



## Phytoplankton Community Structure, Cyanobacterial Proliferation, and Water Quality Relationships in the River Benue Basin, Adamawa State, Nigeria

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### ABSTRACT

Phytoplankton communities are sensitive bioindicators of freshwater ecosystem health, yet their composition, diversity, and cyanobacterial status have never been quantitatively characterised for the River Benue Basin, Adamawa State, Nigeria. This study presents the first multi-location quantitative assessment of phytoplankton composition, abundance, and diversity across three contrasting anthropogenic pressure zones, and evaluates the public health significance of toxigenic cyanobacterial genera. Phytoplankton were collected monthly at Boronji, Dasin Hausa, and Njoboliyo during dry (February–April 2025) and rainy (June–August 2025) seasons by horizontal net towing (55 µm mesh), preserved in Lugol's iodine, and enumerated using Sedgewick-Rafter chambers under compound microscopy. Diversity was assessed using Shannon-Wiener ( $H'$ ) and Pielou's evenness ( $J'$ ) indices. Nineteen taxa were recorded at Boronji and Njoboliyo, and 20 at Dasin Hausa, spanning four divisions: Bacillariophyta, Chlorophyta, Cyanobacteria, and Chrysophyta. *Fragilaria* sp. dominated at all sites, peaking at 17,783 ind./L at Dasin Hausa, which also recorded the highest total abundance (46,895 ind./L), followed by Njoboliyo (27,636 ind./L) and Boronji (26,713 ind./L). Shannon-Wiener indices ranged from  $H' = 1.94$  (Njoboliyo) to  $H' = 2.27$  (Boronji). Four toxigenic genera *Anabaena*, *Aphanocapsa*, *Oscillatoria*, and *Aphanizomenon* occurred at all locations throughout the study, with *Oscillatoria* anomalously elevated at the most metal-contaminated site, Njoboliyo (868 vs. 282–284 ind./L elsewhere). The basin has crossed ecological thresholds enabling sustained cyanobacterial establishment at all sites; the Chlorophyta/Bacillariophyta ratio is identified as a sensitive bioindicator of heavy metal stress. Cyanobacterial surveillance and riparian buffer restoration are recommended as priority actions.

**Keywords:** Phytoplankton; Bacillariophyta; Cyanobacteria; *Fragilaria*; *Anabaena*; Shannon Diversity; River Benue; Freshwater Ecology; Nigeria

### INTRODUCTION

Phytoplankton constitute the primary trophic level of aquatic food webs and account for approximately 50% of global primary production (Song et al., 2020; Reynolds, 1994). Their short generation times and high metabolic sensitivity to physico-chemical conditions make them among the most rapid and reliable bioindicators of freshwater ecosystem health (Kutama et al., 2014; Gao et al., 2024). Changes in phytoplankton species composition and diversity reflect nutrient loading, heavy metal toxicity, turbidity, and organic enrichment with greater temporal resolution than most physico-chemical parameters alone (Odulate et al., 2017; Zhang et al., 2024).

Of particular concern in impacted tropical freshwater systems is the proliferation of Cyanobacteria — a division whose members include strains capable of producing hepatotoxins (microcystins), neurotoxins (anatoxin-a, saxitoxins), and multi-organ toxins (cylindrospermopsins) hazardous to humans, livestock, and aquatic biota (Gebrehiwot et al., 2022; WHO, 2022). Across West and Central Africa, where rural populations depend on river water for drinking, cooking, and personal hygiene without access to formal treatment infrastructure, the proliferation of toxigenic cyanobacteria represents an acute but under-monitored public health challenge. The WHO (2022) guideline for microcystin-LR in drinking water is 1 µg/L, and recreational contact advisory thresholds are triggered at approximately 2,000 cyanobacterial cells/mL.

The River Benue Basin in Adamawa State supports millions of riparian residents dependent on the river for domestic water, irrigation, artisanal fishing, and livestock watering.

The basin is simultaneously under pressure from agricultural land use encroaching to within 5–15 metres of the riverbank, domestic waste disposal, artisanal sand mining, and probable artisanal metal processing near community settlements (Alkali et al., 2022; Samuel et al., 2024). These pressures generate nutrient enrichment, turbidity, organic loading, and chemical contamination — conditions conducive to cyanobacterial proliferation. A companion study (Abdulazeez et al., 2025a) confirmed that more than 50% of the basin population depends directly on natural resource exploitation for livelihoods, and a complete regulatory vacuum governs riparian land use at all three study sites. Despite this significance, no previous study has characterised phytoplankton species composition, diversity, or cyanobacterial status for the Adamawa State reach of the River Benue Basin.

This study aims to characterise phytoplankton species composition and abundance at three contrasting anthropogenic pressure zones, quantify community diversity using Shannon-Wiener ( $H'$ ) and Pielou's evenness ( $J'$ ) indices, and document toxigenic cyanobacterial genera and their public health significance. It further examines relationships between phytoplankton community structure and prevailing water quality conditions.

### MATERIALS AND METHODS

#### Study Area

The study was conducted at three locations along the River Benue Basin in Adamawa State, Nigeria: Boronji (9°15'43"N, 12°28'39"E, Yola North LGA), Dasin Hausa (9°16'23"N, 12°39'29"E, Fufore LGA), and Njoboliyo (9°13'40"N,

12°34'58"E, Yola South LGA). The basin experiences a tropical climate with distinct dry (November–April) and rainy (May–October) seasons, annual rainfall of 700–1,600 mm, and water temperatures of 18.2–23.5°C during the study period (Adebayo and Tukur, 1999). Agricultural land occupies an estimated 55–65% of the catchment immediately adjacent to all three study sites, with riparian buffer zones essentially absent.

#### Phytoplankton Sample Collection

Phytoplankton samples were collected monthly from February to August 2025, covering the dry season (February–April) and rainy season (June–August); May was excluded as a transitional month. Sampling was conducted during morning hours (07:00–10:00 h) (APHA, 2017). At each location, phytoplankton were collected by horizontal towing of a plankton net (55 µm mesh, 25 cm mouth diameter) for five minutes through the top 0.3 m of the water column. Concentrated samples were preserved immediately in Lugol's iodine (1% final concentration). Three replicate tows were composited before enumeration. The volume of water filtered was estimated from tow distance and net mouth area.

#### Laboratory Identification and Enumeration

Sub-samples (1 mL) were examined using compound microscopes (Olympus CX23) at ×100–×400 magnification with Sedgewick-Rafter counting chambers. Phytoplankton were identified to genus or species level using standard taxonomic keys (Bellinger and Sigeo, 2015; Guiry and Guiry, 2024). A minimum of 200 cells was counted per sub-sample. Abundance was calculated as individuals per litre (ind./L)

using the formula:  $N = (n \times V_s) / (v \times V_f)$  (Bellinger and Sigeo, 2015), where  $N$  = cells per litre,  $n$  = cells counted in sub-sample,  $V_s$  = volume of concentrated sample (mL),  $v$  = volume of sub-sample examined (mL), and  $V_f$  = volume of water filtered (L).

#### Diversity and Evenness Indices

Shannon-Wiener diversity ( $H'$ ) was calculated as  $H' = -\sum p_i \ln(p_i)$ , where  $p_i$  is the proportional abundance of the  $i$ -th taxon;  $H' < 1.0$  = low; 1.0–3.0 = moderate; >3.0 = high diversity (Magurran, 2021). Pielou's evenness ( $J'$ ) was calculated as  $J' = H' / \ln(S)$ ;  $J' > 0.75$  indicates balanced community distribution (Jost, 2007).

#### Concurrent Water Quality Parameters

Concurrent physico-chemical parameters and heavy metal concentrations (Pb, Ni, Cd, Fe, Mn) were measured following Rice et al. (2017) and USEPA (1994) as detailed in the companion physico-chemical study (Abdulazeez et al., 2025b). These parameters are presented in Table 8 solely to contextualise phytoplankton community patterns.

## RESULTS AND DISCUSSION

### Overview of Community Composition

Phytoplankton comprised four algal divisions' at all three locations: Bacillariophyta, Chlorophyta, Cyanobacteria, and Chrysophyta. A total of 19 taxa were recorded at Boronji and Njoboliyo, and 20 at Dasin Hausa. *Fragilaria* sp. (Bacillariophyta) was numerically dominant at all sites. Summary metrics are presented in Table 1.

**Table 1: Summary of Phytoplankton Community Metrics at the Three Study Locations**

Metric	Boronji	Dasin Hausa	Njoboliyo
Total species richness (S)	19	20	19
Total abundance (ind./L)	26,713	46,895	27,636
Bacillariophyta taxa/abundance (ind./L)	5 / 15,589	5 / 29,503	5 / 18,705
Chlorophyta taxa/abundance (ind./L)	7 / 7,064	9 / 12,118	7 / 4,687
Cyanobacteria taxa/abundance (ind./L)	4 / 3,707	4 / 5,428	4 / 3,794
Chrysophyta taxa/abundance (ind./L)	2 / 351	2 / 845	2 / 450
Most abundant taxon	<i>Fragilaria</i> sp.	<i>Fragilaria</i> sp.	<i>Fragilaria</i> sp.
Peak single-taxon abundance (ind./L)	9,365	17,783	12,929
Shannon-Wiener Index $H'$	2.27	2.23	1.94
Pielou's Evenness $J'$	0.77	0.74	0.66

### Species Composition and Abundance at Boronji

Nineteen phytoplankton taxa were recorded at Boronji, with total abundance 26,713 ind./L and  $H' = 2.27$  (Table 2). Bacillariophyta dominated numerically (58.36%; 5 taxa), led by *Fragilaria* sp. (9,365 ind./L). Cyanobacteria comprised

four taxa (13.88% of total): *Anabaena* sp. (1,762 ind./L) was the most abundant, followed by *Aphanizomenon* sp. (902 ind./L), *Aphanocapsa* sp. (759 ind./L), and *Oscillatoria* sp. (284 ind./L).

**Table 2: Phytoplankton Species Composition and Abundance at Boronji**

S/N	Division	Species/Taxon	Abundance (ind./L)
1	Bacillariophyta	<i>Fragilaria</i> sp.	9,365
2	Bacillariophyta	<i>Tabellaria</i> spp.	2,457
3	Bacillariophyta	<i>Naviculales</i> sp.	2,754
4	Bacillariophyta	<i>Nitzschia</i> sp.	553
5	Bacillariophyta	<i>Cyclotella</i> sp.	460
6	Chlorophyta	<i>Ankistrodesmus</i> sp.	2,627
7	Chlorophyta	<i>Chlorella</i> sp.	740
8	Chlorophyta	<i>Enteromorpha</i> sp.	1,188
9	Chlorophyta	<i>Closterium</i> sp.	1,566
10	Chlorophyta	<i>Eudorina</i> sp.	283
11	Chlorophyta	<i>Oocystis</i> sp.	260

S/N	Division	Species/Taxon	Abundance (ind./L)
12	Chlorophyta	<i>Zugrema sp.</i>	100
13	Chlorophyta	<i>Microspora sp.</i>	302
14	Cyanobacteria	<i>Aphanocapsa sp.</i>	759
15	Cyanobacteria	<i>Anabaena sp.</i>	1,762
16	Cyanobacteria	<i>Oscillatoria sp.</i>	284
17	Cyanobacteria	<i>Aphanizomenon sp.</i>	902
18	Chrysophyta	<i>Mallomonas sp.</i>	287
19	Chrysophyta	<i>Synura sp.</i>	64
		Total	26,713
		Shannon-Wiener Index (H')	2.27

#### Species Composition and Abundance at Dasin Hausa

Dasin Hausa recorded the highest species richness (20 taxa) and total abundance (46,895 ind./L), with  $H' = 2.23$  (Table 3). *Fragilaria sp.* reached its basin-wide peak of 17,783 ind./L.

*Ulothrix sp.* (500 ind./L) was uniquely recorded at Dasin Hausa and absent from the other two sites. *Anabaena sp.* (3,211 ind./L) was the most abundant cyanobacterial taxon across all three sites.

**Table 3: Phytoplankton Species Composition and Abundance at Dasin Hausa**

S/N	Division	Species/Taxon	Abundance (ind./L)
1	Bacillariophyta	<i>Fragilaria sp.</i>	17,783
2	Bacillariophyta	<i>Tabellaria spp.</i>	4,904
3	Bacillariophyta	<i>Naviculales sp.</i>	4,943
4	Bacillariophyta	<i>Nitzschia sp.</i>	1,077
5	Bacillariophyta	<i>Cyclotella sp.</i>	796
6	Chlorophyta	<i>Ankistrodesmus sp.</i>	3,459
7	Chlorophyta	<i>Chlorella sp.</i>	1,414
8	Chlorophyta	<i>Ulothrix sp.</i>	500
9	Chlorophyta	<i>Enteromorpha sp.</i>	1,477
10	Chlorophyta	<i>Closterium sp.</i>	2,082
11	Chlorophyta	<i>Eudorina sp.</i>	1,121
12	Chlorophyta	<i>Oocystis sp.</i>	707
13	Chlorophyta	<i>Zugrema sp.</i>	198
14	Chlorophyta	<i>Microspora sp.</i>	160
15	Cyanobacteria	<i>Aphanocapsa sp.</i>	1,695
16	Cyanobacteria	<i>Anabaena sp.</i>	3,211
17	Cyanobacteria	<i>Oscillatoria sp.</i>	282
18	Cyanobacteria	<i>Aphanizomenon sp.</i>	240
19	Chrysophyta	<i>Mallomonas sp.</i>	502
20	Chrysophyta	<i>Synura sp.</i>	343
		Total	46,895
		Shannon-Wiener Index (H')	2.23

#### Species Composition and Abundance at Njoboliyo

Nineteen phytoplankton taxa were recorded at Njoboliyo, with total abundance 27,636 ind./L and  $H' = 1.94$  — the lowest diversity of the three sites (Table 4). Pielou's evenness ( $J' = 0.66$ ) fell below the 0.75 balanced-community threshold. *Oscillatoria sp.* recorded its basin-wide maximum abundance

at Njoboliyo (868 ind./L vs. 284 ind./L at Boronji and 282 ind./L at Dasin Hausa). Chlorophyta taxa showed markedly reduced abundances at Njoboliyo: *Eudorina sp.* (100 ind./L vs. 283–1,121 ind./L at other sites), *Zugrema sp.* (20 ind./L vs. 100–198 ind./L), and *Microspora sp.* (40 ind./L vs. 160–302 ind./L).

**Table 4: Phytoplankton Species Composition and Abundance at Njoboliyo**

S/N	Division	Species/Taxon	Abundance (ind./L)
1	Bacillariophyta	<i>Fragilaria sp.</i>	12,929
2	Bacillariophyta	<i>Tabellaria spp.</i>	2,569
3	Bacillariophyta	<i>Naviculales sp.</i>	2,857
4	Bacillariophyta	<i>Nitzschia sp.</i>	150
5	Bacillariophyta	<i>Cyclotella sp.</i>	200
6	Chlorophyta	<i>Ankistrodesmus sp.</i>	2,259
7	Chlorophyta	<i>Chlorella sp.</i>	290
8	Chlorophyta	<i>Enteromorpha sp.</i>	450
9	Chlorophyta	<i>Closterium sp.</i>	1,048
10	Chlorophyta	<i>Eudorina sp.</i>	100

S/N	Division	Species/Taxon	Abundance (ind./L)
11	Chlorophyta	<i>Oocystis sp.</i>	480
12	Chlorophyta	<i>Zugrema sp.</i>	20
13	Chlorophyta	<i>Microspora sp.</i>	40
14	Cyanobacteria	<i>Aphanocapsa sp.</i>	856
15	Cyanobacteria	<i>Anabaena sp.</i>	1,750
16	Cyanobacteria	<i>Oscillatoria sp.</i>	868
17	Cyanobacteria	<i>Aphanizomenon sp.</i>	320
18	Chrysophyta	<i>Mallomonas sp.</i>	60
19	Chrysophyta	<i>Synura sp.</i>	390
		Total	27,636
		Shannon-Wiener Index (H')	1.94

#### Divisional Relative Abundance

Table 5 shows the percentage contribution of each algal division to total abundance. Bacillariophyta dominance increased along the contamination gradient (58.36% at Boronji → 67.68% at Njoboliyo). Chlorophyta relative

abundance declined sharply at Njoboliyo (16.96%) compared to Boronji (26.45%) and Dasin Hausa (25.84%), reflecting greater sensitivity of green algae to heavy metal toxicity. Cyanobacteria maintained a consistent presence of 11.58–13.88% across all sites.

**Table 5: Divisional Relative Abundance (% of Total Phytoplankton) by Location**

Algal Division	Taxa (all sites)	Boronji (%)	Dasin Hausa (%)	Njoboliyo (%)
Bacillariophyta	5	58.36	62.91	67.68
Chlorophyta	9*	26.45	25.84	16.96
Cyanobacteria	4	13.88	11.58	13.73
Chrysophyta	2	1.31	1.80	1.63
Total	—	100.00	100.00	100.00

#### Cyanobacterial Taxa, Abundance, and Toxin-Producing Capacity

Four cyanobacterial genera were recorded at all three locations throughout the entire study period (Table 6). *Anabaena sp.* was consistently the most abundant

cyanobacterial genus, peaking at Dasin Hausa (3,211 ind./L). *Oscillatoria sp.* peaked at Njoboliyo (868 ind./L) against 282–284 ind./L at the other sites. All four genera include strains with confirmed cyanotoxin-producing capacity.

**Table 6: Cyanobacterial Taxa: Abundance and Confirmed Toxin-Producing Capacity**

Taxon	Boronji (ind./L)	Dasin Hausa (ind./L)	Njoboliyo (ind./L)	Principal Toxins Produced
<i>Anabaena sp.</i>	1,762	3,211	1,750	Microcystins, Anatoxin-a, Cylindrospermopsin
<i>Aphanocapsa sp.</i>	759	1,695	856	Microcystins
<i>Oscillatoria sp.</i>	284	282	868	Microcystins, Oscillapeptin
<i>Aphanizomenon sp.</i>	902	240	320	Anatoxin-a, Saxitoxins, Cylindrospermopsin
Total Cyanobacteria (ind./L)	3,707	5,428	3,794	—

#### Shannon-Wiener Diversity and Pielou's Evenness

Both H' and J' declined directionally from Boronji to Njoboliyo, inversely mirroring the increasing heavy metal

contamination gradient (Table 7). Njoboliyo was the only site where J' fell below the 0.75 balanced-community threshold.

**Table 7: Shannon-Wiener Diversity (H') and Pielou's Evenness (J') by Location**

Location	Richness (S)	Abundance (ind./L)	H' (Shannon-Wiener)	J' (Pielou's Evenness)	Community Interpretation
Boronji	19	26,713	2.27	0.77	Moderate diversity; balanced community
Dasin Hausa	20	46,895	2.23	0.74	Moderate diversity; near-balanced community
Njoboliyo	19	27,636	1.94	0.66	Moderate–low; incipient stress signal

#### Concurrent Water Quality and Heavy Metal Parameters

Table 8 presents key physico-chemical and heavy metal parameters measured concurrently at all three study sites. Turbidity exceeded the WHO (2022) drinking water guideline

(5 NTU) by 9–10 times at all sites. Lead concentrations at Boronji and Njoboliyo substantially exceeded WHO limits; Dasin Hausa exhibited near-background metal concentrations throughout.

**Table 8: Concurrent Water Quality and Heavy Metal Parameters by Location (Mean ± SD; 2025)**

Parameter	WHO Guideline	Boronji Mean ± SD	Dasin Hausa Mean ± SD	Njoboliyo Mean ± SD
Ph	6.5–8.5	7.628 ± 0.343	7.889 ± 0.404	7.833 ± 0.297
Temperature (°C)	—	21.178 ± 1.327	21.300 ± 1.512	21.372 ± 1.444
Turbidity (NTU)	5	48.767 ± 6.540	48.172 ± 7.123	46.500 ± 9.775
Dissolved Oxygen (mg/L)	≥5	5.300 ± 0.325	5.539 ± 0.223	5.839 ± 0.730

TDS (mg/L)	600	58.222 ± 4.250	55.556 ± 2.255	44.000 ± 4.102
Conductivity (µS/cm)	—	7.267 ± 0.197	5.622 ± 0.135	4.667 ± 0.954
Fluoride (mg/L)	1.5	0.255 ± 0.062	0.029 ± 0.002	0.001 ± 0.000
Nitrate (mg/L)	50	0.274 ± 0.075	0.032 ± 0.014	0.244 ± 0.062
Lead Pb (mg/L)	0.010	0.063 ± 0.075	0.005 ± 0.001	0.188 ± 0.111
Nickel Ni (mg/L)	0.070	0.003 ± 0.001	0.002 ± 0.001	0.046 ± 0.013
Cadmium Cd (mg/L)	0.003	0.004 ± 0.004	0.002 ± 0.001	0.003 ± 0.001
Iron Fe (mg/L)	0.300	0.005 ± 0.001	0.005 ± 0.001	0.014 ± 0.012
Manganese Mn (mg/L)	0.400	0.003 ± 0.001	0.003 ± 0.002	0.005 ± 0.001

## Discussion

The consistent numerical dominance of Bacillariophyta (58.36–67.68% of total abundance) is characteristic of large, turbid, well-oxygenated tropical rivers and is consistent with findings from comparable African and Asian river systems (Gao et al., 2024; Odulate et al., 2017). Diatoms possess siliceous frustules that confer chemical resilience in turbulent, mixed water columns — conditions prevailing at all three Benue Basin sites (turbidity 46.5–48.8 NTU; dissolved oxygen 5.3–5.8 mg/L mean).

*Fragilaria* sp. was numerically dominant at all three sites, peaking at 17,783 ind./L at Dasin Hausa. *Fragilaria* is documented as an opportunistic coloniser of mesotrophic to mildly eutrophic systems with moderate nutrient availability (Bellinger and Sigeo, 2015). Its substantially higher abundance at Dasin Hausa — the site with the lowest metal contamination and slightly elevated nutrients — is consistent with Shang et al. (2024), who demonstrated that phytoplankton productivity in rivers is driven by nutrient availability but suppressed by heavy metal toxicity. At Njoboliyo, where lead reached a mean of 0.188 mg/L (18.8 times the WHO guideline), *Fragilaria* abundance was 31% lower than at Dasin Hausa despite comparable nutrient levels, consistent with metal-mediated suppression of primary productivity.

The progressive decline in Chlorophyta relative abundance — from 26.45% at Boronji and 25.84% at Dasin Hausa to only 16.96% at Njoboliyo — along the heavy metal contamination gradient is the most ecologically informative spatial pattern in this study. This suppression occurred with stable Chlorophyta species richness (7 taxa at both sites), confirming sublethal growth inhibition rather than species elimination — characteristic of early-stage metal toxicity in algal communities (Rai et al., 2019).

The differential sensitivity of Chlorophyta to heavy metal stress relative to Bacillariophyta is well established: green algae lack the protective silica frustule of diatoms and are more susceptible to lead- and nickel-induced reactive oxygen species that disrupt photosynthetic electron transport and inhibit key enzymes (Das et al., 2011; Rai et al., 2019). At Njoboliyo, lead (mean 0.188 mg/L) and nickel (mean 0.046 mg/L) approaching the WHO guideline of 0.070 mg/L are at concentrations where sublethal Chlorophyta growth suppression is well documented in toxicity studies (Rai et al., 2019). The Chlorophyta-to-total-phytoplankton ratio thus emerges as a sensitive, cost-effective bioindicator of metal stress in tropical river systems.

The presence of four toxigenic cyanobacterial genera — *Anabaena*, *Aphanocapsa*, *Oscillatoria*, and *Aphanizomenon* — at all three locations throughout both dry and rainy seasons confirms that cyanobacterial establishment is a basin-wide, year-round phenomenon. This finding agrees with Gebrehiwot et al. (2022), who documented cyanobacterial proliferation in sub-Saharan African water bodies as a characteristic response to anthropogenic nutrient enrichment and organic loading, and specifically identified these four

genera as those most frequently implicated in cyanotoxin-producing events in the region, including strains producing hepatotoxic microcystins, neurotoxic anatoxin-a, and cylindrospermopsin. Total cyanobacterial counts of 3,707–5,428 ind./L are at or above the WHO (2022) recreational advisory threshold of approximately 2,000 cells/mL, placing communities using the river for bathing, washing, and direct water collection at threshold exposure levels.

The anomalous peak abundance of *Oscillatoria* sp. at Njoboliyo (868 ind./L vs. 282–284 ind./L at other sites) is a critical finding. *Oscillatoria* species are documented as the most metal-tolerant members of the Cyanobacteria, capable of continued active growth at heavy metal concentrations lethal to other cyanobacterial genera and to most Chlorophyta (Rai et al., 2019). The selective competitive advantage of *Oscillatoria* under the catastrophic lead contamination at Njoboliyo therefore represents active community restructuring toward more metal-tolerant and potentially more toxigenic taxa — a combined stressor mechanism that warrants explicit recognition in West African river monitoring frameworks. The finding is in contrast with pristine reference conditions documented by Gebrehiwot et al. (2022) in minimally disturbed Ethiopian highland wetlands, where cyanobacteria were largely absent.

The directional decline in  $H'$  (2.27 → 2.23 → 1.94) and  $J'$  (0.77 → 0.74 → 0.66) inversely mirrors the increasing heavy metal contamination gradient, consistent with Ekperusi et al. (2022), who documented Shannon diversity indices inversely related to metal contamination intensity in the Oghan River, Nigeria. Pielou's evenness at Njoboliyo ( $J' = 0.66$ ) falling below the 0.75 balanced-community threshold indicates that one or a few taxa are beginning to disproportionately dominate — evidenced by the growing relative dominance of *Fragilaria* sp. and *Oscillatoria* sp. at the expense of suppressed Chlorophyta genera. Magurran (2021) confirmed that declining evenness is the earliest measurable signal of pollution-driven community restructuring, preceding species richness loss — placing Njoboliyo at a critical juncture where proactive management intervention is far more effective than reactive measures once community collapse has occurred.

The higher total abundance at Dasin Hausa (46,895 ind./L) relative to Boronji and Njoboliyo reflects Dasin Hausa's near-reference status: lower metal contamination and intact community structure allow full expression of phytoplankton growth potential in response to available nutrients, consistent with the bottom-up trophic dynamics confirmed by Shang et al. (2024).

The coexistence of four toxigenic cyanobacterial genera at all three sites, the selective enrichment of metal-tolerant *Oscillatoria* at Njoboliyo, and the absence of any water treatment infrastructure serving the three communities collectively define a credible and escalating cyanotoxin risk that is currently unmonitored. Three priority management actions are indicated. First, immediate establishment of monthly phytoplankton surveillance targeting cyanobacterial genera — with particular attention to *Oscillatoria* abundance

at Njoboliyo and total cyanobacterial counts relative to the 2,000 cells/mL advisory threshold — should be treated as an emergency public health action. Second, restoration of minimum 30-metre riparian buffer zones is the highest-priority long-term intervention for reducing agricultural nutrient loading: Mateo-Sagasta et al. (2017) documented 50–80% reductions in diffuse nutrient loading from comparable buffer zone restorations in tropical catchments. Third, targeted community water safety communication — emphasising rainy-season cyanobacterial risk intensification (June–August), practical risk-reduction measures, and the specific hazards of *Oscillatoria*-dominated communities — should be delivered through the high-literacy, long-resident populations identified in the companion socio-demographic study (Abdulazeez et al., 2025a).

## CONCLUSION

This study presents the first quantitative characterisation of phytoplankton community structure in the River Benue Basin, Adamawa State, Nigeria. Four main conclusions are drawn: *Fragilaria* sp. dominated numerically at all three study sites, with Bacillariophyta contributing 58–68% of total abundance. The increasing Bacillariophyta dominance along the metal contamination gradient reflects the relative resilience of silica-walled diatoms under chemical stress.

Decline in Chlorophyta relative abundance from 25–26% at near-reference conditions to 17% at the most contaminated site constitutes a biologically meaningful and quantifiable bioindicator of heavy metal stress in tropical river phytoplankton communities.

Four toxigenic genera (*Anabaena*, *Aphanocapsa*, *Oscillatoria*, *Aphanizomenon*) are established year-round at all study sites. Anomalous *Oscillatoria* peak abundance at the most contaminated site represents an early warning of community restructuring toward more toxigenic assemblages under combined metal and nutrient stress.

Immediate routine cyanobacterial surveillance, restoration of minimum 30-metre riparian buffer zones, and community water safety communication are the three evidence-based priority management actions.

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