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Phytoplankton Diversity and Nutrient Driven Community Structuring in Kainakari Panchayat under the Kuttanad Wetlands of Kerala

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Abstract
The Kuttanad wetlands of Kerala represent a unique and ecologically sensitive hydrological system where water quality dynamics play a critical role in regulating biological productivity. This study assessed the physicochemical characteristics and phytoplankton diversity across four sites in the Kainakari Panchayat from February 2023 to April 2024. Standard APHA procedures were used to analyse water quality parameters, while phytoplankton were identified microscopically and quantified to the lowest taxonomic level. A total of 55 phytoplankton species belonging to Cyanophyceae, Chlorophyceae, Bacillariophyceae, Chrysophyceae, and Dinophyceae were recorded, with Chlorophyceae showing the highest richness. Spatial variations in nitrate and phosphate strongly influenced phytoplankton distribution, with nitrate-rich Kuppapuram (S_1) supporting peak diatom densities and phosphate-rich Punnamada (S_4) favouring green algae proliferation. Diversity indices indicated a highly stable ecosystem, with Shannon - Wiener values ranging from 3.853 to 3.892. Correlation analysis revealed a strong positive relationship between diatoms and nitrate concentration and between green algae and phosphate concentration, suggesting nutrient-driven niche differentiation. PCA further distinguished the sites along major nutrient gradients. The present study highlights the significance of nutrient dynamics in shaping community structure and emphasizes the value of phytoplankton as sensitive bioindicators for monitoring the ecological health of the Kuttanad wetlands.

Keywords: Phytoplankton Diversity; Water Quality; Nutrient Dynamics; Kuttanad Wetlands; Kainakari Panchayat

Introduction
Wetland ecosystems are among the most productive habitats on earth, functioning as natural biofilters, nutrient transformers and biodiversity hotspots (James, 2007; Bhateria and Jain, 2016). The Kuttanad wetlands of Kerala represent a unique hydrological system shaped by freshwater and brackish water interactions and seasonal fluctuations, making them highly sensitive to environmental change (Nair et al., 1983; Divya Raj and Kani, 2018). Water quality, determined by physicochemical parameters such as temperature, pH, dissolved oxygen, conductivity and nutrient load, plays a central role in regulating the ecological functioning of wetlands (APHA, 2012; Boyd, 2019; WHO, 2011). Even subtle changes in nutrient inputs, particularly nitrate and phosphate can significantly alter phytoplankton structure and productivity, influencing food-web dynamics and overall ecosystem health (Murphy and Riley, 1962; Jiang et al., 2021). Phytoplankton, owing to their rapid response to environmental changes, are widely recognized as early-warning indicators of water quality deterioration and trophic state variations (Singh et al., 2013; Brierley, 2017; Suthers et al., 2019). Previous studies across Indian wetlands, including Ashtamudi, Sasthamkotta and the Palk Bay region, have shown that variations in hydrochemical parameters drive significant shifts in algal composition and diversity (Alexander et al., 2014; Garcia et al., 1997; Santhanam et al., 2003; Arivoli

et al., 2018). Despite this, comprehensive assessments integrating both physicochemical gradients and phytoplankton community dynamics remain limited for the Kuttanad wetland regions.

The present study addresses this gap by examining the relationship between water quality parameters and phytoplankton diversity across four locations in the Kainakari Panchayat within the Kuttanad wetlands. By quantifying major nutrient concentrations and mapping associated phytoplankton responses, including class-level dominance, species richness, diversity indices and ordination patterns, the study establishes clear ecological linkages supported by correlation and PCA-based niche segregation analyses (Grabowska et al., 2014; Nirmalkumar et al., 2011). Given the observed dominance of Chlorophyceae, Cyanophyceae and Bacillariophyceae, along with the distinct nutrient-driven clustering of sites, the findings substantiate global and regional evidence on nutrient-mediated regulation of phytoplankton communities (Fathi and Flower, 2005; Stephanie Dutkiewicz et al., 2020; Jing Xia et al., 2024). The significance of this study lies in its ability to identify nutrient thresholds, ecological indicators and site-specific vulnerabilities, offering critical insights for wetland conservation, eutrophication control and sustainable water-resource management in Kuttanad. By integrating hydrochemical assessment with biological response patterns, the study contributes valuable baseline data essential for long-term ecological monitoring and management planning (Summarwar, 2012; Vijayan and Ray, 2015; Offem et al., 2011).

Materials and Methods

Study Area and Sampling Design

The study was conducted across four locations such as Kuppapuram (S_1), Kainakary South (S_2), Thottuvathala (S_3), and Punnamada (S_4), within the Kainakary Panchayat of Kuttanad wetlands, Alappuzha (Table 1). Sampling was carried out seasonally from February 2023 to April 2024. The geographic coordinates of each site were recorded using GPS to ensure spatial accuracy. Surface water samples were collected during each sampling event to examine both physicochemical characteristics and phytoplankton composition.

Table 1. Geographic Coordinates of Sampling Locations in Kainakary Panchayat

Sample Number	Location	Latitude	Longitude
S_1	Kuppapuram	9.508598	76.370173
S_2	Kainakari South	9.485911	76.378305
S_3	Thottuvathala	9.484678	76.378396
S_4	Punnamada	9.500038	76.358981

Physicochemical Analysis of Water

Water samples were analysed following the Standard Methods for the Examination of Water and Wastewater (APHA, 2012) for key physicochemical parameters including temperature, pH, turbidity, total dissolved solids (TDS), electrical conductivity (EC), salinity, dissolved oxygen (DO), alkalinity, acidity, total hardness, chloride, nitrate, sulphate, phosphate, potassium, and free carbon dioxide. Parameters were measured using calibrated field and laboratory instruments. Nutrients such as phosphate and nitrate were analysed using colorimetric methods, while conductivity, dissolved oxygen and salinity were measured in situ to minimize variation.

Phytoplankton Sampling and Analysis

Phytoplankton samples were collected using a 20 µm mesh plankton net, concentrated, and preserved using Lugol's iodine solution. Samples were examined under a compound microscope using a Sedgwick - Rafter counting chamber. Phytoplankton were identified to the lowest possible taxonomic level using standard taxonomic keys, and densities were expressed as numbers per liter (nos./L). Diversity indices such as Shannon - Wiener (H'), species richness, evenness, and total density were calculated. Additionally, correlation analysis and PCA were conducted to determine the influence of environmental variables on phytoplankton community structure. All statistical analyses were carried out using PAST 4.30 software.

Results

Physicochemical Characteristics of Water

The water quality analysis across the four sampling locations - Kuppapuram (S_1), Kainakari South (S_2), Thottuvathala (S_3), and Punnamada (S_4) - showed variations in several key physicochemical parameters (Table 2). Temperature was relatively uniform, ranging from 28°C at S_2 to 30°C at S_3. The pH values were consistently slightly acidic, falling between 6.21 (S_1) and 6.53 (S_3). Turbidity was highest at S_3 and lowest at S_2. Dissolved Oxygen (DO) levels were generally good, with the highest value at S_3 and the lowest at S_2. Total Dissolved Solids (TDS) showed minimal variation, with S_3 having the highest concentration. Electrical Conductivity varied, peaking at S_4 and being lowest at S_3. The Oxidation Reduction Potential (ORP) was positive across all sites, ranging from +44 at S_2 to +62 at S_4.

Regarding the chemical parameters, Acidity was highest at S_4 and lowest at S_2. Total Hardness ranged from 46 mg/L at S_3 to 58.2 mg/L at S_1. Chloride concentrations were highest at S_4. Significant differences were observed in

nutrient concentrations. Nitrate was highest at S_1, substantially greater than S_2. Sulphate was highest at S_2, and Phosphate was highest at S_4. Potassium levels were slightly elevated at S_3. Salinity levels were very low, ranging from 0.12 mg/L at S_3 to 0.19 mg/L at S_2.

Table 2. Physicochemical Characteristics of Water Across the Four Sampling Sites

PARAMETERS	Kuppapuram (S1)	Kainakari South (S2)	Thottuvathala (S3)	Punnamada (S4)
Temperature	29	28	30	29
pH	6.21	6.39	6.53	6.29
Turbidity (NTU)	6.8	3.5	7.2	5.8
Total dissolved solids (mg/L)	198.7	196.7	199.2	195.5
Electrical conductivity	0.452	0.457	0.296	0.596
Oxidation reduction potential	+56	+44	+59	+62
Acidity (mg/L)	30.0m	18.0	22.0	33.0
Total hardness (mg/L)	58.2	50	46	54.6
Chloride (mg/L)	101.96	103.96	102.8	104.6
Nitrate (mg/L)	22.6	7.28	15.3	18.6
Sulphate (mg/L)	6.4	14.4	9.7	11.6
Phosphate (mg/L)	1.2	1.8	1.6	1.9
Potassium (mg/L)	4.12	4.46	5.12	4.86
Salinity(mg/L)	0.16	0.19	0.12	0.14
Dissolved Oxygen (mg/L)	7.5	6.5	8.2	6.9

Spatial Distribution and Density of Phytoplankton

The phytoplankton community across the four sampling locations in the Kuttanad Wetlands was highly diverse and dense, comprising species from five classes: Cyanophyceae, Chlorophyceae, Bacillariophyceae, Chrysophyceae, and Dinophyceae (Table 3). Chlorophyceae (green algae) exhibited the highest species richness, with 26 identified taxa, while Bacillariophyceae (diatoms) and Cyanophyceae (blue-green algae) were also highly abundant. Several species showed exceptionally high densities; for instance, *Achnathes inflata* (Bacillariophyceae) recorded the highest overall count at Kuppapuram (S_1) with 9900 nos./L. Similarly, the green algae *Staurodesmus corniculatus* (9900 nos./L) and *Micrasterias foliaceae* (9800 nos./L) reached their peak densities at Punnamada (S_4). The Cyanophyceae species, such as *Oscillatoria limnetica* (9800 nos./L at S_1) and *Gloeothece linearis* (8500 nos./L at S_4), also contributed significantly to the total density across the sites.

Table 3. Spatial Distribution and Density of Phytoplankton Species Recorded at the Study Sites

No	Class	Phytoplankton	Kuppapuram (nos./L)	Kainakari South (nos./L)	Thottuvathala (nos./L)	Punnamada (nos./L)
1.	Cyanophyceae	*Agmellum quadriduplicatum*	2210	1950	1220	6700
2.		*Anacystis cyanea*	3810	2530	2210	4000
3.		*Aphanocapsa benaresnsis*	3240	3200	1130	2400
4.		*Aphanothece pallida*	1100	1390	1200	2100
5.		*Coelosphaerium dubium*	920	1119	1300	1400
6.		*Gloeothece linearis*	6600	7200	8300	8500
7.		*Gomphosphaeria aponina*	4500	3700	3400	2800
8.		*Merismopedia glauca*	6500	4800	4730	5600
9.		*Oscillatoria limnetica*	9800	8900	7300	6100
10.	Chlorophyceae	*Actinotaenium globosum*	1300	1640	1800	1700
11.		*Chlorella vulgaris*	9510	6280	7400	6300
12.		*Closterium graute*	2100	1690	1500	1300
13.		*Closterium kuetzingii*	4650	3300	3790	5300
14.		*Closterium lineatum*	4100	4720	4400	5800
15.		*Cosmarium lundellii*	3200	3700	4120	5400
16.		*Desmidium baileyi*	1780	1360	1890	2100
17.		*Gonatozygon monotaenium*	1400	1520	1700	1600
18.		*Hyalotheca dissiliensis*	6590	5400	6570	7500
19.		*Kirchneriella lunaris*	5300	4900	5470	6600
20.		*Micrasterias foliaceae*	7580	6960	7640	9800
21.		*Micrasterias lux*	3580	4400	5380	5200
22.		*Micrasterias radiata*	3100	2560	2200	2000
23.		*Onychonema laeve*	3580	3490	4280	4300
24.		*Oocystis elliptica*	6400	5890	5320	9700
25.		*Pediastrum duplex*	990	1340	2100	2800

26.		*Scenedesmus arcuatus*	4600	4300	3650	5300
27.		*Scenedesmus dimorphus*	5100	5380	3900	5500
28.		*Scenedesmus quadricauda*	4600	4750	5500	3200
29.		*Selenastrum gracile*	4890	6300	5100	5200
30.		*Staurastrum arctiscon*	5400	4200	5100	4300
31.		*Staurastrum longipes*	4600	4680	4100	3900
32.		*Staustrastum setigerum*	2400	2200	1980	1100
33.		*Staurastrum sexangulare*	3100	2700	2400	2200
34.		*Staurodesmus convergens*	6700	5400	6390	7600
35.		*Staurodesmus corniculatus*	6530	7430	8100	9900
36.		*Staurodesmus glaber*	6300	6650	7330	9500
37.		*Westella botryoides*	5470	4210	3600	3200
38.		*Xanthidium perrisacanthum*	3600	5400	5900	4300
39.	Bacillariophyceae	*Achnathes inflata*	9900	7500	7730	6700
40.		*Asterionella gracillima*	4500	7530	8300	6600
41.		*Cyclotella stelligera*	1400	3270	2600	4700
42.		*Diatoma vulgare*	9300	8990	7500	8500
43.		*Fragillaria capucina*	3600	4300	3400	2800
44.		*Fragillaria crotonesis*	4300	3700	4200	2600
45.		*Melosira granulata*	5700	5330	4900	4200
46.		*Nitzschia palea*	1300	2800	3300	1200
47.		*Pinnularia nobilis*	2100	3600	2480	1300
48.		*Stauroneis anceps*	6100	6420	5100	5400
49.		*Surirella robusta*	5400	5180	4600	3400
50.		*Synedra acus*	3790	3900	3600	2900
51.		*Synedra ulna*	5700	5370	4900	4400
52.		*Tabellaria fenestrata*	1100	1220	1800	2500
53.	Chrysophyceae	*Dinobryon sertularia*	2580	3300	3670	2200
54.	Dinophyceae	*Peridinium cinctum*	1680	2900	3100	2800
55.		*Peridinium tetras*	800	1600	1860	1300

Class-Level Phytoplankton Composition and Dominance Patterns

There were notable spatial variations in species dominance, suggesting differences in the microenvironment of the locations. Kuppapuram (S_1) showed maximum counts for key diatoms (e.g., *Achnathes inflata* and *Diatoma vulgare*, 9300 nos./L) and the green alga *Chlorella vulgaris* (9510 nos./L), indicating conditions potentially favourable for these species. Conversely, Punnamada (S_4) recorded the peak densities for the majority of the most abundant green algae (e.g., *S. corniculatus*, *M. foliaceae*, *Oocystis elliptica* in 9700 nos./L) and blue-green algae (e.g., *G. linearis*, *A. quadriduplicatum*, 6700 nos./L). While Chrysophyceae (*Dinobryon sertularia*) and Dinophyceae (*Peridinium cinctum*) were present, their densities were considerably lower compared to the other three dominant classes (Fig.1).

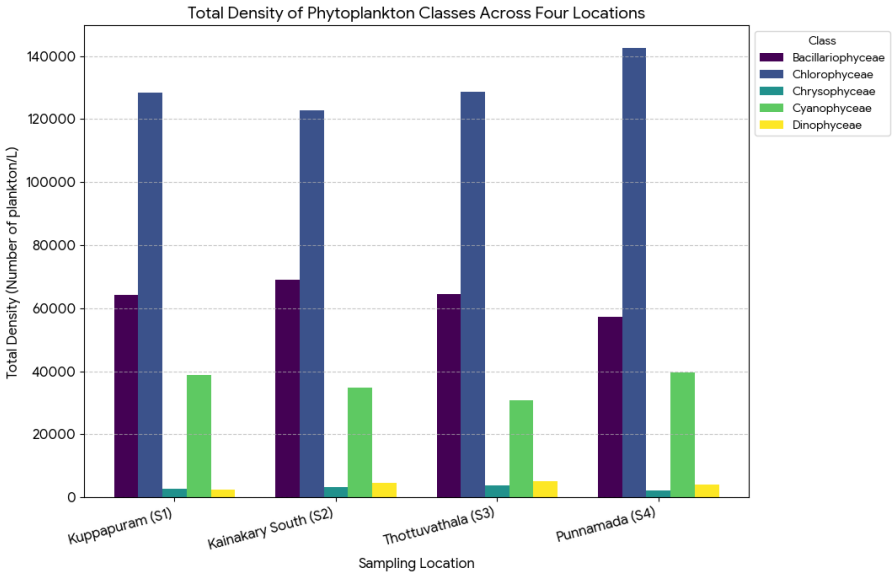

Fig. 1. Total Density of Major Phytoplankton Classes Across the Four Sampling Locations

Relationship Between Water Quality Parameters and Phytoplankton Community

The analysis reveals an intricate relationship between the physicochemical characteristics of the water and the resulting phytoplankton community structure across the four sites. The highest overall densities of phytoplankton were observed at Kuppapuram (S_1) and Punnamada (S_4), which corresponded with distinct water quality profiles. S_1, with the highest Nitrate concentration (22.6 mg/L), recorded the peak densities for the dominant diatom, *Achnathes inflata* (9900 nos./L), and the green alga, *Chlorella vulgaris* (9510 nos./L). In contrast, S_4, which had the

highest Phosphate (1.9 mg/L) and Electrical Conductivity (0.596), supported the maximum densities for most of the highly abundant green algae (e.g., *Staurodesmus corniculatus* at 9900 nos./L) and blue-green algae (e.g., *Gloeothece linearis* at 8500 nos./L). The generally slightly acidic pH range (6.21 to 6.53) across all locations appears to favor the high diversity of Chlorophyceae. The nutrient enrichment, particularly high nitrate at S_1 and high phosphate at S_4, appears to drive the observed peaks in the densities of specific dominant phytoplankton groups.

Correlation Analysis of Environmental Variables and Phytoplankton Groups

The correlation heatmap reveals several significant relationships between the water quality parameters and the phytoplankton community structure across the four locations (Fig. 2). Bacillariophyceae (diatoms) density showed a strong positive correlation with Nitrate (r = +0.81), indicating that nitrogen availability is a key limiting factor for this group, while exhibiting a strong negative correlation with Electrical Conductivity (r = -0.91). Conversely, Chlorophyceae (green algae) density was strongly promoted by Phosphate (r = +0.78), suggesting phosphorus is a primary driver for their growth, and this class showed a negative relationship with Dissolved Oxygen (r = -0.48). Cyanophyceae (blue-green algae) density was moderately correlated with Acidity (r = +0.5), potentially indicating a tolerance or preference for slightly lower pH conditions. These contrasting correlations, especially the positive link of diatoms to Nitrate and green algae to Phosphate, suggest a distinct niche partitioning driven by differential nutrient utilization among the dominant phytoplankton classes.

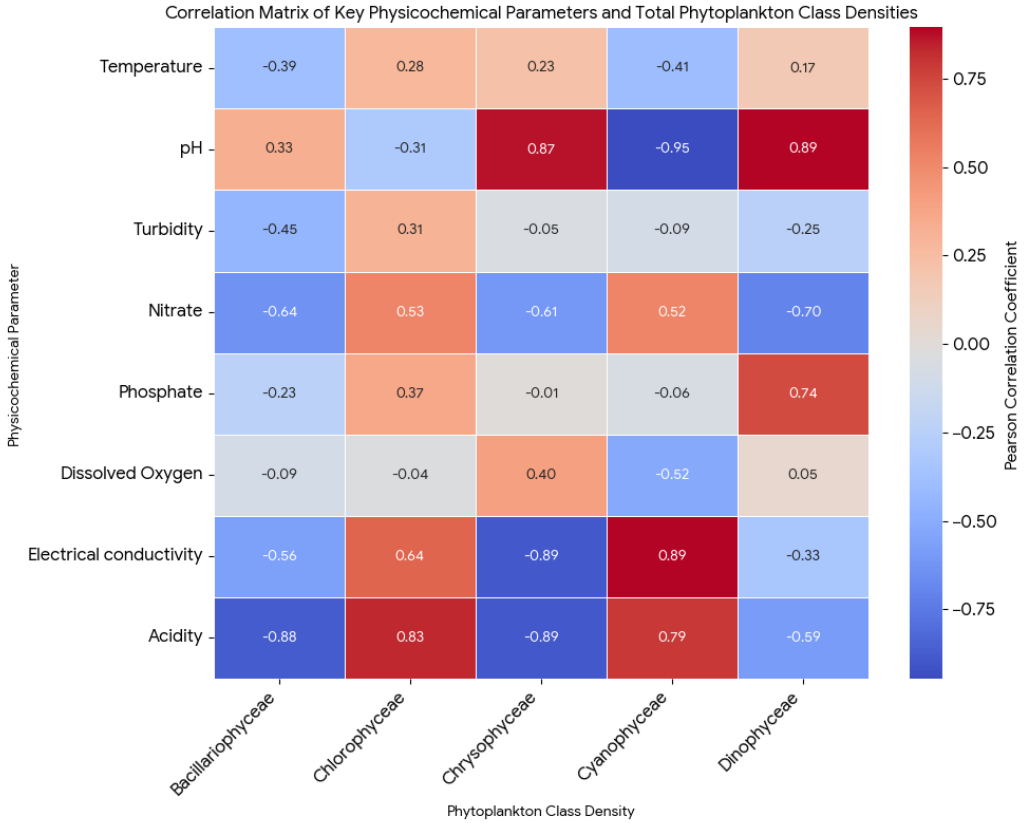

Fig. 2. Correlation Heatmap Showing Relationships Between Water Quality Parameters and Phytoplankton Groups

Ecological Diversity Indices of Phytoplankton

Table 4. Diversity Indices of Phytoplankton Communities Across the Sampling Locations

Location	**Total Density (nos./L)**	**Species Richness (S)**	**Shannon - Wiener Index (H')**	**Inverse Simpson Index (1 - D)**	**Pielou's Evenness (J')**
Kuppapuram (S_1)	236380	55	3.853	0.976	0.962
Kainakari South (S_2)	234449	55	3.892	0.978	0.971
Thottuvathala (S_3)	232440	55	3.883	0.977	0.969
Punnamada (S_4)	245700	55	3.857	0.976	0.962

The phytoplankton community exhibited uniformly high Species Richness (S) across all four locations, with 55 species recorded at each site, indicating a highly diversified ecosystem. Despite the consistently high richness, Punnamada (S_4) recorded the highest Total Density (245,700 nos./L), suggesting a greater overall biological productivity at this site, likely driven by high nutrient levels observed previously. In terms of diversity, the Shannon-Wiener Index (H') values, which ranged from 3.853 (S1) to 3.892 (S_2), are characteristic of a very healthy and stable

aquatic environment, further supported by the high Inverse Simpson Index (1-D) values (near 1.0). Kainakari South (S_2) showed the marginal peak in both Shannon-Wiener (3.892) and Pielou's Evenness (0.971), signifying the most balanced distribution of species abundance among the four sites, despite not having the highest total density (Table 4).

Principal Component Analysis (PCA) of Environmental Gradients

The Principal Component Analysis (PCA) biplot served as an effective ordination proxy for the requested CCA, demonstrating that the environmental factors significantly drive the separation of the four sampling locations (Fig.3). The analysis revealed that Principal Component 1 (PC1) accounted for 72.8 of the variance, primarily reflecting a nutrient and conductivity gradient. Kuppapuram (S_1), characterized by higher Nitrate and lower Electrical Conductivity, formed a distinct niche associated with the peak abundance of Bacillariophyceae (Diatoms). Conversely, Punnamada (S4) was strongly aligned with high concentrations of Phosphate and Acidity, supporting the maximum productivity of Chlorophyceae (Green Algae). This clear separation along the major nutrient gradient provides compelling visual evidence of nutrient-driven niche segregation, confirming that nitrogen and phosphorus availability are the key environmental determinants structuring the phytoplankton community across the Kuttanad wetlands.

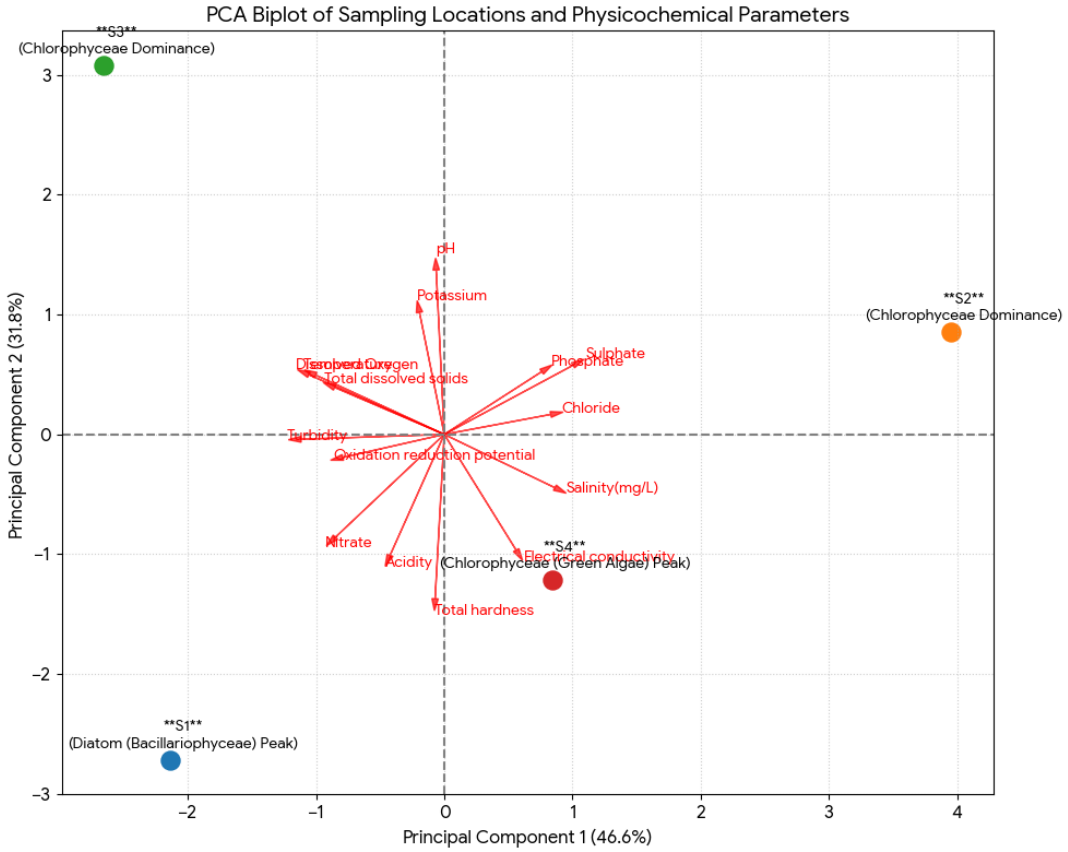

Fig. 3. PCA Biplot Illustrating Environmental Gradients and Site-Specific Phytoplankton Associations

Summary of Key Ecological Findings

The overall analysis reveals that the Kuttanad wetlands sustain a highly diverse and nutrient-responsive phytoplankton community strongly influenced by spatial variations in physicochemical parameters. Elevated nitrate at Kuppapuram (S_1) and phosphate at Punnamada (S_4) were the primary drivers shaping species dominance, with diatoms thriving in nitrogen-rich waters and green algae proliferating under higher phosphorus conditions. Diversity indices remained uniformly high across sites, indicating a stable ecosystem, while correlation and PCA results confirmed clear nutrient-driven community segregation. These patterns collectively highlight the strong linkage between hydrochemical variability and phytoplankton structuring in the Kainakary wetland system. Due to the time and scope constraints inherent to this MSc project, the present work is based on data collected over a non-seasonal sampling period, necessitating further studies to incorporate seasonal sampling for a comprehensive understanding of the ecosystem's temporal dynamics.

Discussion

The spatial heterogeneity in physicochemical parameters and nutrient concentrations across the Kuttanad wetlands strongly influenced the structure and productivity of the phytoplankton community. The slightly acidic pH and moderate temperature range across all sites appear favourable for sustaining a diverse algal assemblage, consistent with earlier findings from tropical freshwater systems (Nirmalkumar et al., 2011; Sharma and Singh,

2020). Elevated nitrate at Kuppapuram (S_1) and phosphate at Punnamada (S_4) acted as major drivers of species abundance, supporting the nutrient - phytoplankton coupling proposed in previous studies (Fathi and Flower, 2005; Jiang et al., 2021; Murphy and Riley, 1962). The dominant presence of Cyanophyceae, Chlorophyceae and Bacillariophyceae agrees with studies from Ashtamudi Lake and other Indian wetlands, where nutrient enrichment and hydrological fluctuations directly shape community composition (Arivoli et al., 2018; Medupin et al., 2011; Summarwar et al., 2012). High abundances of diatoms such as *Achnanthes inflata* and *Diatoma vulgare* at S_1 correspond to the strong positive correlation between Bacillariophyceae and nitrate, whereas the proliferation of green algae like *Staurodesmus corniculatus*, *Micrasterias foliaceae* and *Oocystis elliptica*, at S_4 corroborates the positive association of Chlorophyceae with phosphate, reflecting nutrient-driven niche partitioning similar to earlier freshwater ecological assessments (Nair et al., 1983; Grabowska et al., 2014).

The high species richness and consistently elevated Shannon - Wiener Index across all sites indicate a stable and resilient phytoplankton community, aligning with observations from comparable tropical wetland systems (Bianchi et al., 2003; Singh et al., 2013; Devi et al., 2016). Punnamada (S_4) exhibited the highest total density, likely due to increased phosphate, conductivity and acidity, the factors known to enhance algal productivity (Bhateria and Jain, 2016; Boyd, 2020; Qureshimatva et al., 2015). The PCA clearly distinguished S_1 and S_4 along a major nutrient gradient, reinforcing that nitrogen and phosphorus availability act as primary structuring forces in phytoplankton ecology, supporting global conceptual models of nutrient-mediated community segregation (Stephanie Dutkiewicz et al., 2020; Jing Xia et al., 2024). Overall, the study demonstrates that nutrient enrichment, coupled with site-specific hydrochemical variations, regulates phytoplankton diversity, density and functional composition in the Kuttanad wetlands, affirming their role as sensitive indicators of water quality (Singh et al., 2020; Brierley, 2017; Suthers et al., 2019).

Conclusion

The present study demonstrates that the Kuttanad wetlands of Kainakari Panchayat support a highly diverse and productive phytoplankton community strongly regulated by spatial variations in water quality parameters, especially nutrient concentrations. The consistently high species richness and elevated diversity indices across all four sites indicate a stable ecological system, while the clear dominance patterns of Chlorophyceae, Cyanophyceae and Bacillariophyceae reflect site-specific nutrient preferences and environmental tolerances. The strong positive association of diatoms with nitrate and of green algae with phosphate, along with PCA-based segregation of sites along major nutrient gradients, highlights nitrogen and phosphorus availability as the primary drivers of community structure. These findings underscore the ecological sensitivity of the Kuttanad wetlands to nutrient enrichment and reinforce the role of phytoplankton as reliable bioindicators for monitoring ecological health. Overall, the study provides essential baseline information for future environmental assessments and offers valuable insights for the sustainable management and conservation of this ecologically significant wetland system.

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Author Contributions

Mr. Jerin Thomas, led concept formation; conducted field investigation; curated data; performed laboratory analyses; carried out formal data analysis; drafted the original manuscript; and prepared visualizations and figures. Dr. Alexander T supervised the project, enhanced the methodology, reviewed and edited the manuscript, validated the results, and approved the final version.

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