemical fluctuations, influencing morphological and physiological responses in Nile tilapia (Ekpo et al. 2025).

The environmental gradient observed between dams may also reflect broader watershed impacts. Irrigational activities and nonpoint source pollution have previously been shown to alter water quality and biodiversity in northern Nigerian freshwater systems (Bwala 2021a;

Bwala 2021b). Bioindicator studies further confirm that *C. gariepinus* parasites reflect water quality conditions (Olubiyo et al. 2024).

5.0 Conclusion

This study demonstrates that the combined PCA and CCA analyses suggests that water quality parameters were associated with the reproductive and physiological indices of *O. niloticus* and *C. gariepinus* in Biu and Alau Dams. Additionally, the multivariate analyses also revealed that spatial environmental gradients between the two reservoirs are the may contribute to observed variation of biological variability.

Nutrient enrichment, electrical conductivity, and dissolved solids were identified as the primary environmental factors structuring reproductive investment, particularly female gonadosomatic index. The observed associations suggest that water quality parameters and biological indices such as GSI and HSI are sensitive ecological indicators of environmental change. The separation of dams along the principal component and canonical axes highlights substantial ecological heterogeneity between the systems.

The findings emphasize that fluctuations in nutrient loading and water chemistry are associated with physiological allocation patterns in freshwater fish. Effective water quality monitoring and management are therefore critical for sustaining fish reproductive performance, maintaining reservoir productivity, and ensuring long-term ecological stability.

5.1 Environmental/Ecological Management Recommendations

Based on the findings of this study, several management strategies are recommended to sustain the ecological integrity and fisheries productivity of Alau and Biu Dams.

1. **Routine Water Quality Monitoring:** Regular monitoring of key physicochemical parameters, including temperature, pH, dissolved oxygen, electrical conductivity, total dissolved solids, nitrate, sulphate, biochemical oxygen demand, and chemical oxygen demand, should be conducted to detect early signs of environmental deterioration. Particular attention should be given to Alau Dam, which exhibited significantly higher nutrient concentrations and dissolved solids.
2. **Control of Agricultural and Urban Runoff:** The high concentration levels of nitrate, EC, TDS, and BOD observed in Alau Dam suggest possible influences of runoff and anthropogenic activities. Appropriate watershed management practices, including the establishment of vegetative buffer zones and the regulation of agricultural inputs around the reservoirs, should be encouraged to reduce nutrient loading.
3. **Periodic Fish Health and Biological Assessment:**Routine assessment of fish biological indices such as gonadosomatic index, hepatosomatic index, stomach repletion index, and condition factor should be incorporated into fisheries monitoring programmes. These indices may serve as useful indicators of changes in fish physiological condition and environmental quality.
4. **Strengthening Reservoir Fisheries Management:** Fisheries management authorities should implement sustainable harvesting practices, regulate fishing activities during breeding periods, and encourage community participation in reservoir management to ensure long-term fish productivity.
5. **Long-Term Ecological Monitoring:** Since this study was conducted over a three-month period, future investigations should include dry and wet season assessments to evaluate seasonal variations in water quality and fish biological responses. Long-term monitoring would provide a more comprehensive understanding of ecological changes within the reservoirs.
6. **Environmental Awareness and Stakeholder Engagement:** Local communities, fishermen, and other stakeholders should be sensitized on the importance of protecting reservoir water quality. National Environmental Standards and Regulations Enforcement Agency (NESREA) should intensify on public awareness campaigns aimed at

reducing waste disposal, nutrient enrichment, and other anthropogenic disturbances around the reservoirs should be encouraged.

Implementation of these management measures will contribute to improved water quality, sustainable fisheries production, and long-term ecological stability of Alau and Biu Dams.

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CONFLICT OF INTERESTS

The author(s) declared no potential conflicts of interest

ETHICAL CONSIDERATIONS

All experimental procedures (both in the laboratory and field) involving the sampled fish species (*C. gariepinus* and *O. niloticus*) were conducted in accordance with internationally accepted guidelines for the care and use of experimental animals. Additionally, handling, sampling, and euthanasia were performed using humane methods to minimize stress and suffering, and all efforts were made to reduce the number of animals used while ensuring scientific validity.

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