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Interrelationships Among Phytoplankton Communities Structure in the Calabar River Ecosystem

*¹Ogidiaka-Obende, E., ²Kaine, E. A. and ³Ndinwa, G.C.C.

¹Department of Marine Science, University of Delta, Agbor, Delta State, Nigeria.

²Department of Animal and Environmental Biology, Delta State University, Abraka, Delta State, Nigeria.

³Department of Environmental Management and Toxicology, University of Delta, Agbor, Delta State, Nigeria.

*efeogis@yahoo.com

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ABSTRACT

Phytoplankton communities are essential bioindicators of aquatic ecosystem health due to their sensitivity to environmental variations. This study examined the interrelationships among phytoplankton community structures across spatial and seasonal gradients in the Calabar River ecosystem, Southern Nigeria. Surface water samples were collected from four stations during the wet and dry seasons in 2020. Standard methods were used for phytoplankton enumeration and identification whereas inter-species relationships were analyzed using Pearson's correlation matrices and heatmap visualization in R and python environments. The results revealed marked seasonal and spatial differences in phytoplankton composition, with dominant taxa including *Cyclotella comta*, *Skeletonema costatum*, *Bacillaria paradoxa*, *Penium* sp., *Eudorani elegans* and *Oscillatoria* sp. During the wet season, strong positive correlations ($r = 0.74-0.99$) were recorded among most species, suggesting co-occurrence and mutual ecological tolerance among species sharing similar environmental preferences. In contrast, the negative correlation ($r = -0.83$ to -0.29) between *Staurastrum rotula* and *Cyclotella comta* suggested competition for resources under fluctuating hydrological conditions. The dry season analysis revealed a shift in dominance, with centric diatoms and desmids co-dominating and cyanobacteria showing reduced association strength. Spatially pronounced heterogeneity was observed among the stations, with *Eudorina elegans* and *Oscillatoria* sp. dominating the upstream zone, whereas *Skeletonema costatum* and *Cyclotella comta* thrived at the mid-stream and downstream zones. The study established that phytoplankton interrelationships are important ecological indicators for water quality assessment.

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1. INTRODUCTION

Aquatic ecosystems worldwide rely fundamentally on their phytoplankton communities, which constitute the primary producers at the base of the food web, linking basal resources to higher trophic

levels (Li *et al.*, 2019; Sindt and Wolf, 2021; Kaine and Ogidiaka, 2022). These microscopic communities influence global biogeochemical cycles, particularly carbon fixation and oxygen production. Phytoplankton are highly sensitive to changes in their ambient environment, making their structure, composition, and diversity excellent indicators of water quality and ecological health. The structural composition, abundance, and diversity of these communities reflect the health and ecological stability of the water body.

Tropical estuary and marine ecosystems, such as those found along the coast of southern Nigeria, are highly dynamic environments where physical forces interact with chemical factors to shape primary productivity (Ochieng *et al.*, 2022). These systems, particularly the Calabar River ecosystem, are subjected to complex interactions of natural tidal forces, freshwater inflow, and increasing anthropogenic pressures, including industrial discharge, municipal sewage, and agricultural runoff (Abua *et al.*, 2005; Eni *et al.*, 2014). These factors drive pronounced spatial and temporal variations on important physicochemical parameters, such as temperature, pH, dissolved oxygen, turbidity and other essential nutrient concentrations NO_3^- , PO_4^{3-} and SO_4^{2-} . The structure, composition, and abundance of phytoplankton communities are strongly shaped and regulated by these dynamic environmental gradients. Salinity and temperature define the range of species tolerances, while nutrient enrichment often dictates bloom formation and shifts in community dominance. Increased levels of nitrogen and phosphorus promote fast-growing cyanobacteria or specific diatom species, thereby potentially disrupting balanced food web structures (Zaghloul *et al.*, 2020). Therefore, analyzing the relationships between the plankton community and its habitat provides critical insights into the ecological state and functioning of the river.

Despite the ecological and economic importance of the Calabar River as a major transportation corridor and fisheries resource in the Niger Delta region, empirical studies that specifically addresses the direct interrelationships between the measured environmental variables and the resulting phytoplankton community structure are limited. Previous research works on Calabar River includes; Abua *et al.*, 2005 who established that the water quality of the river is influenced by sediment and input of nutrients; Ewa *et al.*, 2013 worked on the heavy metal status of the river while Eni *et al.*, (2014) determined the plankton composition of the river with the aim of assessing the biological integrity of water quality. The interrelationships among phytoplankton communities in this ecosystem are poorly understood. This study was therefore designed to assess the phytoplankton community structure across the Calabar River ecosystem with the aim to understand the spatial and temporal distribution of phytoplankton community structure in the river ecosystem. To achieve this aim, we hypothesized that phytoplankton assemblages would show significant spatial and temporal variability between the observed and expected distributions of phytoplankton species from the river.

2. MATERIALS AND METHODS

2.1. The Study Area

The study was conducted along the Calabar River, which is a major tributary of the Cross River estuary in Cross River State, Southern Nigeria. The water body is located in the southeastern part of south-south Nigeria and originated from the Oban Hills in the Cross River National Park, flowing southwards through rainforest and low-gradient coastal plains before discharging into the Cross River estuary, which eventually empties into the Gulf of Guinea (Eni *et al.*, 2014). The river basin covers an estimated area of 1,514 km² and is geographically located between latitude 4°56'59.99" N and longitude 8°19'18.00" E (Figure 1). It is characterized by a geology that includes the pre-Cambrian Oban Massif and Cretaceous sedimentary rocks, and is influenced by the humid climate zone, characterized by distinct wet and dry seasons. The wet season typically runs from April to October, accounting for approximately 80% of the annual rainfall, with peaks often observed in June and September. The dry season occurs from November to March. The average annual rainfall is substantial, averaging around 1,803 mm, while relative humidity remains high, typically within the ranges of 80-100%. Air temperatures are consistently high throughout the year, with an average range from 24-75°C during the cold wet months (August) to approximately 86°C during the hotter dry months (February). The hydrology of the river is dominated by a marked tidal regime due to its proximity to the

Atlantic Ocean and a semi-diurnal tidal cycle causing significant variations in water level and salinity, particularly in its lower reaches which collectively defines the physical environment for phytoplankton communities (Ewa *et al.*, 2013).

The surrounding landscape of the river includes mangrove forest and other riparian vegetation, particularly in the marine zone which plays a major role as a nursery ground for various fish and invertebrate species. The upper reaches of the river is bordered by tropical rainforest and agricultural lands. The Calabar River ecosystem is under considerable anthropogenic pressure due to its location adjacent to a major urban center and port activities; and receives significant amount of contaminants from effluent discharge from the surrounding industries and municipal sources, runoff from agricultural activities; sand mining and dredging operations. Consequently, the phytoplankton community structure of the river is exposed to a dynamic mix of natural marine conditions and environmental stressor, making it a critical area for ecological investigation.

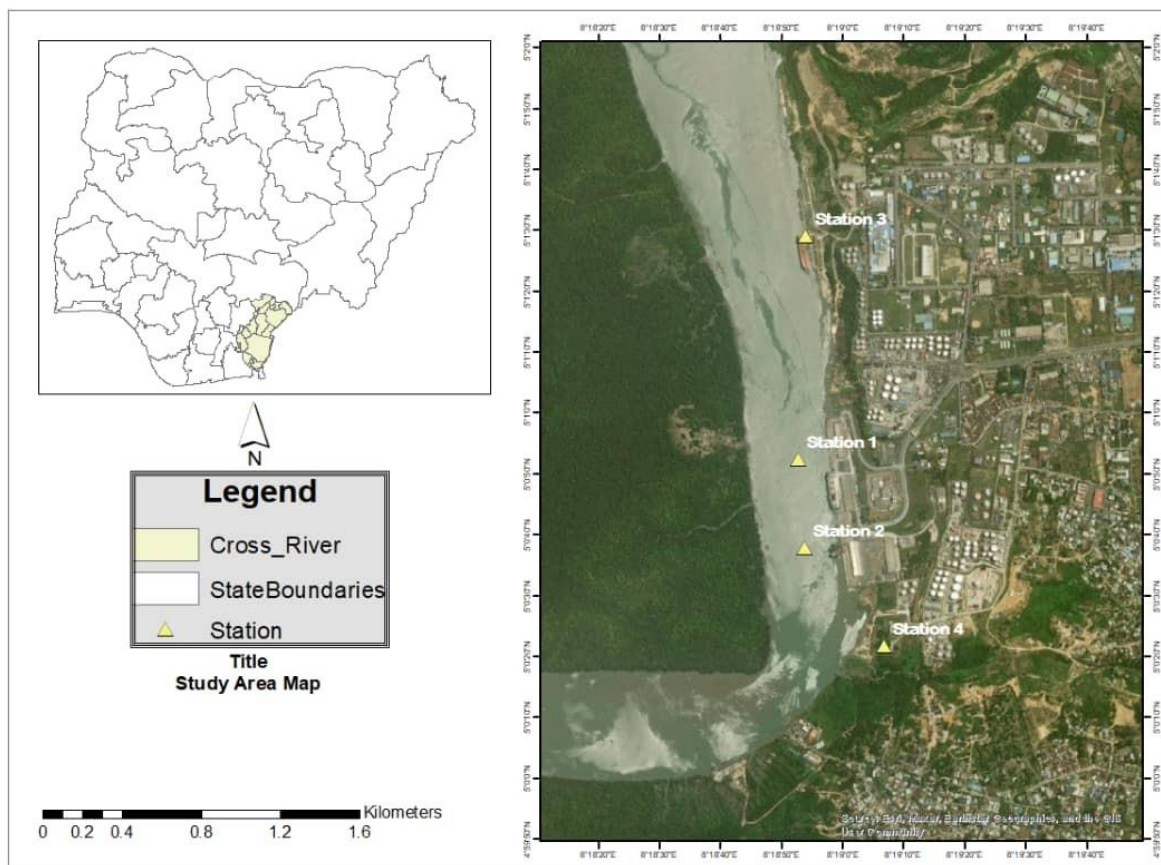


Figure 1: Map of study area showing sampling stations

2.2. Sampling Design, Collection, and Preservation

Four (4) sampling stations were established along the main channel and adjacent areas of the Calabar River. These stations were strategically selected to capture and represent the different ecological zones and inherent spatial heterogeneity covering the less anthropogenically impacted upstream areas to the highly brackish marine zone near the river confluence. Sampling was conducted across these stations during the wet and dry seasons to assess temporal variations. Samples were collected in January 2020 to represent the dry season and in September 2020 for wet season. These samples were collected during high tide to ensure consistency in hydrological conditions across the sampling periods and the location of each station was recorded using a hand-held GPS receiver. The location and geographical coordinates for the sampling stations are detailed in Table 1.

Table 1: Coordinates and geographical description of the sampling stations in Calabar River ecosystem

Station	Description	Latitude	Longitude
S1	Upstream/mid river reach	5°0'52.32' N	8°18'52.81" E
S2	Mid-river reach (high urban influence area)	5°0'37.74' N	8°18'53.84" E
S3	Less tidal influence	5°1'29.09' N	8°18'54.07" E
S4	Lower marine zone (strong tidal and saline influence)	5°0'52.32' N	8°18'52.81" E

Surface water (1L) was collected for plankton analysis at each sampling station using a water sampler and plankton net (55 µm) into clean, labeled plastic bottles. The samples were immediately preserved with 4% unbuffered formalin for long-term storage. At the laboratory, the samples were allowed to settle for 24 hours and later decanted to a known volume. 1 ml sub-sample was transferred to a Sedgwick-rafter counting chambers and plankton taxa were sorted and counted using Zeiss binocular microscope (X40, X100 and X400) at 400 magnifications. Identification of taxa was carried out to the lowest possible taxonomic level using standard keys by Sharma (1986); Olaniyan (1975); Prescott (1970).

2.3. Data Analysis

The data obtained were subjected to statistical treatment using R statistical software (v. 4.3.2) and the Python programming language. Pearson's product-moment correlation matrix was used to determine the interspecific relationships and visualize the inter-species association among the phytoplankton community structure in both seasons.

3. RESULTS AND DISCUSSION

The correlation analysis presented in Figures 2 and 3 represents the interspecies relationships of phytoplankton communities during the wet and dry seasons, respectively. The analysis shows the possible ecological interactions among the taxa influenced by the environmental conditions of the studied water body. From the analysis, it was observed that the inter-species relationships among the dominant taxa showed distinct patterns across the wet and dry seasons. During the wet season, strong positive correlations were observed between *Cydotella comta* and *Staurastrum apiculatus* ($r = 0.99$) and *Penium sp.* and *Oscillatoria* ($r = 0.99$). This implies a near perfect co-occurrence pattern due to similar ecological preferences during the rainy season. Such patterns indicate mutual tolerance and similar ecological optimization as observed in other tropical rivers where diatoms and desmids proliferate under moderate nutrient enrichment and stable photic conditions (Bucak *et al.*, 2018; Namugize *et al.*, 2018). Similarly, *Actinocyclus* species and *Surirella sp.* showed a very strong positive correlation ($r = 0.98$). The diatoms *Bacilaria paradoxa* and *Skiletonema costatum* were also tightly linked ($r = 0.97$). Strong positive correlations were further observed between *Bacilaria paradoxa* and *Penium sp.* ($r = 0.85$), *Skiletonema costatum* and *Penium sp.* ($r = 0.75$), *Bacilaria paradoxa* and *Oscillatoria* ($r = 0.75$) and *Skiletonema costatum* and *Eudorina elegama* ($r = 0.71$). These similar observations revealed that the species pairs either share similar ecological requirements, or respond similarly to the prevailing environmental conditions during the wet season, potentially benefiting from each other's presence. In contrast, strong negative correlation was observed in *Staurastrum rotula* and *Cydotella comta* ($r = -0.83$), indicating potential competition for shared ecological niches and contrasting responses to changes during the wet season. This pattern aligned with the observations in Small Aral Sea (Klimaszyk *et al.*, 2022), where competition among diatom and chlorophyte taxa intensified under fluctuating turbidity and salinity conditions.

A similar strong negative association was observed between *Staurastrum rotula* and *Staurastrum apiculatus* ($r = -0.79$). Moderate negative correlation were observed between *Staurastrum apiculatus* and *Eudorina elegama* ($r = -0.63$) and between *Staurastrum rotula* and *Oscillatoria* ($r = -0.60$). This negative correlation points towards a shift in dominance as a result of contrasting environmental preferences and antagonistic interactions between these species pairs during the wet season. The study further revealed interesting perspective into the inter-species relationships between phytoplankton taxa in Calabar River ecosystem, showing clear correlation patterns during the wet and dry seasons, implying that environmental conditions have a great influence in shaping community interactions (Kondowe *et al.*, 2022). Furthermore, strong positive correlations were recorded between multiple species pairs, including *Cydotella comta* and *Staurastrum apiculatus* ($r = 0.99$), *Penium sp.* and *Oscillatoria* ($r = 0.99$), and *Actinocyclus* species and *Surirella sp.* ($r = 0.98$) during the wet season period. These findings infer that these species share same

ecological preferences and likely benefit from each other (Townsend *et al.* (2000). The strong positive correlations recorded imply a near-perfect co-existence pattern, probably due to the prevailing environmental conditions during the wet season. On the other hand, strong negative correlations were established between *Staurastrum rotula* and *Cydotella comta* ($r = -0.83$), and between *Staurastrum rotula* and *Staurastrum apiculatus* ($r = -0.79$). These negative correlations suggest potential competition among these species for shared ecological resources and contrasting responses to variations in environmental conditions during the wet season (Pinto-Coelho *et al.*, 2005).

During the dry season, interspecific association shifted markedly indicating a significant seasonal shift in community interactions. *Actinocyclus* species showed a strong positive correlation with *Oscillatoria* ($r = 0.74$) and *Eudorina elegans* ($r = 0.58$), unlike the antagonistic relationship we observed with most species during the wet season. *Cydotella comta* was positively correlated with *Skeletonema costatum* ($r = 0.79$) and *Staurastrum apiculatus* ($r = 0.82$), indicating a co-dominance of centric diatoms and desmids, which may be attributed to clearer water and stable temperature conditions favoring their phototrophic efficiency. A strong positive correlation was also recorded between *Penium sp.* and *Surirella sp.* ($r = 0.90$), suggesting that both taxa may share adaptive traits to desiccation and nutrient stress prevalent in the dry season. Similar transitions from cyanobacteria to diatom dominance during the dry seasons have been report in estuaries of Kenya and Tanzania, where reduced nutrient inflow and stable salinity favored silica-dependent taxa (Kondowe *et al.*, 2023). The negative correlation between *Cydotella comta* and *Staurastrum rotula* weakened considerably from the wet ($r = -0.83$) to the dry season ($r = -0.29$) (figure 2). It was observed that *Oscillatoria* which had positive correlations with several species in wet season became increasingly isolated in the dry season. There was inverse relationship between *Surirella sp.* and *Cydotella comta* ($r = -0.85$) in the dry season and *Penium sp.* was observed to positively correlate with *Bacillaria paradoxa* ($r = -0.85$). These seasonal dynamics in community interactions revealed the adaptability and competitive interactions of phytoplankton species under changing hydrological regimes. The observed positive correlations implied shared ecological requirements and mutualistic interactions, whereas the negative correlations highlighted the potential antagonistic relationships due to resource competition. Similar seasonal restructuring of phytoplankton assemblages has been observed in Lake Beysehir (Turkey) and Mngeni River (South Africa), where desiccation and conductivity gradients favored salt-tolerant diatoms and cyanobacteria (Namugize *et al.*, 2018; Bucak *et al.*, 2018).

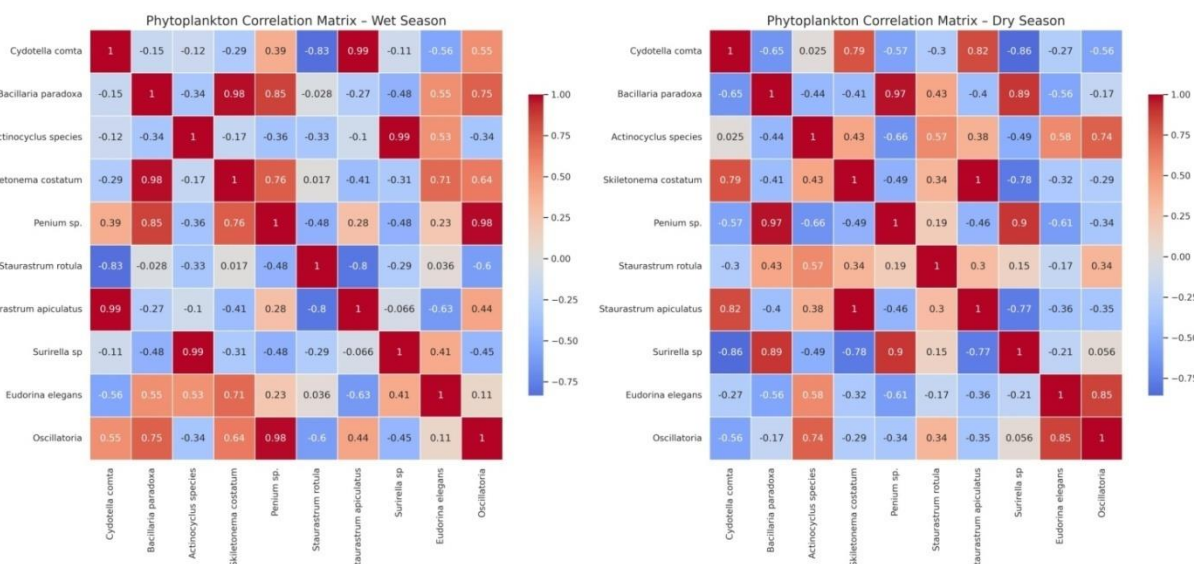


Figure 2: Heatmap of phytoplankton species correlation during the wet and dry seasons in the study area

Note: The figure illustrates the Pearson correlation coefficients among the ten dominant phytoplankton species observed during the wet (left panel) and dry (right panel) seasons. Positive correlations are represented by blue shades, while negative correlations are shown in red, with the intensity indicating the strength of the correlation. The seasonal variation in inter-species relationships highlights differential ecological interactions and environmental responses across the hydrological cycle.

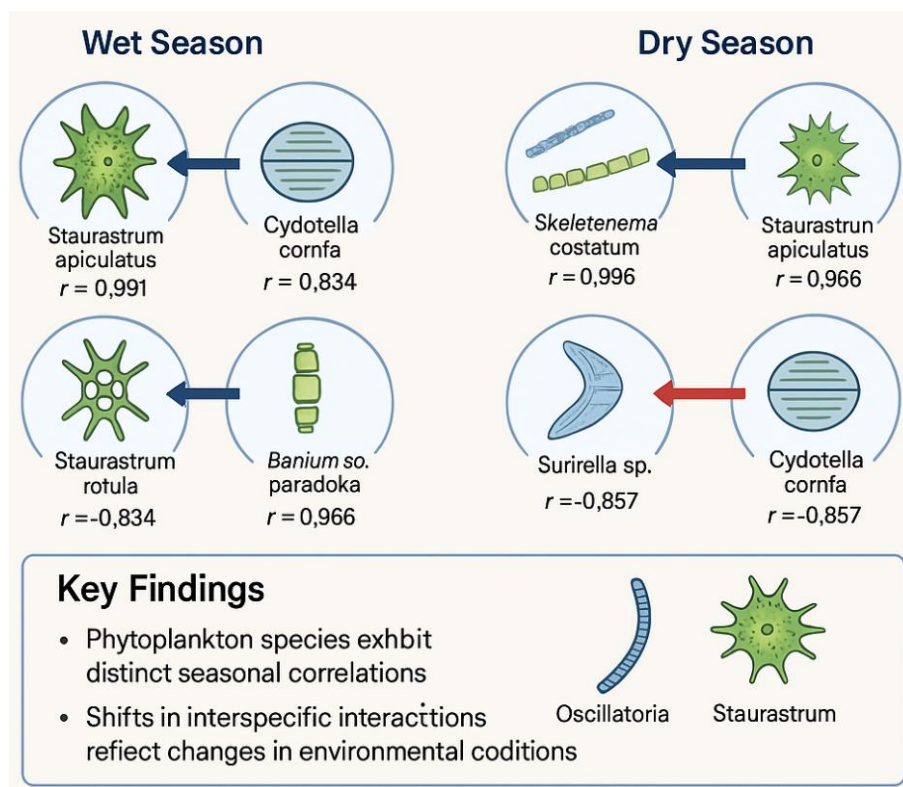


Figure 3: Correlation of phytoplankton during the wet and dry seasons in the study area

Examination of the standardized residuals (Figure 4) revealed the specific species-station combinations contributing most strongly to this significant result. From Figure 4, *Eudorina elegans* and *Oscillatoria* were observed to have higher counts than expected by chance at station 1 (residuals = 5.90 and 13.96) and markedly less frequent count than expected at station 2 (residuals = -9.53 and -6.74). Conversely, *Bacillaria paradoxa* and *Penium* sp. showed significantly higher counts than expected at station 2 (residuals = 16.16 and 14.37) respectively and lower counts at station 1 (residuals = -4.47 and -5.86) and Station 4 (residuals = -5.01 and -0.64); though *Penium* at station 4 was less pronounced. Station 3 showed particularly high abundances of *Cyclotella comta*, *Skeletonema costatum*, and *Staurastrum apiculatus* (residuals = 9.00, 16.40, and 10.34), while *Penium* sp. and *Bacillaria paradoxa* had lower than expected count (residuals = -5.57 and -5.29) respectively. Station 4 had notably higher counts of *Cyclotella comta* and *Eudorina elegans* (residuals = 5.90 and 7.05, respectively) relative to several other species and compared to expectations. These distinct patterns across the stations suggest that there were varying environmental conditions that influenced the phytoplankton community structure at each location.

To evaluate the spatial distribution patterns of phytoplankton across the four sampling stations during the dry season, a comparative heatmap analysis of the observed and expected frequencies was conducted (Figure 5). The comparative heatmap presents a visual side-by-side comparison of the actual counts recorded at each station and the counts predicted under the hypothetical distribution assuming no significant association between species occurrence and station location. The analysis in Figure 5 revealed marked spatial variation in species abundance across the stations, indicating spatial heterogeneity in phytoplankton composition. *Eudorina elegans* was observed to show an overwhelmingly dominance in station 1 (243 individuals) and station 4 (134 individuals), but completely absent in station 2. In a similar situation, *Oscillatoria* showed pronounced abundance in station 1 (211 individuals), with no recorded presence in stations 2 and 4. In contrast, *Oscillatoria* was found to be heavily concentrated in station 2 (121 individuals) and virtually undetected in stations 3 and 4. *Skeletonema costatum* was observed primarily in station 3 (112 individuals), with no significant presence in other stations. These sharp contrasts in spatial distribution, revealed that these species were responding to localized environmental conditions such as nutrient enrichment, light penetration and anthropogenic influences.

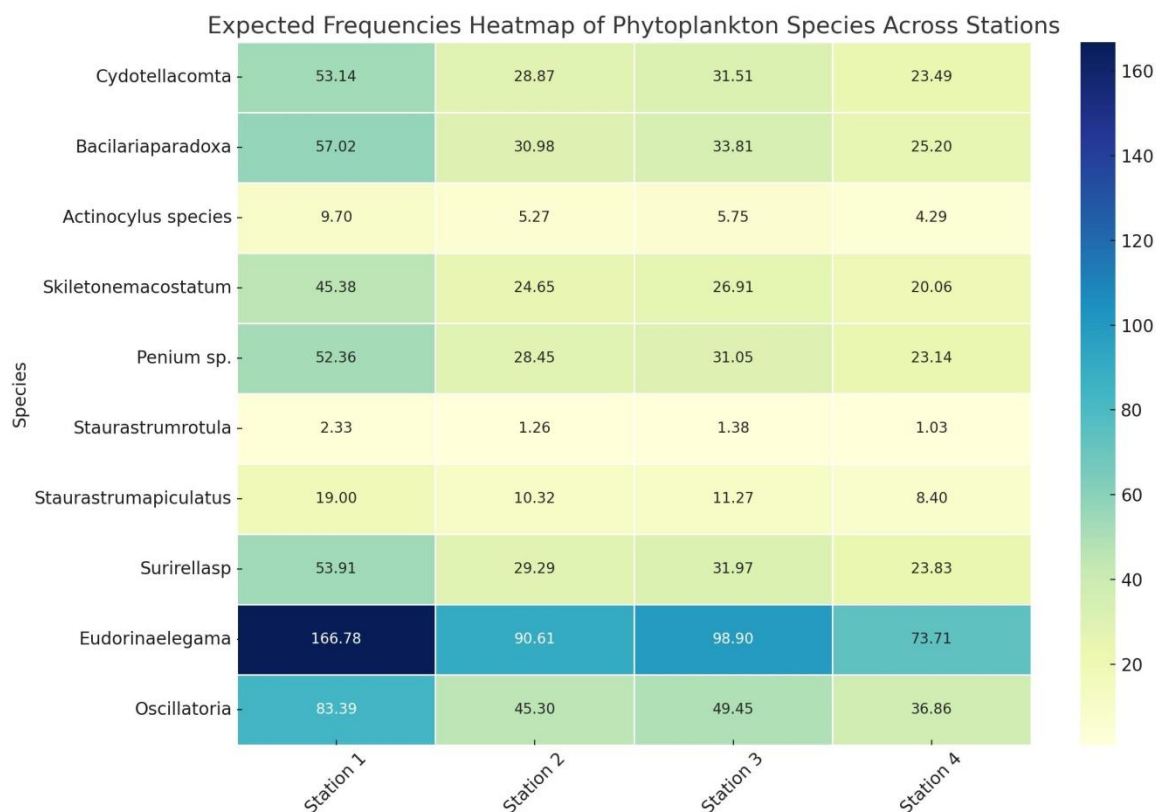


Figure 4: Heatmap showing the standardized residuals (expected frequencies) of diatom taxa across the four sampling stations during the dry season

In comparison, the expected frequency heatmap illustrated a theoretical evenness in distribution across all the stations based on the marginal totals of species and station-wise phytoplankton counts. It was deduced from Figure 5 that *Eudorina elegama* was expected to be more evenly distributed across the stations, but was not supported by the observed data. The same was observed for *Oscillatoria*, whose strong concentration in station 1 greatly exceeded its expected presence in other stations. The pronounced spatial heterogeneity observed suggests that the species assemblages were likely shaped by the prevailing environmental factors and anthropogenic influences unique to each station. These results underscore the ecological importance of site-specific conditions in structuring phytoplankton communities and provide evidence for the potential use of phytoplankton as bioindicators of localized water quality monitoring.

The positive correlation between *Penium sp.* and *Surirella sp.* ($r = 0.90$) points to the fact that both taxa may likely share adaptive traits to nutrient stress associated with the dry season. The reduction of the negative correlation between *Cydotella comta* and *Staurastrum rotula* from the wet to dry season ($r = -0.29$) further establishes the seasonal dynamics in community interactions. Parmar *et al.* (2016) opined that phytoplankton species develop and survive in diverse aquatic ecosystems defined as a niche, depending on their physiological requirements and environmental limitations. Phytoplankton species distribution varied significantly across four stations, indicating spatial heterogeneity in phytoplankton composition (Klimaszyk *et al.*, 2022). Station 1 was characterized by significantly higher counts of *Skeletonema costatum* and *Oscillatoria*, while *Cyclotella comta* was underrepresented. This suggests that Station 1 may provide favorable conditions for *Skeletonema costatum* and *Oscillatoria*, such as high nutrient levels or suitable water temperature. Station 2 had higher-than-expected counts of *Cyclotella comta*, *Staurastrum apiculatus*, and *Oscillatoria*, indicating that these species may thrive in the environmental conditions present at this station. Conversely, *Skeletonema costatum* and *Bacillaria paradoxa* were underrepresented, suggesting that they may not be well-suited to the conditions at station 2.

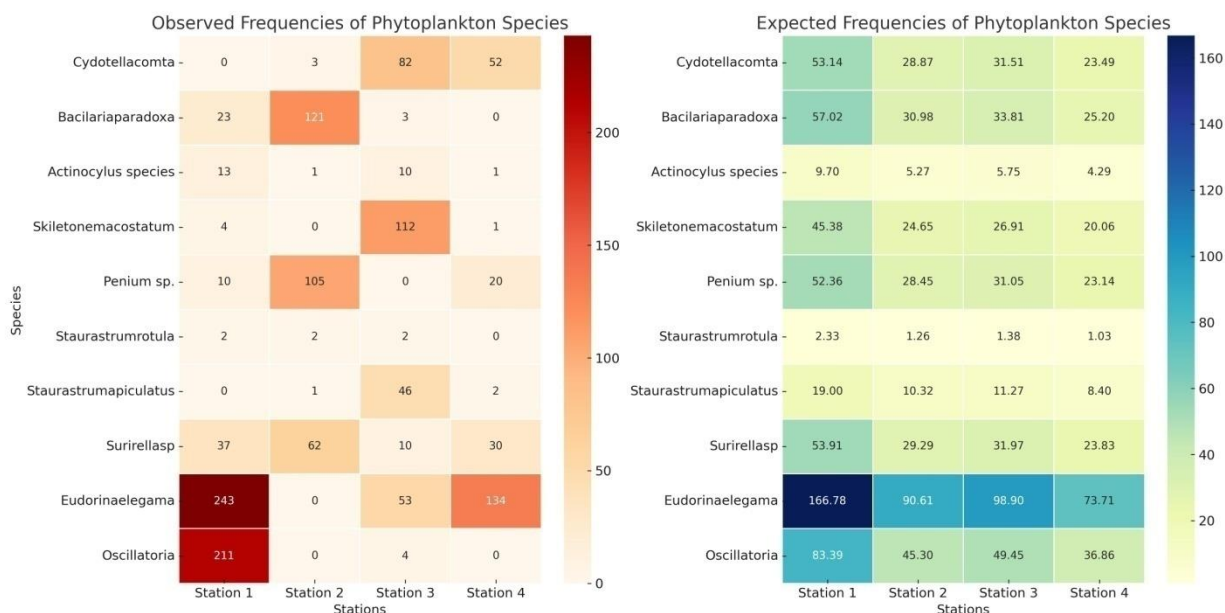


Figure 5: Comparative heatmap showing the observed (left panel) and expected (right panel) frequencies of phytoplankton species across the four sampling stations during the dry season.

Note: The observed frequencies represent actual counts recorded during field sampling, while the expected frequencies were derived from a chi-square test of independence under the assumption of no association between the species and stations. Color intensities indicate the magnitude of frequencies, with warmer tones representing higher values. Notable deviations between observed and expected values highlight station-specific ecological preferences and distribution patterns among taxa contributing to the significant chi-square result ($\chi^2(27) = 1873.52, p < 0.001$).

Station 3 was dominated by *Actinocyclus* species, *Surirella* sp., and *Eudorina elegans*, which had substantially higher abundances than expected. This suggests that these species may have adapted to the specific environmental conditions present at station 3. *Skeletonema costatum* and *Oscillatoria* were significantly less abundant than expected, indicating that they may not be competitive in this environment. Station 4 had slightly higher counts of *Staurastrum rotula*, but lower counts of *Actinocyclus* species and *Oscillatoria*. This indicates that *Staurastrum rotula* may be more tolerant of the environmental conditions at station 4. *Bacillaria paradoxa* was ubiquitous at station 1 and underrepresented at the other stations, suggesting that it may have a specific requirement or niche that is met at station 1. *Eudorina elegans* and *Penium* sp. showed relatively slight deviation from expected counts across the majority of the stations, suggesting that they can thrive in a variety of environmental conditions. There were significant spatial distribution patterns of phytoplankton species recorded across the four stations. Certain species recorded lower or higher counts than expected at specific stations.

Station 1 had higher-than-expected counts of *Eudorina elegans* and *Oscillatoria*, suggesting that the environmental conditions at this station were favourable (Kaine and Ogidiaka, 2022). On the contrary, these species recorded lower counts at station 2, indicating that the environment may be hostile to these species. Station 2 had higher counts of *Bacillaria paradoxa* and *Penium* sp., which points to the fact that these species could have possibly adapted to certain environmental conditions present at this station. Furthermore, the species were underrepresented at stations 1 and 4, suggesting that the conditions at these stations are not suitable for them. Station 3 was dominated by *Skeletonema costatum*, *Cyclotella comta*, and *Staurastrum apiculatus*, which had significantly high abundances. This suggests that these species have adapted to the environmental conditions present in station 3. Conversely, *Penium* sp. and *Bacillaria paradoxa* had lower-than-expected counts, indicating that they may not be competitive in this environment.

Station 4 had notably higher counts of *Cyclotella comta* and *Eudorina elegans*, suggesting that these species may thrive in the environmental conditions present at this station. The comparative heatmap analysis showed significant spatial variation in phytoplankton species abundance across the various stations, indicating spatial heterogeneity in phytoplankton composition. This suggests that the distribution of phytoplankton species is not random, but rather influenced by specific environmental conditions or factors associated with each station. The analysis showed that certain species exhibited distinct spatial patterns. For instance, *Eudorina elegans* was overwhelmingly dominant in station 1 (243 individuals) and station 4 (134 individuals), but was completely absent in station 2. This suggests that *Eudorina elegans* may have specific requirements or preferences that were met at stations 1 and 4, but not at station 2. Similarly, *Oscillatoria* showed pronounced abundance in station 1 (211 individuals), with no recorded presence in stations 2 and 4. However, another species, possibly *Bacillaria paradoxa* was heavily concentrated in station 2 (121 individuals), with virtually no detection in Stations 3 and 4. This suggests that different species or strains may have distinct spatial distributions.

Skeletonema costatum was primarily found in station 3 (112 individuals), with no significant presence in other stations. This indicates that *Skeletonema costatum* may have specific requirements or preferences that are met at station 3. The study suggests that phytoplankton species occupy specific ecological niches, with some species exhibiting niche partitioning and others co-occurring due to shared preferences or benefits (Lewis, 2020). The concept of realized niche is crucial in understanding species distributions, biotic diversity, and community composition (Bucak *et al.*, 2018). The concept of niche in ecology refers to the universal tendency of species populations to occupy a specific part of environment to which they are adapted for survival and reproduction. Physical, chemical, and biological factors set boundaries on the niche of each species; the environment within these boundaries is the fundamental niche of the species. The presence of one or more species that will compete with the species in question restricts the size of the fundamental niche of a species to a smaller space, which is the realized niche. Knowledge related to the realized niche supports scientific understanding of species distributions, biotic diversity, and species composition of communities and ecosystems (Lewis, 2020).

The observed frequency of phytoplankton individuals across stations were compared with the expected frequency in a hypothetical even distribution. The findings revealed significant discrepancies between the observed and expected distributions of phytoplankton. For example, *Eudorina elegans* was expected to be more evenly distributed across the stations, but the observed data showed a strong dominance in stations 1 and 4, and complete absence at station 2. Also, *Oscillatoria*'s had a strong concentration in station 1 which greatly exceeded its expected presence in the other stations. The observed spatial heterogeneity observed in the study indicates that phytoplankton species assemblages are shaped by prevailing environmental factors and anthropogenic influences unique to each station (Davies *et al.*, 2009). This highlights the ecological importance of site-specific conditions in structuring phytoplankton communities.

4. CONCLUSION

This study revealed that phytoplankton community structure of the Calabar River showed distinct seasonal and spatial variations shaped by significant seasonal shifts in nutrient load, hydrology and anthropogenic pressures. The positive correlation observed among certain species revealed that the increased level of nutrients during the wet season fostered positive coexistence among diatom and desmid taxa, whereas the stability observed during the dry season promoted the dominance of centric diatoms and the decline of cyanobacteria due to competitive adjustment under stress. Spatially, the upstream and midstream zones supported distinct assemblages shaped by nutrient gradients and the influence of tides. The study revealed that the phytoplankton distribution was strongly influenced by localized environmental conditions. Notably, taxa such as *Oscillatoria*, *Straurastrum* and *Penium* displayed consistent sensitivity to seasonal drivers, reinforcing their potential role as bioindicators for environmental monitoring. Although, the Calabar River remained functionally productive, however, the increasing presence of eutrophic-tolerant taxa signaled the need for proactive management to avert further degradation. This study has therefore provided valuable insights for assessing ecological resilience and monitoring the impacts of human activities on tropical aquatic ecosystems.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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