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ORIGINAL RESEARCH ARTICLE

# Limnological Characteristics, Phytoplankton Assemblage and Environmental Assessment of Hadejia River, North-Western Nigeria: A Comprehensive Survey

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## ABSTRACT
This study assesses variations in phytoplankton abundance, composition, and distribution in the Hadejia River in relation to key limnological characteristics across both spatial and temporal dimensions. Over a period of six months in 2018, water samples were collected from the river and analyzed for environmental variables alongside the quantification and identification of phytoplankton using standard protocols. pH and temperature measurements were conducted in situ. Results indicated significant variations ($P < 0.05$) in pH, temperature, turbidity, nitrate, and phosphate levels across different months, although no significant differences were observed between sampling stations. The highest nitrate value (5.41 mg/L) and phosphate levels (6.55 mg/L) were recorded in August at Station B (STB). 693 Phytoplankton individuals from five divisions were identified, with peak abundance, composition, and distribution observed during the dry season. Key species such as *Selenastrum bibraianum*, *Tetraedron regulare*, *Tabellaria flocculosa*, *Gomphosphaeria lacustris*, *Microcystis aeruginosa*, *Rhabdoderma lineare* and *Tabellaria fenestrate* were consistently present throughout the study period. Shannon_H diversity index values for Cyanophyta, Pyrrophyta, and Euglenophyta ranged between 1.34-2.02, while Bacillariophyta and Cyanophyta exhibited reduced diversity (1-1.32) and species richness (0.55-0.68) at STB. Canonical correspondence analysis revealed that the selected environmental variables strongly influenced phytoplankton abundance and diversity, with the exception noted for *Microcystis aeruginosa*, *Gomphosphaeria lacustris*, *Rhabdoderma lineare,* and *Chlamydomonas ehrenbergii*. These results suggest deterioration in water quality, particularly at STB, possibly due to anthropogenic activities. Furthermore, this study provides valuable baseline data for future research endeavors aimed at monitoring and managing the ecological health of River Hadejia.

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## INTRODUCTION

Freshwater is a natural resource that is both renewable and practically limited. This body of water offers vital ecosystem services that enable human transit, recreation, waste disposal and remediation, and food and energy production (Aldaya *et al*., 2012; Albert *et al*., 2021). Freshwater species and ecosystems are under threat due to a multitude of human activities, including habitat modification, water pollution, overfishing, exotic species introduction, river diversions, flow fragmentation and regulation, expansion of agricultural and urban landscapes, climate change, rising sea levels, and altered precipitation regimes (Dudgeon, 2019; Grill *et al*., 2019). In many regions of the world, the fast increase in human population and related food production (such as crops and livestock) puts more strain on freshwater resources (Albert *et al*., 2021), Nigeria inclusive. As a result, the freshwater ecosystem's biodiversity is declining. Even though it is commonly acknowledged that human activity significantly affects the biosphere, freshwater ecosystems are frequently left out of discussions on these effects (Albert *et al*., 2021).

In Nigeria, like many other parts of the world, population increase has led to increased developmental activities in agriculture, industry, and the discharge of domestic waste due to urbanization (Bichi *et al*., 2016). The buildup of wastes from these heavy anthropogenic activities ends up directly or indirectly in aquatic systems such as rivers, streams, and lakes that serve as freshwater sources to nearby communities. This tends to degrade the water

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quality, conversely affecting the aquatic biota. In addition, climatic factors as sources of variation including rainfall, light intensity and temperature have been reported to significantly affect the aquatic system's physical and chemical properties (Bwala, 2022).

Phytoplankton are photosynthetic micro-organisms best suited to inhabit and float in open surface waters of lakes, rivers, and seas. They are comprised of cyanobacteria, diatoms, and dinoflagellates. Phytoplankton are the main food producers in a balanced ecosystem, serving as food for various aquatic organisms in addition to their crucial role in the carbon cycle (Muhammad *et al.*, 2021a). Since phytoplankton respond quickly and sensitively to environmental changes, they are regarded as bioindicators of variations in water quality (Stanca *et al.*, 2012).

Moreover, any aquatic system's species composition, abundance, and temporal distribution represent that body of water's biological integrity or environmental health (Limbu & Kyewalyanga, 2015). Nutrient enrichment (nitrate and phosphate) of aquatic systems that may result from agrochemicals coupled with increasing temperatures due to climate change may result in not only the growth and development of phytoplankton but could lead to the formation of noxious toxin-producing cyanobacteria (Xu *et al.*, 2013). Therefore, co-management of these nutrients and continuous monitoring of phytoplankton growth and development towards minimizing toxic algal bloom is important (Muhammad *et al.*, 2021a). As a result, several studies have been conducted to better understand phytoplankton dynamics in relation to changes in environmental factors in freshwater aquatic systems as a result of anthropogenic activities (Piirsoo *et al.*, 2008; Zakariya *et al.*, 2013; Adesakin *et al.*, 2020)

River Hadejia flows through Hadejia town and drains into Lake Chad. The river catchment falls within the semi-arid zone with humid climates. Because this river flows through Hadejia town, it is highly exposed to effluents from rain-fed and irrigated agricultural lands, and market gardens. These activities stretch very long distances along the river bank. Also, increased urbanization has resulted in increased discharge of untreated wastewater from domestic and industrial activities. These wastes directly or indirectly end up in the river with the potential of altering its physical and chemical properties, resulting in the deterioration of the water quality that may negatively affect the aquatic biota. This is corroborated by reports from previous studies (Umar *et al.*, 2018; Garba *et al.*, 2022) on the water body, which showed deterioration of the Hadejia river system due to urbanization. Garba *et al.* (2022) stated that the deterioration of the water quality status of the Hadejia River has negatively affected sustainable ecosystem service delivery, a major drawback from achieving the global goal of clean water and sanitation for all. Other studies on the Hadejia River include those of Ahmed *et al.* (2018), Umar *et al.* (2019), Muhammad *et al.* (2021b), and Maryam *et al.* (2020). However, none of these studies has focused on the dynamics and ecology of phytoplankton and how they are influenced by changes in environmental parameters in relation to anthropogenic activities over time and space. Thus: (a) to understand the spatial and temporal variations in the river's physicochemical parameters; (b) to gain insight into the phytoplankton abundance, composition, and distribution over time and space; and (c) evaluate the impact of environmental variables on phytoplankton abundance, composition, and distribution in relation to anthropogenic activities, this study was conducted on the Hadejia River. Furthermore, this study provides valuable baseline data for future research endeavors aimed at monitoring and managing the ecological health of River Hadejia using algal indices.

## MATERIALS AND METHODS

### Study area

The investigation was conducted on the Hadejia River watershed located in Hadejia Town, situated between Latitude 12°13'–13°60' N and Longitude 9°22'–11° 00' E. The Hadejia River is a tributary of the Yobe River, ultimately flowing into Lake Chad. Surrounding communities engage in rain-fed and irrigation farming and fishing activities.

### Sample stations

Three sampling stations were selected for this study (Figure. 1) based on the anthropogenic assessment of the area as highlighted below:

1. Station A (STA) at Bakin Gada (latitude 12°26'26.1" N and longitude 10°01'56.4" E). Activities such as artisinal mining, bathing, laundry, animal and human feaces liter along the river bank characterized this station.
2. Station B (STB) at Yan Wanki (latitude 12°26'08.6" N and longitude 10°02'20.4" E). Heavy agricultural activities characterize the area.
3. Station C (STC) at Aguyaka (latitude 12°26'20.4" N and longitude 10°04'37.2" E). The area is also characterized by less agricultural activities with vegetable growing gardens.

### Sample collection

Water samples were collected once every month in the early hours of the day between 7-10 am for six (6) months (March to August 2018). The time frame matched three months of the rainy season (June, July, August) and three months of the dry season (March, April, and May).

*Environmental Variables*

A total of seven (7) environmental variables, namely temperature, pH, dissolved oxygen (DO), biochemical oxygen demand ($BOD_5$), turbidity, nitrate (N), and phosphate (P) were selected for this study. They are common variables used to assess alterations in an aquatic ecosystem's physical and chemical compositions and their influence on phytoplankton abundance, composition, and diversity. All instruments were tested to be within the limit of precise accuracy before use. Field meters were calibrated according to manufacturer's specification and care was taken during sampling to avoid contamination.

Surface water temperature and pH were determined in situ using a mercury-in-glass thermometer and a pH meter (Hanna model HI 9828).

The azide modification of Winkler's method was applied to determine DO. The water sample was collected in sample bottles and fixed with 2 ml of manganous sulfate. To 300 ml of the sample, 2 ml of Alkaline Iodide-Sodium Azide solution and 2 ml of concentrated $H_2SO_4$ was added and titrated against 0.0125 N sodium thiosulphate ($Na_2S_2O_{3(aq)}$) until a color change to pale yellow. A starch indicator (2 ml) was then added and titrated until the colour changed from blue to colorless and the titre value was recorded. The DO was then calculated in mg/L (Clesceri *et al.*, 1998; Rice *et al.*, 2012).

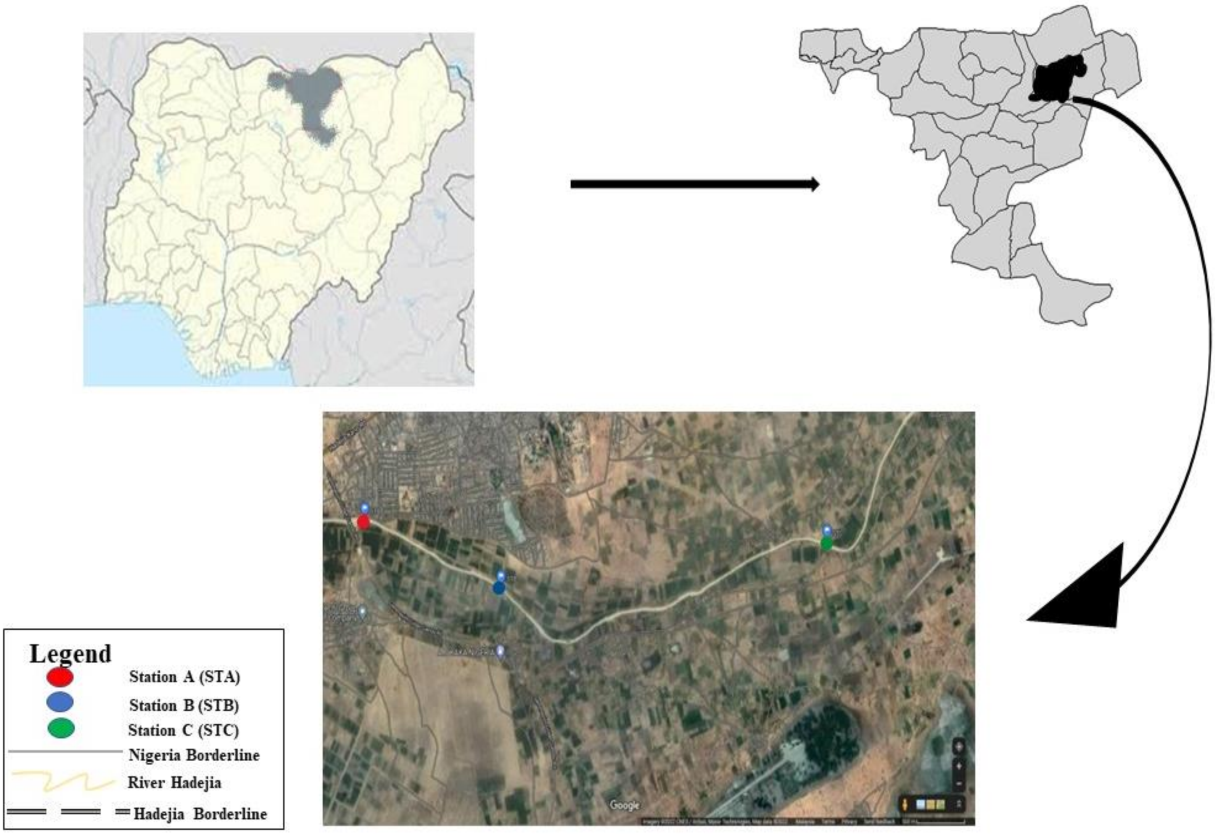


**Figure 1:** Study area map with sampling points indicated.

Winkler's method was used for $BOD_5$ determination. The water sample was collected in sample bottles and incubated in the dark. After five days of incubation, 300 ml of the sample containing 2 ml of Alkaline Iodide-Sodium Azide solution and 2 ml of concentrated $H_2SO_4$ was titrated against 0.0125 N sodium thiosulphate ($Na_2S_2O_{3(aq)}$). A colour change from pale to yellow was followed by adding a 2 ml starch indicator and was further titrated until a colour change from blue to colorless and the titre value was recorded. $BOD_5$ in mg/L was calculated as the difference between $DO_1$ and $DO_5$, as described by Clesceri *et al.* (1998) and Rice *et al.* (2012).

Turbidity was determined using a spectrophotometer model 257 at 430 nm (Clesceri *et al.*, 1998; Rice *et al.*, 2012). Distilled water was used as blank.

Nitrate (N) determination was carried out using the phenoldisulphonic acid method according to the protocol of Clesceri *et al.* (1998). Briefly, 100 ml of water sample was evaporated to dryness, then adding 2 ml of phenoldisulphonic acid for 10 minutes. Subsequently, 15 ml of distilled water was added, followed by 5 ml of strong ammonia ($NH_3$) solution. The resultant yellow mixture was stirred and allowed to cool. The absorbance was measured at 430 nm on a spectrophotometer model 257, using distilled water as blank. Nitrate concentration in mg/L was then determined using a standard calibration curve.

The stannous chloride method (Clesceri *et al.*, 1998) was used to determine Phosphate (P). To 100 ml of the water sample, 2 drops of stannous chloride were added, followed by 1 ml of Denings reagent. After 10 minutes, the absorbance at 660nm was measured with a spectrophotometer, model 257, using distilled water as blank. Phosphate concentration in mg/L was determined using a standard calibration curve.

*Phytoplankton*

Using a quantitative approach (filtration), phytoplankton samples were collected from the sampling locations. A conical-shaped plankton net attached to a 60 ml collecting vial was used to collect phytoplankton (Verlencar & Desai, 2004). The content of the collecting vial was fixed with 4% formaldehyde. Phytoplankton biomass was determined using the drop count method Perry (2003) adopted. The organisms were identified using phytoplankton identification manuals and monographs (Perry, 2003; Taylor *et al.*, 2007; Bellinger & Sigee, 2010).

**Data analysis**

Data analysis was done using analysis of variance (ANOVA), and where a significant result was found, the means were separated using the Duncan multiple range test (DMRT). Paleontology statistics (PAST) was used to analyze diversity, species richness, Taxa_(S), and number of phytoplankton in each division. The relationship between phytoplankton and physicochemical characteristics was assessed using canonical correspondence analysis (CCA).

## RESULTS AND DISCUSSION

**Environmental Variables**

The surface water temperature recorded was between 24 and 30 °C. The mean water temperatures were consistent between sample stations in the months corresponding to the rainy season. In May 2018, STB and STC had the highest values, while STA and STB (March) and STA (April) recorded the lowest values (Figure 2a). The temperature of surface water varied significantly, as indicated by the Duncan multiple range test ($p<0.05$) between months but not between sample stations (Table 1). Considerably, high-water temperatures above the recommended (25°C) Federal Ministry of Environment (FMEnv)/National Environmental Standards and Regulation Enforcement Agency (NESREA) 2011 (FMEnv/NESREA, 2011) were observed in this study. This could threaten the homeostatic balance of aquatic species in the water body (Beshiru *et al.*, 2018). These high temperatures could be attributed to, on the one hand, the semi-arid nature of the environment and, on another hand, the possible effect of climate change (increasing temperatures) (Rajesh & Rehana, 2022). Similar findings have been reported (Zakariya *et al.*, 2013; Raji *et al.*, 2015).

**Table 1:** Mean values for environmental variables of Hadejia River showing statistical significance.

| Months | T (°C) | pH | TB (NTU) | DO (mg/L) | BOD (mg/L) | N (mg/L) | P (mg/L) |
|---|---|---|---|---|---|---|---|
| **March** | 24.33±0.57$^{a}$ | 7.60±0.17$^{a,b}$ | 141.73±2.80$^{a}$ | 5.37±0.70$^{a}$ | 0.43±0.37$^{a}$ | 1.79±0.01$^{a}$ | 2.15±0.01$^{a}$ |
| **April** | 25.00±1$^{a}$ | 8.03±0.57$^{b}$ | 141.17±6.09$^{a}$ | 5.32±0.33$^{a}$ | 0.45±0.43$^{a}$ | 1.63±0.02$^{a}$ | 1.52±0.01$^{a,b}$ |
| **May** | 29.67±0.57$^{b}$ | 7.67±0.11$^{a,b}$ | 147.00±5.29$^{a}$ | 5.30±0.30$^{a}$ | 0.68±0.45$^{a}$ | 1.64±0.02$^{a}$ | 1.80±0.02$^{a,b}$ |
| **June** | 29.00±0$^{b}$ | 7.27±0.23$^{a}$ | 135.30±4.30$^{a}$ | 5.27±0.46$^{a}$ | 0.93±0.50$^{a}$ | 0.85±0.01$^{b}$ | 0.83±0.04$^{b}$ |
| **July** | 27.00±0$^{c}$ | 7.03±0.23$^{a}$ | 137.73±2.53$^{a}$ | 5.67±0.70$^{a}$ | 0.98±0.38$^{a}$ | 1.02±0.06$^{b}$ | 1.40±0.11$^{a,b}$ |
| **August** | 28.00±0$^{d}$ | 7.33±0.40$^{a}$ | 178.27±21.18$^{b}$ | 5.23±0.43$^{a}$ | 0.88±0.25$^{a}$ | 5.14±0.24$^{c}$ | 5.10±1.49$^{c}$ |

A significant difference ($P<0.05$) exists between the means with different letters in each column. Temperature (T), pH, Dissolved oxygen (DO), Biological oxygen demand (BOD), Turbidity (TB), Nitrate (N), Phosphate (P).

The pH range of 6.9 to 8.7 was observed in this study. The pH value at STA was highest in March, and the pH value at STA and STB was lowest in July (Figure 2b). Compared to the wet season, pH levels were somewhat higher at the sample stations during the dry season (March-May). This was similar to the report of Garba *et al.* (2022) on the Hadejia River. As shown in Table 1, the results of the Duncan multiple range test showed that while the pH changed considerably ($p<0.05$) throughout the months in the dry season (March–May), it did not vary significantly ($p>0.05$) during the rainy season (June–August). In rivers, pH generally decreases as rainfall increases due to increased organic matter inflow into the river as rainfall increases (Alum & Okoye, 2020). Duncan multiple range test revealed that the pH did not vary significantly ($p>0.05$) in the rainy season (June-August) but varied significantly ($p<0.05$) among the months in the dry season (March-May), as shown in Table 1. Values obtained were within the FMEnv/NESREA permissible limit (6.5-8.5). The pH range (6.80 and 8.74) described in other studies (Igbinosa *et al.*, 2012; Zakariya *et al.*, 2013) is comparable to the values obtained in this study.

Turbidity was highest in August corresponding to the wet season. STC in August recorded the highest turbidity level compared to other sample stations (Figure 2c). The least turbidity was observed at STB in June. In the months corresponding to the dry season, turbidity was generally high across the stations. This was attributed to sand mining, bathing, washing, and irrigation farming. Turbidity, however, decreased in the early months of the rainy season (June and July) and then showed a marked increase in August. The marked increase in turbidity was associated with sediments that runoff washes into the river and increased sand mining activity. Anyanwu *et al.* (2021) reported similar turbidity values associated with these anthropogenic activities at the stations. Analysis of variance revealed no significant ($p>0.05$) variation between the stations. However, there was significant ($p<0.05$) variation among the months where DMRT revealed that only the month of August varied significantly from all the other months (Table 1). This study's turbidity levels were generally high and above the FMEnv/NESREA permissible limit (5 NTU). Very high turbidity levels in water for domestic use tend to increase the risk of exposure to gastrointestinal diseases (Mann *et al.*, 2007). This is highly unsafe, especially in immunocompromised individuals, as pathogens such as enteric bacteria and/or viruses can attach themselves to the suspended particles (Beshiru *et al.*, 2018). Also, the absorption of dissolved oxygen by fish gills will be affected due to high turbidity levels in water. The turbidity of the Hadejia River, as observed in this study, is also comparable to that of Ogbozige *et al.* (2018), who found turbidity values in the range of 44.30-151.38 NTU.

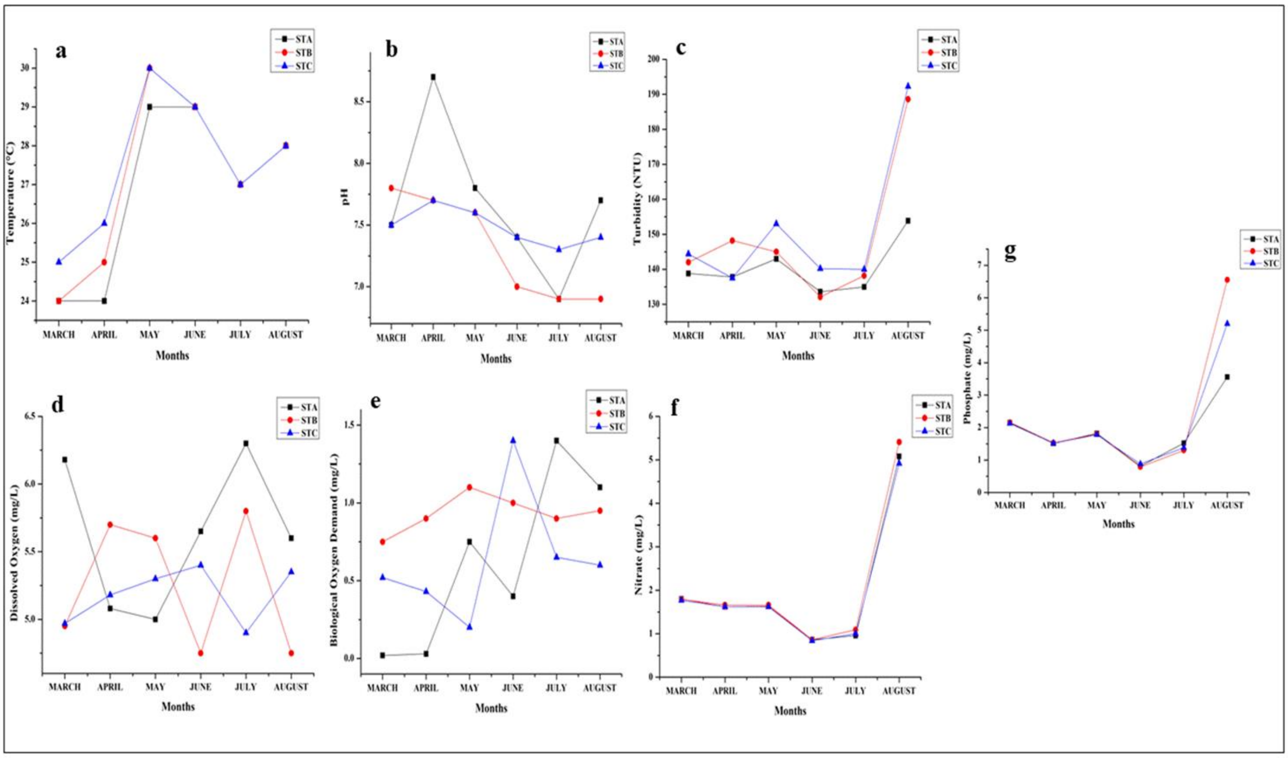


**Figure 2:** Spatial and temporal variations in environmental variables on River Hadejia. Station A (STA), Station B (STB), Station C (STC).

Dissolved oxygen ranged between 4.7-6.3 mg/L. STA recorded the highest value in July, while STB in June and August recorded the least value (Figure 2d). Dissolved oxygen did not vary significantly ($p>0.05$) between the months (Table 1). The availability of high organic matter at STB in June and August may have contributed to the marked reduction in DO value (Figure 2d) compared to other stations. The station may have received increased wastewater discharge from runoffs and other anthropogenic activities. Oxidation of organic matter in aquatic ecosystems by aerobic micro-organisms involves the consumption of DO available in the water. The finding in this study is similar to that reported by (Ewa-Oboho *et al.*, 2022) on another river. This may have accounted for the reduced DO value at STB. Ewa-Oboho *et al.* (2022) reported reduced DO with high organic pollution in another river. The values observed throughout the study period were below the FMEnv/NESREA permissible limit (>6 mg/L), indicating deterioration of the water body. This could be attributed to the high organic matter released into the river in direct discharge of untreated sewage, agricultural wastewater, and industrial effluents. The release of organic wastes such as those from domestic and animal sewage, industrial effluents, slaughterhouse sewage and agricultural wastewater have been shown to decrease dissolved oxygen levels in water bodies (Bozorg-Haddad *et al.*, 2021). Oxygen depletion in an aquatic system is principally dependent on the turbulence of the rivers (Giri *et al.*, 2022), the amount of waste added, as well as the temperature of the water (Bozorg-Haddad *et al.*, 2021). Thus, River Hadejia can be inferred to have these factors at high levels, deteriorating dissolved oxygen concentrations, which could be detrimental to aquatic life. Furthermore, DO levels were observed to be inversely proportional to the temperature of the water. Thus, DO decreased at stations with higher temperatures. This finding agrees with those of Mokuolu *et al.* (2018) and Ogbozige *et al.* (2018) for river waters in northern Nigeria.

$BOD_5$ ranged between 0.02 and 1.40 mg/L in this study (Table 1). The highest $BOD_5$ value was recorded at STC and STA in June and July. STA in June recorded the lowest $BOD_5$ value (Figure 2e). $BOD_5$ was observed to be higher in the months that corresponded to the rainy season (June-August) compared to the dry season (March-May). In the dry season, STB recorded higher values than other sample stations. This could result from the direct impact of the area's heavy agricultural activities (irrigation farming), resulting in the release of high content of organic matter into the water at this station. The marked increase in $BOD_5$ at STC and STA in June and July respectively could be associated with wastewater discharge brought about by runoffs at the early stage of rainy season. Values recorded for $BOD_5$ were however, below the FMEnv/NESREA permissible limit (3 mg/L) across all the sample stations. In this study, $BOD_5$ did not correlate with dissolved oxygen unlike in Beshiru *et al.* (2018). Statistically, there was no significant ($p>0.05$) variation between the months (Table 1). Higher $BOD_5$ (2.5-19.87 mg/L) were recorded in related studies in Nigeria and elsewhere (Igbinosa *et al.*, 2012; Zakariya *et al.*, 2013; Gupta *et al.*, 2017; Beshiru *et al.*, 2018)

**Table 2.** Phytoplankton species of Hadejia River grouped into division

| Species | Division | Species | Division |
|---|---|---|---|
| *Conscinodiscus sp* | | *Anabaenopsis racibolskii* | |
| *Cymbela lata* | | *Anabaena spiroides* | |
| *Gyrosigma attenua* | | *Gomphosphaeria lacustris* | |
| *Melosira granulata* | | *Microcystis aeruginosa* | **Cyanophyta (27.42%)** |
| *Melosira distans* | | *Microscystis pulverea* | |
| *Melosira varians* | **Bacillariophyta (15.58%)** | *Microscystis gravellei* | |
| *Nitzschia longissima* | | *Rivularia planctonica* | |
| *Nitzschia filiformis* | | *Rhabdoderma lineare* | |
| *Surirella robusta* | | *Aphanithece clathrate* | |
| *Synedra acus* | | | |
| *Tabellaria flocculosa* | | | |
| *Tabellaria fenestrata* | | *Ceratium furca* | |
| *Pinnularaia major* | | *Ceratium lineatum-gamete* | |
| *Nitzschia sigmoidea* | | *Cryptomonas obovata* | |
| | | *Dinophysis* sp | |
| | | *Lingulodnium polyedrum* | |
| *Anthrodesmum incus* | | *Peridinium bipes* | **Pyrrophyta (13.85%)** |
| *Cosmarium antilopeum* | | *Peridinium umbonata* | |
| *Cosmarium granatum* | | *Peridinium* sp | |
| *Closterium parvulum* | | *Peridinium pusillium* | |
| *Coelastrum reticulatum* | | *Protoperinium depressum* | |
| *Chlamydomonas ehrenbergii* | | | |
| *Gonatozygon aculeatum* | | | |
| *Kirchneriella obesa* | | *Colacium cyclopicola* | |
| *Nephrocytium agardhianum* | | *Euglena gracilis* | |
| *Oocystis eremosphaeria* | **Chlorophyta (35.79%)** | *Euglena caudata* | |
| *Pediastrum simplex* | | *Euglena sanguine* | |
| *Pediastrum biradiatum* | | *Euglena deses* | |
| *Pediastrum clathratum* | | *Euglenopsis vorax* | **Euglenophyta (7.36%)** |
| *Pediastrum duplex* | | *Trachelomonas tambowiea* | |
| *Staurastrum apiculatum* | | *Euglena oxyuris* | |
| *Staurastrum dickiei* | | *Euglena* sp | |
| *Selenastrum bibraianum* | | | |
| *Tetraedron tumidulum* | | | |
| *Tetraedron regulare* | | | |
| *Tetralanthos lagerhelmii* | | | |
| *Volvox aureus* | | | |
| *Glenodinium cinatum* | | | |

The nitrate and phosphate concentrations ranged from 0.8-5.4 mg/L and 0.7-6.5 mg/L respectively. The highest nitrate and phosphate concentrations were recorded at STB in August. This could be attributed to the heavy agricultural activity around the area where agrochemicals are transported into the water body via run-offs. This is in agreement with the finding of Bwala (2022), where high nitrate and phosphate concentrations were observed during the irrigation regime. Also, Alum and Okoye (2020) reported higher concentrations of nitrate in rivers in eastern Nigeria's agricultural belt. The least nitrate and phosphate concentrations were recorded at STC and STA in June (Figure 2f and 2g). These nitrate concentrations were below the FMEnv/NESREA permissible limit of 40 mg/L, while phosphate was above FMEnv/NESREA permissible limit of 3.5 mg/L in the month of August, indicating deterioration of the water quality in that month. Wastewater and industrial effluents carried by run-offs as a result of increased rainfall in August could be responsible for the increased nitrate and phosphate values across the stations. Furthermore, the early wet season (June) recorded decreased concentrations for both nitrate and phosphate possibly due to pollutant dilution as rainfall sets inn (Ogbozige *et al.*, 2018), but later increased as rainfall intensified, and this could be attributed to allochthonous inputs from run-offs (Ravi *et al.*, 2021). High nitrate and phosphate concentrations have been previously recorded in the months corresponding to the rainy season, which were associated with run-offs from surrounding agricultural lands pointing towards human activities disturbing the aquatic balance (Zakariya *et al.*, 2013; Jimoh *et al.*, 2021). Statistically, nitrate did not vary significantly ($p>0.05$) between March, April, May, and June and July (Table 1). However, phosphate concentrations varied significantly ($p<0.05$) between March and June, while August varied significantly ($p<0.05$) from other months (Table 1). Increased nitrate and phosphate concentrations in water bodies can lead to eutrophication and dissolved oxygen depletion (Chia *et al.*, 2011).

**Phytoplankton community**

*Abundance and distribution*

Phytoplankton form an integral part of the aquatic system where they serve as primary producers, occupying a critical position in the energy cycle and playing an important role in maintaining ecological balance (Liu *et al.*, 2021). A total of 693 Phytoplankton individuals from five divisions were recorded. Division Chlorophyta accounted for the highest species relative abundance (35.79 %) and was closely followed by Cyanophyta, 27.42 % (Table 2). This was contrary to the report of Zakariya *et al.* (2013) on the lower Niger River, where Bacillariophyta accounted for the most phytoplankton individuals. Umar *et al.* (2021) and Anyanwu *et al.* (2021) reported Chlorophyta as the dominant division in their study on River water in northern and southern Nigeria, respectively. This could be associated with a high intensity of light in the tropics, favoring the growth and development of this division of phytoplankton (Jimoh *et al.*, 2021). Euglenophyta accounted for the least division (7.36 %) of phytoplankton recorded in this study. Members of the Chlorophyta division have been associated with unwanted odor in drinking water and indicate eutrophication (Palmer, 1964; Salem *et al.*, 2019).

March accounted for the highest relative abundance of phytoplankton, with *Pediastrum duplex* having the highest abundance (Table 3). The highest abundance was recorded at STC (96 cell/L) in March, followed by STB (73 cell/L) in April. The least abundance (24 cells/L) was recorded at STA in June. Phytoplankton relative abundance was higher during the dry season (March–May) than during the wet season (June-August), correlating with the temperature values recorded in these months. Nutrients (nitrate and phosphate) were shown to be relatively elevated as well, suggesting that stability resulting from low rainfall, reduced flow velocity, and high evaporation as a result of elevated temperatures (thus concentrating the nutrient levels) may have contributed to the high abundance of phytoplankton in these months. This is in agreement with the study of Bwala (2022), which reported that high temperatures promote evaporation, which causes wind action and nutrient mixing in surface water bodies. A marked reduction in the relative abundance of phytoplankton was recorded in June, which also witnessed a fall in temperature before gradually increasing in the subsequent months (Table 3). This could result from an increase in the flow velocity of the river due to rainfall. Also, low concentration of nutrients (nitrate and phosphate), as shown in (Figure 2f and 2g) may have contributed to the marked reduction of phytoplankton abundance in June. The abundance, composition, and distribution of phytoplankton at a given point in any river describe an instantaneous environmental condition of the water, which depends upon the flow velocity changes in the physical and chemical characteristics of the water body (Evi *et al.*, 2014). *Microcystis aeruginosa* accounted for higher relative abundance in April, June, July, and August (Table 3), possibly due to their high tolerance for increased temperature and availability of adequate nutrients. In addition, due to their competitive nature, they produce cyanotoxins which exerts allelopathic effects on other phytoplankton and eradicate their predators like the zooplankton (Pascale *et al.*, 2022), thus making them abundant, as observed in this study. *Microcystis aeruginosa* is a primary cause of the hazardous cyanobacterial bloom that is common around the world and affects freshwater systems (Yang & Wang, 2019). Analogous pollutants have been demonstrated in the past to have an impact on cyanobacteria growth and cyanotoxin generation, which may have an adverse effect on aquatic life and upset the equilibrium of aquatic ecosystems (Wang *et al.*, 2018; Zhang *et al.*, 2018). *Microcystis pulverea,* on the other hand, only occurred in March. The presence of these cyanobacteria species calls for concern, hence the need to assess Hadejia River for possible cyanotoxin contamination. Other species of phytoplankton such as *Euglena sp* (July), *Nitzschia sigmoidea*, *Aphanithece clathrate*, *Euglena oxyuris* (June), *Cymbela lata*, *Synedra acus*, *Anthrodesmum incus* (May), *Kirchneriella obesa*, *Peridinium bipes* (April) and *Cosmarium antilopeum*, *Closterium parvulum*, *Coelastrum reticulatum*, *Nephrocytium agardhianum*, *Staurastrum dickiei*, *Protoperinium depressum* (March) only occurred at specific sample stations in these months (Table 3). While species such as *Selenastrum bibraianum*, *Tetraedron regulare*, *Tabellaria flocculosa*, *Gomphosphaeria lacustris*, *Microcystis aeruginosa*, *Rhabdoderma lineare* and *Tabellaria fenestrate* had species representation in all the months studied.

**Table 3:** Phytoplankton Composition, Abundance, and Distribution of Hadejia River

| Phytoplankton individuals | MARCH | | | APRIL | | | MAY | | | JUNE | | | JULY | | | AUGUST | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | STA | STB | STC | STA | STB | STC | STA | STB | STC | STA | STB | STC | STA | STB | STC | STA | STB | STC |
| *Conscinodiscus* sp | 3 | - | - | - | - | - | - | - | - | - | - | - | 5 | - | - | - | - | - |
| *Cymbela lata* | - | - | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - |
| *Gyrosigma attenua* | - | - | - | - | - | - | 1 | - | - | 2 | - | - | 2 | - | - | - | 4 | - |
| *Melosira granulata* | - | - | - | 2 | - | 2 | - | - | - | - | - | - | - | - | 2 | 3 | - | - |
| *Melosira distans* | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Melosira varians* | - | - | - | - | - | - | 1 | - | 1 | - | - | 2 | 4 | - | - | 3 | 1 | - |
| *Nitzschia longissima* | - | - | - | 3 | - | - | 1 | - | 2 | - | - | 3 | - | - | - | - | - | - |
| *Nitzschia filiformis* | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | 3 | - | - | 3 |
| *Surirella robusta* | - | - | - | - | - | - | - | - | 1 | 1 | - | 3 | - | - | - | - | - | - |
| *Synedra acus* | - | - | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - |
| *Tabellaria flocculosa* | 1 | 2 | - | - | 5 | - | - | 2 | - | 1 | 11 | - | - | - | - | - | - | - |
| *Tabellaria fenestrata* | - | - | 1 | - | - | 1 | - | 3 | - | - | 3 | - | - | 3 | - | 2 | - | 1 |
| *Pinnularaia major* | - | - | - | 3 | - | - | - | - | - | - | - | - | 2 | - | - | - | - | - |
| *Nitzschia sigmoidea* | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| *Anthrodesmum incus* | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Cosmarium antilopeum* | - | - | 4 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cosmarium granatum* | - | - | - | - | - | 2 | - | 3 | - | - | 3 | - | 3 | - | - | 1 | - | 2 |
| *Closterium parvulum* | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Coelastrum reticulatum* | - | - | 2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *C. ehrenbergii* | - | - | - | 4 | 3 | 4 | - | - | - | - | - | 1 | - | - | 1 | 1 | 1 | - |
| *Gonatozygon aculeatum* | - | - | - | - | - | - | 3 | 4 | - | 2 | 2 | - | 3 | - | - | 3 | - | - |
| *Kirchneriella obesa* | - | - | - | - | 4 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *N. agardhianum* | - | 5 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Oocystis eremosphaeria* | - | - | - | - | - | - | 7 | - | - | 1 | - | - | 7 | - | - | 3 | 2 | - |
| *Pediastrum simplex* | - | - | - | - | 15 | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| *Pediastrum biradiatum* | - | - | - | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Pediastrum clathratum* | - | - | - | 3 | - | - | - | - | - | - | - | - | 3 | - | - | - | - | - |
| *Pediastrum duplex* | 6 | 15 | 45 | - | - | - | - | - | - | - | - | - | 3 | 3 | 8 | 3 | 5 | - |
| *Staurastrum apiculatum* | - | - | - | - | - | 3 | - | 3 | - | - | - | - | - | - | - | - | 1 | - |
| *Staurastrum dickiei* | - | - | 4 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Selenastrum bibraianum* | - | 1 | - | 1 | - | 4 | - | 2 | 4 | - | 3 | - | - | 3 | - | - | 2 | 2 |
| *Tetraedron tumidulum* | - | 5 | - | 1 | 0 | - | - | - | - | - | - | - | - | - | - | - | 2 | - |
| *Tetraedron regulare* | - | - | 3 | 5 | 7 | - | - | 3 | 1 | 1 | - | 1 | - | 3 | 2 | 3 | 3 | - |
| *Tetralanthos lagerhelmii* | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - | - | - |
| *Volvox aureus* | - | - | 1 | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - |
| *Glenodinium cinatum* | - | - | - | - | - | - | - | - | - | 3 | - | - | - | - | - | - | - | - |
| *Anabaenopsis racibolskii* | - | - | - | - | 1 | - | - | 1 | - | - | - | 2 | - | 2 | - | - | 1 | - |
| *Anabaena spiroides* | - | - | - | - | - | - | - | - | 2 | - | - | 3 | - | - | - | - | - | - |
| *Gomphosphaeria lacustris* | - | - | - | - | 1 | - | 9 | 3 | 5 | 5 | 2 | - | - | 4 | - | - | - | 2 |
| *Microcystis aeruginosa* | 5 | 4 | - | 4 | 5 | 5 | - | 6 | 3 | 3 | 4 | 9 | 7 | 4 | 4 | 3 | 6 | 6 |
| *Microscystis pulverea* | - | - | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Microscystis gravellei* | - | - | - | 3 | - | - | 7 | - | 3 | - | - | - | - | - | - | - | 3 | 4 |
| *Rivularia planctonica* | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Rhabdoderma lineare* | 1 | 1 | 1 | 5 | 14 | 2 | 4 | - | 3 | - | - | 2 | 1 | - | 2 | 4 | - | 2 |
| *Aphanithece clathrata* | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| *Ceratium furca* | 2 | 2 | 11 | - | - | - | - | - | - | - | - | - | 3 | - | - | - | 2 | 2 |
| *Ceratium lineatum-gamete* | 5 | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | 1 | - |
| *Cryptomonas obovata* | - | - | - | - | - | 3 | - | 1 | - | - | 3 | - | - | - | 3 | - | - | - |
| *Dinophysis* sp | 1 | 4 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Lingulodnium polyedrum* | 3 | 3 | 8 | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | 4 |
| *Peridinium bipes* | - | - | - | - | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Peridinium umbonata* | - | - | - | - | - | - | - | 2 | 6 | - | - | - | - | 2 | - | - | - | - |
| *Peridinium* sp | - | - | 3 | - | - | - | - | - | - | - | - | - | - | - | 2 | - | - | - |
| *Peridinium pusillium* | - | 2 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 |
| *Protoperinium depressum* | - | 2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Colacium cyclopicola* | - | - | - | - | - | 2 | 1 | - | - | - | - | - | - | - | - | - | - | - |
| *Euglena gracilis* | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Euglena caudata* | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *Euglena sanguine* | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - | 2 | 4 | - | 2 |
| *Euglena deses* | - | - | - | - | - | - | - | - | 3 | - | - | 3 | - | - | - | - | 3 | - |
| *Euglenopsis vorax* | - | - | - | - | 6 | 1 | - | - | - | - | - | - | - | - | 5 | - | 2 | - |
| *Trachelomonas tambowiea* | - | - | - | 3 | - | 1 | - | - | - | - | - | - | - | - | 2 | - | - | - |
| *Euglena oxyuris* | - | - | - | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - |
| *Euglena* sp | - | - | - | - | - | - | - | - | - | - | - | - | - | 4 | - | - | - | - |
| **TSS** | **27** | **47** | **95** | **49** | **73** | **36** | **37** | **33** | **39** | **24** | **31** | **29** | **44** | **28** | **36** | **34** | **39** | **31** |
| **Total by months** | **169** | | | **158** | | | **109** | | | **84** | | | **108** | | | **104** | | |

*KEY: C. ehrenbergii = Chlamydomonas ehrenbergii, N. agardhianum = Nephrocytium agardhianum, TSS* = Total by sample stations

*Diversity*

Chlorophyta exhibited the highest taxa (S) with 37, followed by Bacillariophyta with 23, both observed in STA. Euglenophyta displayed the lowest taxa with consistent values across all stations (see Figure 3a). Regarding individual count, Chlorophyta dominated with 248 individuals, followed by Cyanophyta with 190. STB recorded the highest species count for Chlorophyta. Conversely, Cyanophyta exhibited 62 individual species in both STA and STB (see Figure 3b). The noticeable abundance of phytoplankton observed at various stations was attributed to the availability of nutrients, particularly nitrate and phosphate, which are conducive to phytoplankton growth and development. The presence of these nutrients is linked to intensive agricultural activities surrounding the river and the discharge of wastewater from both domestic and industrial sources into the river. Nitrates and phosphates are recognized as essential nutrients for phytoplankton growth, with increased biomass observed when phosphorus is assimilated into cells (Liu *et al.*, 2021), a process largely influenced by light, temperature, and pH (Singh *et al.*, 2018).

The Shannon_H index and Simpson_1-D indicated that Chlorophyta exhibited high diversity and species richness across the sampled stations (see Figure 3d and e), suggesting optimal water conditions conducive to the thriving of this division. The Shannon_H diversity index ranged between 1.34 and 2.02 for Cyanophyta, Pyrrophyta, and Euglenophyta. Conversely, Bacillariophyta and Cyanophyta showed reduced diversity (1–1.32) and species richness (0.55–0.68) at STB, indicating disturbance at this station. Previous studies have demonstrated that higher biodiversity, richness, and evenness indices, indicative of clean water, are associated with more stable environments (Duarte *et al.*, 2017; Dondajewska *et al.*, 2019). Consequently, the condition of the Hadejia River at STB can be classified as polluted.

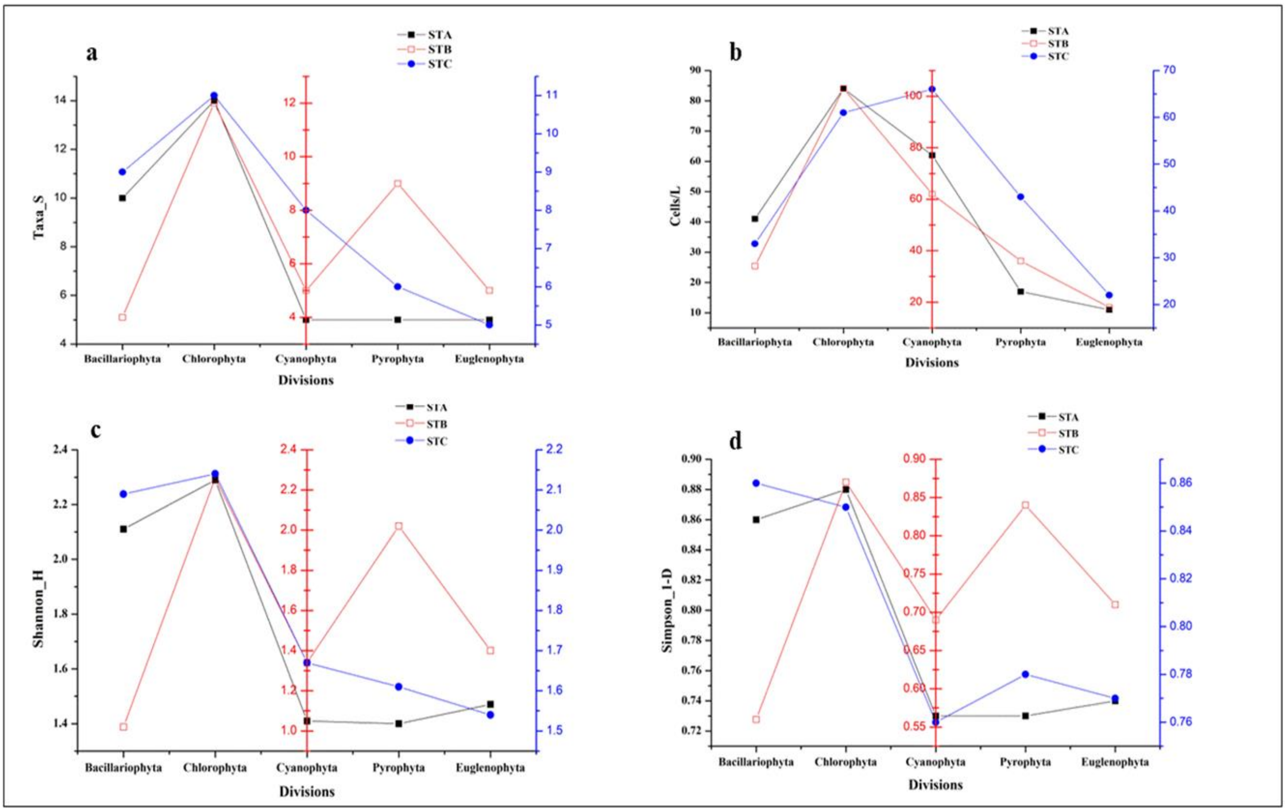


**Figure 3:** Diversity indices for Phytoplankton species on Hadejia river

*Canonical Correspondence Analysis (CCA)*

Canonical correspondence analysis, a multivariate analysis, has been applied to quantitatively assess interactions between environmental variables and phytoplankton communities in complex systems (Pillsbury & Miller, 2008; Devi *et al.*, 2016). Axis 1 (52.57%) and Axis 2 (47.43%) accounted for the total variation observed for the variables analyzed (Figure 4). *Euglena sanguine*, *Nitzschia longissimi*, *Microcystis gravellei,* and *Oocystis eremosphaeria* showed close positive association with pH and DO but negative association with BOD, P and N. *Euglenopsis vorax*, *Anabaenopsis racibolski*, *Tabellaria fenestrate* and *Dinophysis* sp. showed close positive association with BOD, N and P but were negative to pH and DO. TB and T were closely associated with the abundance of *Peridinium umbonate*, *Cryptomonas obovate*, *Pediastrum duplex,* and *Euglena deses*. Interestingly, *Microcystis aeruginosa*, *Gomphosphaeria lacustris*, *Chlamydomonas ehrenbergii*, *Rhabdoderma lineare* did not show a positive nor negative correlation to any of the selected environmental variables in this study, thus implying that these organisms are not influenced by any of the environmental variables in this study, rather they may be influenced by other parameters. *Microcystis aeruginosa* is a cyanotoxin producing blue-green algae and can cause harmful algal blooms. Interestingly, this organism can thrive independently of these common environmental variables that influence phytoplankton growth. Identifying parameters that influence the growth of this organism and bringing them under check is necessary. Previous studies (Chia *et al*., 2011; Sharma *et al*., 2016; Zhao *et al*., 2017; Kumar & Thomas, 2019) have shown that phytoplankton react differently to environmental variables, as observed in this study.

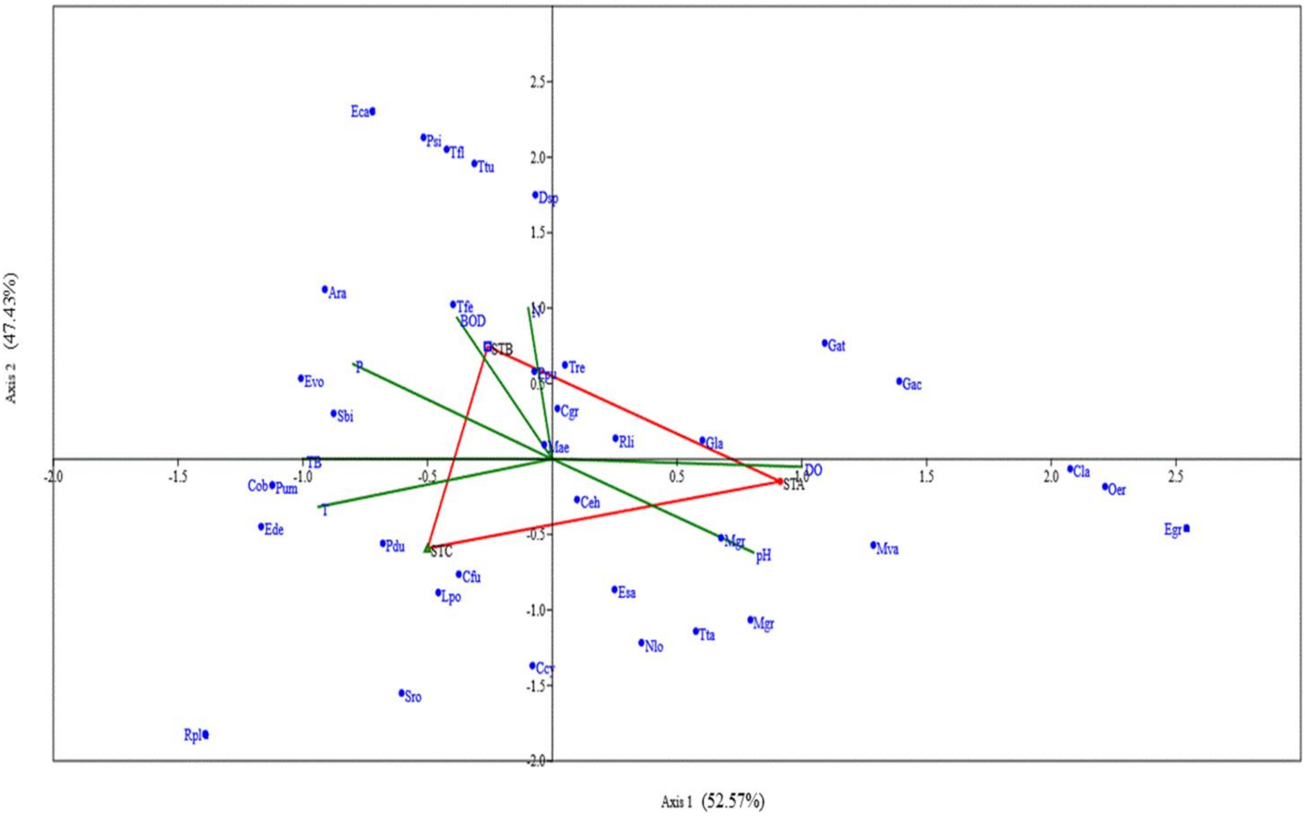


**Figure 4:** CCA plot of Phytoplankton species interaction with environmental variables on Hadejia River. *Cymbela lata* (Cla), *Gyrosigma attenua* (Gat), *Melosira granulata* (Mgr), *Melosira varians* (Mva), *Nitzschia longissima* (Nlo), *Surirella robusta* (Sro), *Tabellaria flocculosa* (Tfl), *Tabellaria fenestrate* (Tfe), *Nitzschia sigmoidea* (Nsi), *Anthrodesmum incus* (Ain), *Cosmarium granatum* (Cgr), *Closterium parvulum* (Cpa), *Chlamydomonas ehrenbergii* (Ceh), *Gonatozygon aculeatum* (Gac), *Kirchneriella obesa* (Kob), *Oocystis eremosphaeria* (Oer), *Pediastrum simplex* (Psi), *Pediastrum biradiatum* (Pbi), *Pediastrum clathratum* (Pcl), *Pediastrum duplex* (Pdu), *Staurastrum apiculatum* (Sap), *Staurastrum dickiei* (Sdi), *Selenastrum bibraianum* (Sbi), *Tetraedron tumidulum* (Ttu), *Tetraedron regulare* (Tre), *Tetralanthos lagerhelmii* (Tla), *Volvox aureus* (Vau), *Glenodinium cinatum* (Gci), *Anabaenopsis racibolskii* (Ara), *Anabaena spiroides* (Asp), *Gomphosphaeria lacustris* (Gla), *Microcystis aeruginosa* (Mae), *Microscystis pulverea* (Mpu), *Microscystis gravellei* (Mgr), *Rivularia planctonica* (Rpl), *Rhabdoderma lineare* (Rli), *Ceratium furca* (Cfu), *Ceratium lineatum-gamete* (Cli), *Cryptomonas obovate* (Cob), *Dinophysis* sp (Dsp), *Lingulodnium polyedrum* (Lpo), *Peridinium bipes* (Pbi), *Peridinium umbonate* (Pum), *Peridinium pusillium* (Ppu), *Protoperinium depressum* (Pde), *Colacium cyclopicola* (Ccy), *Euglena gracilis* (Egr), *Euglena caudata* (Eca), *Euglena sanguine* (Esa), *Euglena deses* (Ede), *Euglenopsis vorax* (Evo), *Trachelomonas tambowiea* (Tta), *Euglena* sp (Esp). Temperature (T), pH, Dissolved oxygen (DO), Biological oxygen demand (BOD), Turbidity (TB), Nitrate (N), Phosphate (P), Station A (STA), Station B (STB), Station C (STC).

## CONCLUSION

The findings of this study underscore the profound impact of environmental variables on phytoplankton dynamics in the Hadejia River, both spatially and temporally. This research represents a pioneering effort to elucidate the intricate relationship between changes in limnological parameters and the consequent effects on phytoplankton abundance, composition, and distribution induced by human activities along the Hadejia River. Significant temporal variations in environmental factors were observed throughout the investigation, whereas spatial differences were negligible. Notably, phytoplankton species known for their tolerance to pollution and as indicators of eutrophication, such as *Pediastrum sp*., *Peridinium sp*., and *Melosira varians*, exhibited elevated abundance levels. Taxa, including *Cymbela lata*, *Pinnularaia major*, *Gonatozygon aculeatum*, *Oocystis eremosphaeria*, and *Microscystis gravellei* were identified as potential pollution indicators. Of particular concern is the consistent presence of cyanotoxin-producing algae, such as *Microcystis* and *Anabaena*, which pose a significant risk of harmful algal bloom development over time. The degradation of water quality, particularly evident at Station B, signifies a trend toward eutrophication, implicating anthropogenic activities as the primary drivers. Thus, vigilant monitoring efforts are imperative to curb further pollution and safeguard the ecological integrity of the Hadejia River, especially considering its economic significance for fish production. Finally, this study furnishes valuable baseline data and highlights the urgent need for proactive measures to mitigate water quality degradation and preserve the aquatic ecosystem of the Hadejia River for future generations. Furthermore, studies on cyanotoxin contamination and their effects on other important phytoplankton species in the food chain need to be comprehensively evaluated to better understand the impact of anthropogenic activities around River Hadejia.

## DATA AVAILABILITY STATEMENT

The corresponding author can provide the datasets created and/or analysed during the current work upon reasonable request.

## CONFLICT OF INTEREST

The writer disclaims any financial affiliation.

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