

The Role of Environmental Factors in Driving Phytoplankton Communities in Winam Gulf, Lake Victoria, Kenya

***Caroline Alupo¹, Simon Agembe¹, Edwine Yongo Omollo¹, Gideon Kuluo¹ & Mutuku Kilonzo²**

¹Department of Fisheries and Aquatic Sciences, School of Environmental Sciences and Natural Resource Management, University of Eldoret, Eldoret, Kenya

²Department of Chemistry and Biochemistry, University of Eldoret, Eldoret, Kenya

***Corresponding E-mail:** carolinealupo236@gmail.com

Abstract

Winam Gulf, a shallow bay of Lake Victoria, Kenya, is increasingly affected by anthropogenic activities that alter its water quality. This study examined the key environmental drivers of phytoplankton community dynamics in the gulf. Physicochemical variables were measured in situ, while nutrients (total phosphorus, total nitrogen, nitrate, nitrite and ammonia) were analysed in the laboratory using standard methods. Phytoplankton were identified and counted microscopically, and diversity indices, including the Shannon-Wiener index, were calculated. One way analysis of variance, repeated-measures analysis of variance, principal component analysis, canonical correspondence analysis and non-metric multidimensional scaling assessed spatial and temporal patterns, while Spearman's correlation and Mantel tests explored relationships between phytoplankton and environmental variables. Influence category significantly affected water depth, total dissolved solids, electrical conductivity, dissolved oxygen, biochemical oxygen demand, pH, Secchi depth and total nitrogen, while season significantly influenced temperature, total dissolved solids, electrical conductivity, dissolved oxygen, biochemical oxygen demand, pH, Secchi depth, nitrite, nitrate, ammonia nitrogen, soluble reactive phosphorus and total nitrogen. Significant category $\times$ season interactions occurred for total dissolved solids, dissolved oxygen, pH, Secchi depth and total nitrogen, showing that seasonal change varied among influence categories. Thirty-four phytoplankton genera from five phyla: Cyanophyta, Bacillariophyta, Chlorophyta, Charophyta and Dinophyta were recorded, with Cyanophyta dominant (44.1%), followed by Chlorophyta, Bacillariophyta, Dinophyta and Charophyta. Nutrients, especially total phosphorus, together with electrical conductivity, dissolved oxygen, pH and temperature, emerged as key environmental correlates of phytoplankton communities in Winam Gulf.

Keywords: phytoplankton, environmental variables, Winam Gulf, Lake Victoria, eutrophication

Introduction

Phytoplankton comprise a taxonomically diverse assemblage of photosynthetic microorganisms, with more than 20,000 described species that form the base of aquatic food webs and drive global primary production (Kruk *et al.*, 2017; Adhiambo, 2017; Yongo *et al.*, 2023). As primary producers, they fix carbon and release oxygen through photosynthesis, playing a central role in biogeochemical cycling and ecosystem stability (Liu *et al.*, 2026); changes in community structure can therefore affect higher trophic levels (Wu *et al.*, 2012). Because of their short generation times and sensitivity to nutrients, temperature and light, phytoplankton assemblages are widely used as bioindicators of ecosystem condition (Aura *et al.*, 2020; Miruka *et al.*, 2021; Skaloud *et al.*, 2025). Community structure arises from both stochastic processes and deterministic environmental filtering, whereby environmental variables favour taxa that best tolerate prevailing conditions (Isabwe *et al.*, 2018; Kraft *et al.*, 2015; Yi *et al.*, 2024; Olokotum *et al.*, 2021). Nitrogen and phosphorus commonly limit algal growth, silica shapes diatom populations, temperature affects metabolic rate and stratification, and transparency determines euphotic depth (Suba *et al.*, 2024; Liu *et al.*, 2025). In tropical lakes, seasonal rainfall can rapidly shift these conditions and favour cyanobacteria in warm, eutrophic and stratified waters.

Lake Victoria is the world's second-largest freshwater lake by surface area and the largest lake in Africa, it is a vital source of food, energy and water, but it also receives human, agricultural and industrial wastes (Lawrence *et al.*, 2023). Winam Gulf, the large shallow northeastern embayment of the Kenyan sector, is particularly vulnerable because of its restricted exchange with the main lake and its proximity to densely populated and intensively cultivated catchments. Ecosystem changes over recent decades have altered the lake's ecological functioning and climate-sensitive processes (Outa *et al.*, 2020), driven largely by anthropogenic and climatic pressures across East Africa (Aura *et al.*, 2022).



Nutrient accumulation has shifted the lake's trophic state from oligotrophic to eutrophic, and to hypereutrophic in areas such as Winam Gulf (Musinguzi *et al.*, 2019), with eutrophication now being a major driver of biodiversity change in the lake (Nyakeya *et al.*, 2022).

This deterioration carries long-term consequences for the ecosystem services the lake provides and for the socio-economic wellbeing of surrounding communities. Notable changes include increased phytoplankton productivity (Hecky & Bugenyi, 1992) and a shift from diatom to cyanobacterial dominance (Kling *et al.*, 2001), which raises the risk of cyanotoxin production (Brown *et al.*, 2024).

The Winam Gulf exemplifies a freshwater ecosystem under intense anthropogenic pressure (Roegner *et al.*, 2023), receiving untreated and poorly treated sewage from urban centers such as Kisumu City alongside agricultural runoff from its intensively farmed catchment (Brown *et al.*, 2024). These nutrient loads promote harmful algal blooms dominated by cyanobacteria. Despite growing recognition of the gulf's water quality problems, quantitative understanding of how specific environmental factors drive phytoplankton dynamics remains limited. This study therefore examined how environmental variables shape spatiotemporal variation in phytoplankton diversity and abundance in Winam Gulf, to inform strategies for mitigating harmful algal blooms and improving ecological health.

Materials And Methods

Study Area and Sampling Stations

The Kenyan section of Lake Victoria lies south of the equator (00°6'S–00°32'S, 34°13'E–34°52'E) at 1,134 m above sea level and covers approximately 3,600 km² (6% of the lake). Winam Gulf, in the northeastern part of this section, covers approximately 1,400 km² and receives drainage from a 3,600 km² catchment through five major rivers: Nzoia, Kuja, Nyando, Yala and Sondu. The gulf connects to the main lake through the 4.8-km-wide Rusinga Channel (Roegner *et al.*, 2023). Nine stations Kisumu Bay, Homa Bay, Sango Bay, Awach, Asembo Bay, Mid Gulf One, Mid Gulf Two, Mbita Bay and Rusinga Channel (Figure 1) were selected to represent four influence categories: urban, river-influenced, transitional and offshore. Stations were grouped according to dominant land use and human activities (Table 1). Sampling was conducted at the beginning and end of December 2026 and at the beginning and end of March 2026, providing two sampling occasions in each of the two study seasons, with three replicates collected at each station on each occasion. This design yielded 54 samples per season (9 stations × 2 sampling occasions × 3 replicates) and 108 observations overall. Triplicate sampling was used to estimate within-station variability and support spatial and seasonal comparisons.

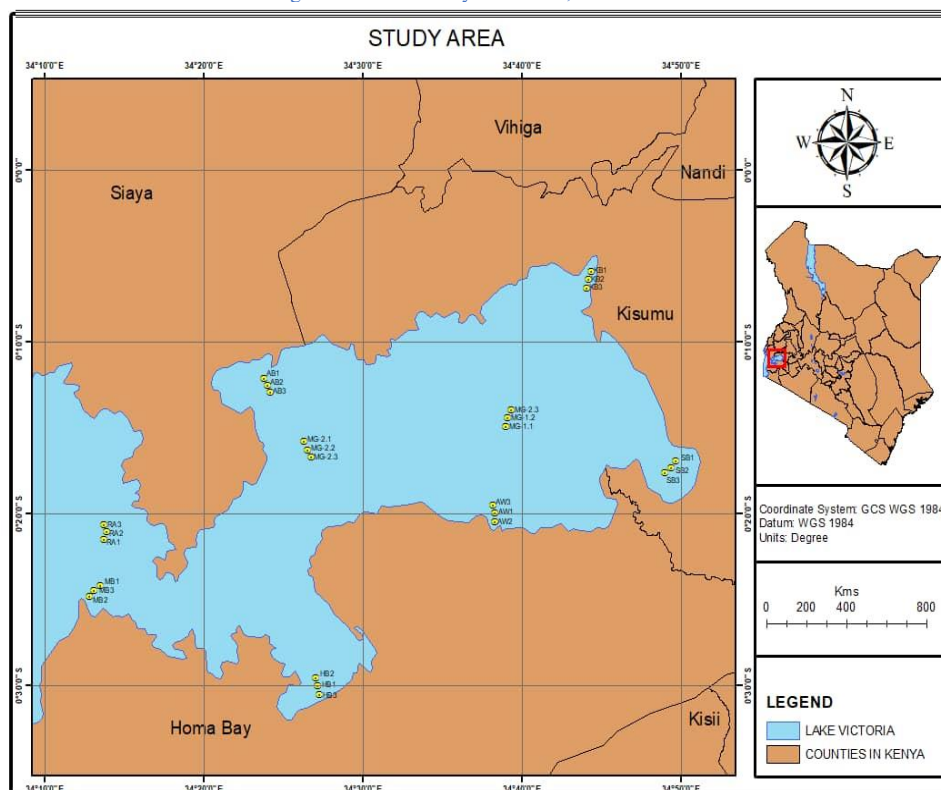


Figure 1: Map of study area showing sampling sites

Sampling Methods

Physicochemical variables. pH, dissolved oxygen, electrical conductivity, total dissolved solids and temperature were measured in situ using a portable multiparameter probe, and Secchi depth was measured using a Secchi disk (APHA, 2017). At each of the nine stations, three replicate subsurface water samples were collected on each sampling occasion in both seasons. Samples for nutrient analysis were placed in 500 mL polypropylene containers and acidified with 0.15 mL concentrated sulfuric acid. BOD samples were incubated in airtight bottles at 20°C in the dark for five days. Three replicate phytoplankton samples were collected at each station on each sampling occasion using a conical net (25- μ m mesh, 30-cm aperture), preserved in acid-washed 500 mL containers with 10 mL Lugol's iodine, stored in a cooler box and transported to the University of Eldoret laboratory (APHA, 2017).

Laboratory analysis. Phytoplankton were identified to genus level using taxonomic keys and enumerated microscopically at 400x (Olympus, Tokyo, Japan). Cell densities were expressed as cells L^{-1} . Soluble reactive phosphorus was determined by the ascorbic acid method without digestion, whereas total phosphorus was determined using the same method following acid persulfate digestion. Total nitrogen was determined using the persulfate digestion method. Ammonium was measured using the salicylate-isocyanurate method, nitrite by the colorimetric method, and nitrate by cadmium reduction. Five-day biochemical oxygen demand was determined by measuring dissolved oxygen depletion after incubation at 20°C in the dark for five days (APHA, 2017).

Determination of Phytoplankton Diversity

The Shannon–Wiener Diversity Index (H'), Pielou's Evenness Index (J'), Margalef's Richness Index (d) and Simpson Diversity Index ($1 - C$) were used to assess phytoplankton diversity as follows.

$$H' = - \sum_{i=1}^S p_i \ln p_i$$

$$J' = \frac{H'}{H_{\max}} = \frac{H'}{\ln S}$$

$$d = \frac{S - 1}{\ln N}$$

$$1 - C = 1 - \sum_{i=1}^S p_i^2$$

where N_i is the number of individuals belonging to taxon i ; N is the total number of individuals across all taxa; p_i is the proportion of individuals belonging to taxon i ; S is the number of taxa; $H_{\max}$ is the maximum Shannon–Wiener diversity; and C is Simpson’s concentration index. The symbol $\ln$ denotes the natural logarithm.

Table 1. Criteria for grouping influence categories of the sampling sites

S/N	Influence categories	Stations	Dominant Land Use / Human Activity
1	Urban	Kisumu Bay, Homa Bay	Urban settlements, municipal discharge, fish landing beaches, domestic waste input, industrial and commercial activities
2	River-influenced	Sango Bay, Asembo Bay, Awach	River inflow zones, agricultural runoff, catchment erosion, small-scale farming, rural settlements
3	Transitional	Mid Gulf One, Mid Gulf Two	Mixed land use, moderate fishing activity, scattered settlements, transitional nearshore-offshore influence
4	Offshore	Mbita Bay, Rusinga Channel	Open-water conditions, limited direct catchment influence, relatively low anthropogenic disturbance, offshore fisheries activity

Statistical Analysis

Spatial distributions of environmental variables and phytoplankton density and diversity were interpolated in ArcGIS 10.8 (ESRI, Redlands, CA, USA). Data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene’s test. Non-normal environmental variables were log-transformed, and phytoplankton counts were $\log(x + 1)$ -transformed. Spatial and seasonal variation in environmental variables was assessed using repeated-measures ANOVA. One-way ANOVA was used to test phytoplankton density and diversity among the four influence categories separately within each season; station density differences were also examined within season. NMDS visualised similarity and dissimilarity among phytoplankton communities, while PCA summarized seasonal environmental gradients. CCA examined associations between environmental variables and phytoplankton composition, and Spearman’s correlation and Mantel tests assessed relationships between phytoplankton and environmental variables.

Results And Discussion

Environmental Variables

Repeated-measures ANOVA showed that influence category significantly affected water depth, TDS, EC, dissolved oxygen, BOD, pH, Secchi depth and total nitrogen (all $p < 0.01$; Table 2), but not temperature, nitrite, ammonia nitrogen, total phosphorus or soluble reactive phosphorus, with only a marginal effect on nitrate ($p = 0.053$). Season significantly influenced most physicochemical variables temperature, TDS, EC, dissolved oxygen, BOD, pH, Secchi

depth, nitrite, nitrate, ammonia nitrogen, soluble reactive phosphorus and total nitrogen (all $p < 0.05$) but not water depth or total phosphorus. Significant category $\times$ season interactions occurred for TDS, dissolved oxygen, pH, Secchi depth and total nitrogen (Table 2), indicating that seasonal change varied among influence categories. Overall, TDS, EC, dissolved oxygen, Secchi depth and total nitrogen were most sensitive to spatial and seasonal gradients, depth was spatially structured but seasonally stable, and total phosphorus remained comparatively stable.

Table 2. Effect of influence category, season, and their interaction on environmental variables (repeated-measures ANOVA)

Variable	Influence F	Influence P	Season F	Season P	Interaction F	Interaction P
Depth	20.05	<0.001	0.00	1.0000	0.00	1.0000
Temp	0.89	0.4516	13.21	0.0007	1.01	0.3956
TDS	54.93	<0.001	798.81	<0.001	6.50	0.0009
EC	68.13	<0.001	7.21	0.0100	0.04	0.9874
DO	42.41	<0.001	24.56	<0.001	5.57	0.0024
BOD	14.45	<0.001	5.15	0.0280	1.90	0.1432
pH	4.46	0.0078	29.67	<0.001	7.09	0.0005
Secchi Depth	84.33	<0.001	4.95	0.0311	9.71	<0.001
NO ₂	1.23	0.3106	7.87	0.0073	0.51	0.6772
NO ₃	2.76	0.0529	369.94	<0.001	2.71	0.0560
NH ₃ -N	0.74	0.5344	10.64	0.0021	0.35	0.7872
TP	1.04	0.3825	3.87	0.0551	0.94	0.4287
SRP	1.37	0.2635	42.26	<0.001	1.16	0.3361
TN	4.79	0.0055	43.51	<0.001	9.66	<0.001

Relationship between Physicochemical Variables and Sampling Sites

Principal component analysis revealed spatial separation among the four influence categories in both seasons (Figure 2). In the dry season, PC1 and PC2 explained 37.71% and 19.09% of the variance, respectively (56.80% cumulatively). Offshore stations aligned with greater depth, dissolved oxygen and Secchi depth on positive PC1, while river-influenced stations were associated with elevated NO₃-N, NO₂-N, TP and TDS on negative PC1. Urban stations were linked to BOD and temperature, whereas transitional stations occupied an intermediate position.

In the wet season, PC1 and PC2 explained 38.85% and 17.97% of the variance, respectively (56.82% cumulatively), with stronger separation among influence categories. Offshore stations were again associated with dissolved oxygen, depth and Secchi depth; river-influenced stations with elevated nutrients; urban stations with EC, TDS, TN and BOD; and transitional stations with SRP. The remaining 43.18% of wet-season variance occurred on later components.

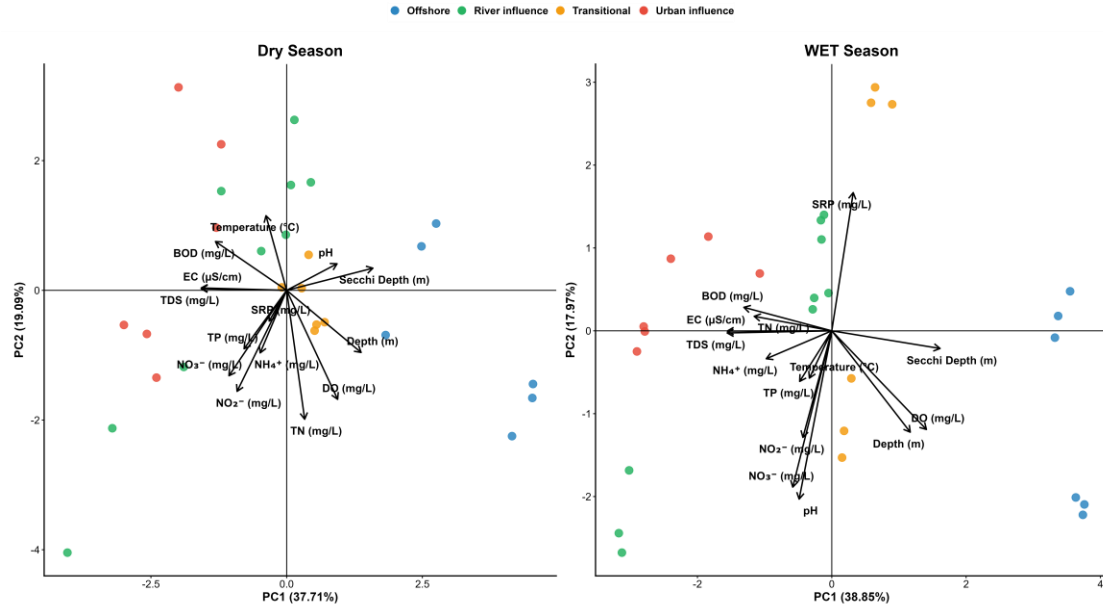


Figure 2: Principal component analysis biplots showing the four influence categories in relation to environmental variables during the dry and wet seasons.

Phytoplankton Community Structure

Thirty-four phytoplankton genera belonging to five phyla were recorded: Cyanophyta, Bacillariophyta, Chlorophyta, Charophyta and Dinophyta (Figure 3). Cyanophyta dominated the assemblage (44.1%), followed by Chlorophyta (29.4%), Bacillariophyta (17.2%), Dinophyta (5.2%) and Charophyta (4.1%). These percentages sum to 100.0%, giving a dominance order of Cyanophyta > Chlorophyta > Bacillariophyta > Dinophyta > Charophyta.

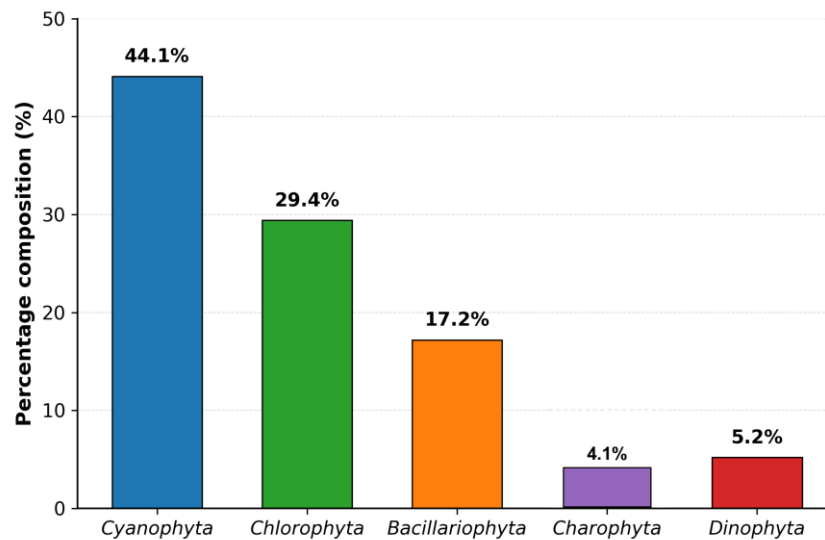


Figure 3: Percentage composition of phytoplankton phyla observed in Winam Gulf.

Phytoplankton Cell Density

Phytoplankton cell density varied spatially and seasonally across the nine stations (Figure 4). In the dry season, densities ranged from 3.66×10^5 to 6.28×10^5 cells L^{-1} , with the highest values around Asembo Bay, Mid Gulf Two and Kisumu Bay. In the wet season, densities ranged from 4.46×10^5 to 1.23×10^6 cells L^{-1} ; Asembo Bay remained highest, with elevated density also occurring at Mid Gulf Two, Kisumu Bay and Homa Bay. One-way ANOVA showed no density difference among the four influence categories in either the dry season ($F = 0.19$, $p = 0.905$) or wet season ($F = 0.83$, $p = 0.490$). At station level, density differences were marginal in the dry season ($F = 2.37$, $p = 0.061$) and significant in the wet season ($F = 14.41$, $p < 0.001$). The broader distribution of high-density areas in the wet season is consistent with a possible influence of rainfall related nutrient inputs; the seasonal maps alone do not establish this mechanism.

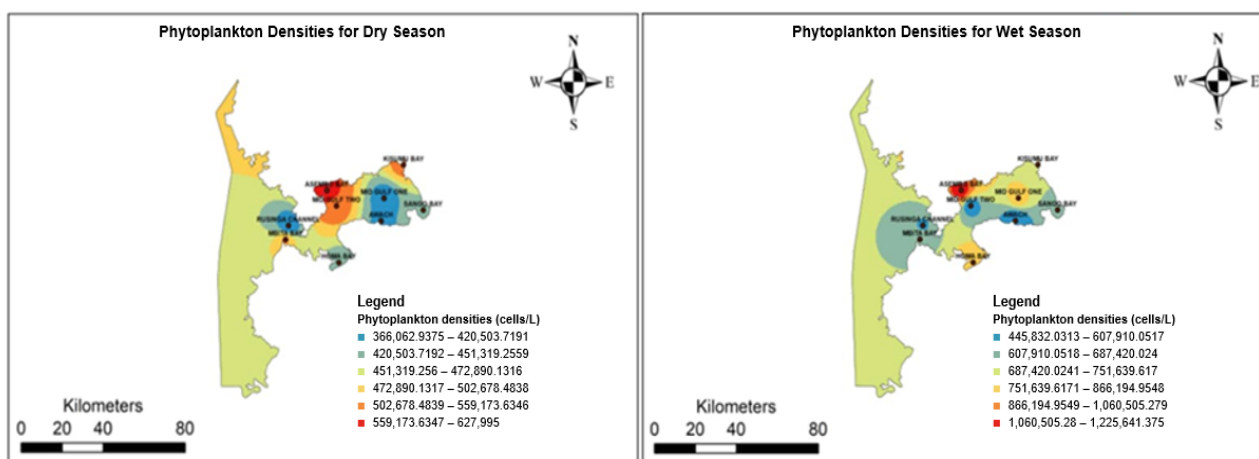


Figure 4: Spatial distribution of phytoplankton cell density (cells L^{-1}) during the dry season and wet season.

Phytoplankton Relative Abundances

Relative abundance also varied spatially and seasonally among influence categories (Figure 5). In the dry season, communities were relatively diverse and were dominated by *Microcystis*, *Anabaena*, *Synedra* and *Protococcus*. Offshore communities were more even, whereas *Microcystis* and *Synedra* prevailed in river-influenced and urban categories. Richness ranged from 12 to 15 genera, with the highest value in the river-influenced category and the lowest in the urban category. In the wet season, *Microcystis* became strongly dominant in river-influenced and urban categories. Richness peaked at approximately 20 genera in offshore and river-influenced categories and declined to approximately 11 genera in the urban category. *Spirogyra*, *Pediastrum*, *Scenedesmus* and *Protococcus* maintained moderate contributions across categories, while wet season communities showed greater dominance and lower evenness than dry season communities.

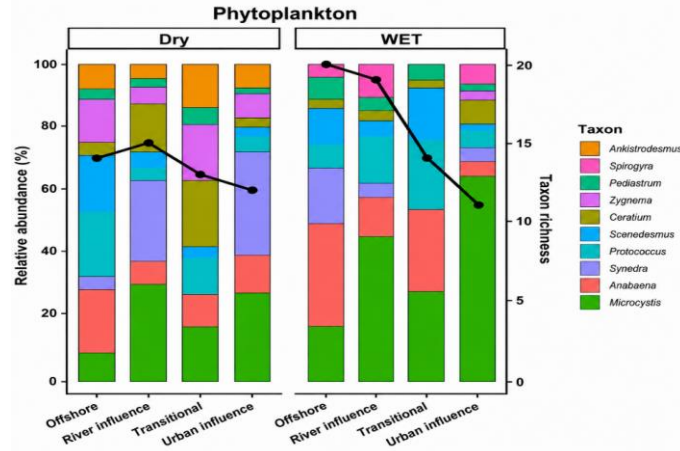


Figure 5: Relative abundance of phytoplankton genera and genus richness across the four influence categories during the dry and the wet season.

Non-metric Multidimensional Scaling (NMDS) of Phytoplankton Communities

NMDS ordinations (stress = 0.130 in the dry season and 0.158 in the wet season) provided acceptable representations of community patterns (Figure 6). In the dry season, the offshore category clustered with *Botryococcus*, *Merismopedia*, *Microspora* and *Tetraspora*; the river-influenced category formed a distinct cluster associated with diatoms and green algae, including *Gonatozygon*, *Synedra*, *Diatoma* and *Coelastrum*; the transitional category overlapped with the offshore assemblage; and the urban category overlapped with the river-influenced and transitional categories. In the wet season, separation among influence categories became more pronounced. The offshore category clustered with *Coelosphaerium*, *Dictyosphaerium*, *Botryococcus* and *Navicula*; the river-influenced category with *Ulothrix*, *Crucigenia*, *Nitzschia* and *Ankistrodesmus*; the transitional category with *Staurastrum*, *Botryococcus* and *Selenastrum*; and the urban category, which showed the greatest variability, with *Zygnema* and *Spirulina*.

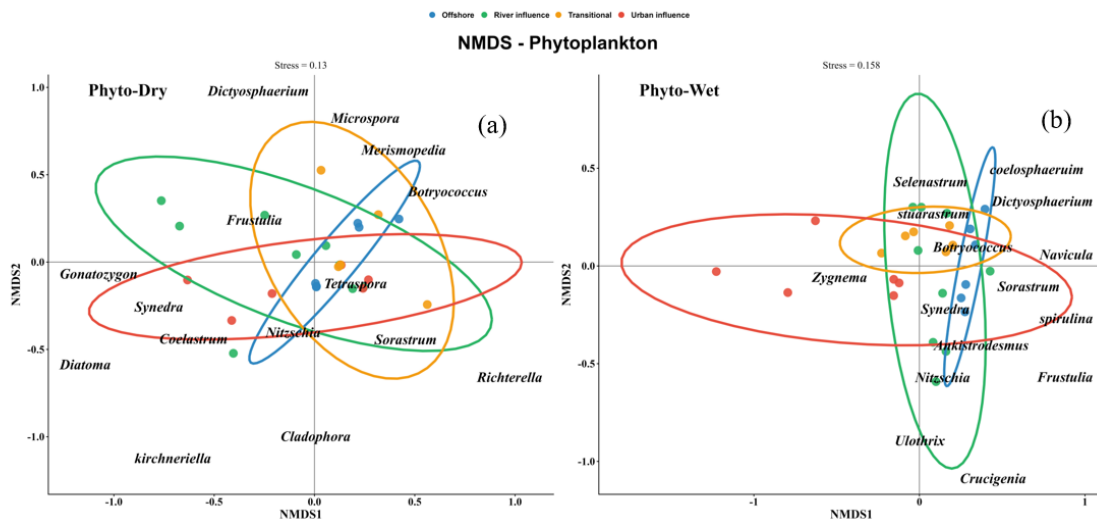


Figure 6: Non-metric multidimensional scaling of phytoplankton communities in the four influence categories during (a) the dry and (b) the wet season in Winam Gulf.

Phytoplankton Diversity

Diversity metrics (Table 3) indicated spatial variation among influence categories. Shannon diversity was highest in the offshore category in both seasons (2.03 ± 0.06 in the dry season and 2.40 ± 0.17 in the wet season). The lowest dry-season mean occurred in the river-influenced category (1.51 ± 0.35), followed by the urban category (1.57 ± 0.10); the lowest wet season mean occurred in the urban category (1.24 ± 0.69). Spatial variation in Shannon diversity was significant in the dry season ($F = 9.61$, $p < 0.001$) and wet season ($F = 11.12$, $p < 0.001$). Dry season Simpson diversity was highest in the transitional category (0.84 ± 0.04), closely followed by the offshore category (0.83 ± 0.02), whereas wet season Simpson diversity was highest offshore (0.89 ± 0.03). Margalef's richness index values were highest offshore in both seasons. Simpson diversity and Margalef's richness index differed significantly among influence categories in both seasons (all $p < 0.001$). Pielou's evenness differed significantly among categories in the dry season ($F = 6.91$, $p = 0.0017$) but not in the wet season ($F = 2.73$, $p = 0.067$; Table 3).

Table 3. Variation in phytoplankton diversity indices in the dry and wet seasons in Winam Gulf. Values are means $\pm$ standard deviation. Richness is expressed as Margalef's index (d). Different superscript letters within a row indicate significant differences between influence categories ($p < 0.05$).

Index	Season	Offshore	River-influenced	Transitional	Urban	ANOVA (F)	P-value
Shannon	Dry	2.03 ± 0.06^a	1.51 ± 0.35^{bc}	1.99 ± 0.18^{ab}	1.57 ± 0.1^c	9.61	<0.001
	Wet	2.4 ± 0.17^a	1.94 ± 0.17^{bc}	2.12 ± 0.21^{ab}	1.24 ± 0.69^c	11.12	<0.001
Simpson	Dry	0.83 ± 0.02^a	0.66 ± 0.14^b	0.84 ± 0.04^a	0.7 ± 0.05^b	8.23	<0.001
	Wet	0.89 ± 0.03^a	0.8 ± 0.04^b	0.86 ± 0.03^a	0.57 ± 0.25^b	8.32	<0.001
Margalef's richness	Dry	10.83 ± 0.41^a	8.56 ± 1.42^b	9 ± 0.63^b	8.5 ± 0.55^c	8.52	<0.001
	Wet	14.17 ± 1.47^a	10.67 ± 1.41^b	11.17 ± 2.4^b	6.17 ± 3.54^c	12.69	<0.001
Evenness	Dry	0.85 ± 0.01^a	0.71 ± 0.14^b	0.91 ± 0.06^a	0.73 ± 0.06^b	6.91	0.001747
	Wet	0.91 ± 0.03^a	0.82 ± 0.05^b	0.88 ± 0.05^a	0.74 ± 0.22^b	2.73	0.067282

Correlation between Phytoplankton Communities and Environmental Variables

Mantel tests revealed significant relationships between phytoplankton composition and environmental variables across influence categories and seasons (Figure 7), with the strongest associations involving nutrients (TN, TP, SRP, NO_3^- -N, NO_2^- -N, NH_3 -N), followed by depth, dissolved oxygen, EC, TDS, pH and Secchi depth. Wet season communities showed stronger nutrient associations, while dry season communities were more linked to transparency and conductivity. Depth correlated positively with Secchi depth ($r = 0.84$, $p < 0.001$) and dissolved oxygen ($r = 0.50$, $p < 0.001$) but negatively with TDS and EC ($r = -0.71$ each, $p < 0.001$); nitrate correlated positively with TN ($r = 0.66$) and negatively with SRP ($r = -0.79$, both $p < 0.001$).

Phytoplankton: Community Composition vs Environmental Factors

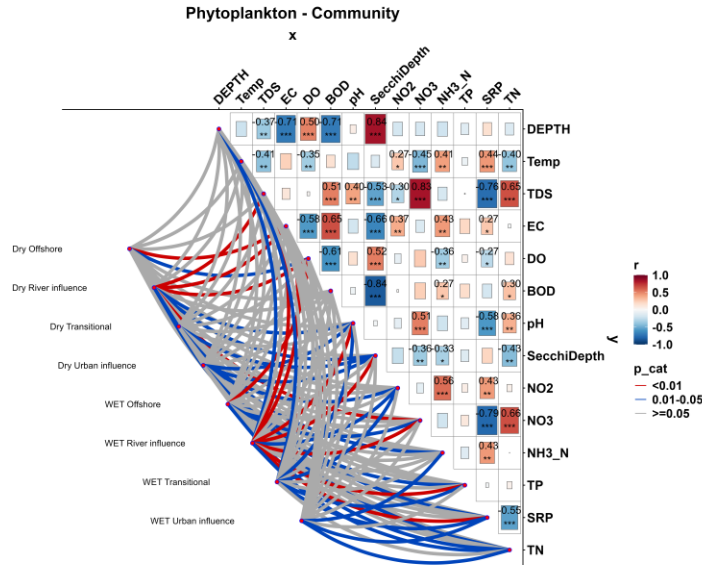


Figure 7: Correlation between phytoplankton community composition and the physicochemical parameters of Winam Gulf.

Influence of Environmental Factors on Phytoplankton

CCA identified the environmental variables most associated with phytoplankton distribution (Figure 8). In the dry season, offshore stations (*Microspora*, *Merismopedia*, *Nitzschia*, *Pediastrum*, *Botryococcus*) were associated with pH and TN; river-influenced stations (*Frustulia*, *Synedra*, *Scenedesmus*) with $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, $\text{NH}_3\text{-N}$ and EC; urban stations (*Coelastrum*, *Zygnema*, *Ankistrodesmus*) with temperature; and transitional stations (*Ceratium*, *Anabaena*) with intermediate conditions. In the wet season, gradients strengthened: offshore stations (*Anabaena*, *Ankistrodesmus*, *Navicula*, *Fragilaria*) aligned with dissolved oxygen; river-influenced stations (*Merismopedia*, *Pediastrum*, *Ceratium*, *Nitzschia*) with pH and TP; and urban/transitional stations (*Spirogyra*, *Protococcus*, *Selenastrum*, *Sorastrum*, *Richterella*) with temperature, $\text{NH}_3\text{-N}$, TN, EC and $\text{NO}_2\text{-N}$, reflecting runoff and nutrient enrichment during the wet season.

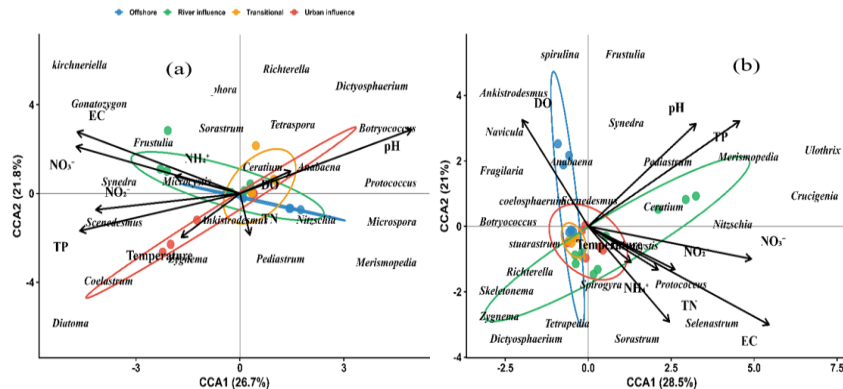


Figure 8: Canonical Correspondence Analysis (CCA) plots illustrating the relationship between phytoplankton communities and environmental variables during the (a) dry and (b) wet seasons

Seasonal and Spatial Variability of Environmental Conditions

The significant seasonal shifts in nutrients, dissolved oxygen, BOD, EC and transparency indicate that hydrological change is an important regulator of water quality in Winam Gulf, consistent with rainfall driven nutrient enrichment reported elsewhere in the gulf (Suba *et al.*, 2024). The concurrent rise in BOD and decline in Secchi depth during the wet season indicate greater organic loading and reduced light penetration, conditions typical of eutrophic systems that favour phytoplankton growth. Spatially, these gradients reflect agricultural runoff and wastewater inputs in river-influenced and urban categories. Ammonia nitrogen varied significantly between seasons ($p = 0.0021$), whereas total phosphorus did not reach the 0.05 significance threshold ($p = 0.0551$). This distinction suggests that seasonal external loading strongly affected dissolved nitrogen, while internal recycling may have contributed to the relative seasonal stability of total phosphorus (Olokotum *et al.*, 2021).

Phytoplankton Responses to Nutrient Enrichment and Influence Categories

The dominance of Cyanophyta, followed by Chlorophyta and Bacillariophyta, reflects sustained eutrophic conditions because cyanobacterial dominance is closely linked to nutrient enrichment, warm temperatures and long water residence times in Lake Victoria's nearshore ecosystems (Suba *et al.*, 2024; Brown *et al.*, 2024). Higher wet season abundance reflects enhanced nutrient loading from runoff, with greater accumulation in inner gulf and river-influenced categories. Urban categories showed lower diversity and were dominated by tolerant taxa, consistent with pollution related stress. The widespread wet season occurrence of *Microcystis*, a recognized eutrophication and bloom indicator in Winam Gulf (Miruka *et al.*, 2021; Brown *et al.*, 2024), and the offshore-to-urban decline in diversity align with environmental filtering theory (Kraft *et al.*, 2015; Isabwe *et al.*, 2018).

Environmental Drivers of Phytoplankton Community Structure

NMDS and CCA results show that phytoplankton community structure was associated primarily with nutrient gradients, particularly total phosphorus and dissolved inorganic nitrogen, consistent with previous findings from Winam Gulf (Suba *et al.*, 2024; Aura *et al.*, 2020). Total phosphorus showed a strong association with community composition, especially in the wet season, and influence categories with high phosphorus were linked to cyanobacterial dominance; nitrogen compounds were also influential, particularly in river-influenced categories. Dissolved oxygen, transparency, EC and temperature were secondary correlates: offshore categories with higher dissolved oxygen and transparency supported more diverse assemblages, while eutrophic and turbid categories favoured cyanobacteria. Because the first two PCA axes explained approximately 56.8% of total environmental variance in each season, the first two axes capture the dominant gradients. The remaining approximately 43.2% was distributed across subsequent axes, indicating additional environmental variation not represented in the two-dimensional biplots.

Ecological and Management Implications

The dominance of cyanobacteria and strong nutrient-community relationships confirm that eutrophication remains a major ecological challenge in Winam Gulf. River-influenced and urban categories showed persistent anthropogenic pressure and an elevated risk of harmful *Microcystis* blooms, with implications for water quality, biodiversity and public health (Miruka *et al.*, 2021; Brown *et al.*, 2024). Community composition was more sensitive to environmental gradients than total abundance; therefore, community-based indicators combined with NMDS and CCA provide a useful framework for detecting category specific ecological change, as recommended for Lake Victoria monitoring (Aura *et al.*, 2020; Yongo *et al.*, 2023).

Effective management will require reducing external nutrient inputs particularly phosphorus from agriculture, urban runoff and wastewater discharge, alongside strengthened catchment management to sustain the gulf's ecological integrity.

Conclusion and Recommendations

This study demonstrates that phytoplankton community structure in Winam Gulf is shaped by spatial and seasonal variation in nutrient availability and water quality. Nutrient enrichment from catchment runoff and anthropogenic

activity was associated with cyanobacterial dominance and reduced diversity in impacted influence categories. Multivariate analyses identified total phosphorus, nitrogen compounds, dissolved oxygen, conductivity and transparency as important environmental correlates. Offshore categories maintained relatively stable and diverse communities, whereas river-influenced and urban categories showed eutrophic conditions and simplified assemblages, supporting the use of phytoplankton as bioindicators of eutrophication in the gulf. Management should prioritise nutrient reduction, particularly phosphorus control, together with long-term phytoplankton monitoring. Catchment interventions should target agricultural and urban runoff, routine cyanobacterial and microcystin surveillance should be instituted for public health protection, and future studies should use higher-frequency temporal sampling to pinpoint the onset of algal blooms in Winam Gulf.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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