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Diversity Studies and Seasonal Variation of Phytoplanktons in Freshwater Lakes of Davanagere, Karnataka

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Abstract

The seasonal variation and diversity of phytoplankton communities in two freshwater lakes namely, Kunduvada Lake and Hadadi Lake located in Davanagere district of Karnataka was investigated during winter and summer seasons of 2024-2025. Water samples were collected from the littoral zone of four sites (K1, K2, H3 & H4) across both lakes during winter and summer seasons with a difference of five months. Microscopic observations of phytoplanktons revealed a seasonal succession characterised by diatom dominance (Bacillariophyceae) in winter and increased abundance of green algae (Chlorophyceae) and cyanobacteria (Cyanophyceae) in summer season. Diversity studies representing, Shannon-Wiener (*H*) and Simpson (1-D) indices indicated higher species richness and diversity during summer, reflecting favourable environmental conditions such as elevated temperature and nutrient availability. Beta diversity analyses demonstrated significant spatial and seasonal species turnover, with greater compositional heterogeneity observed in summer. The observed phytoplankton dynamics correspond to environmental factors such as temperature, pH (6.5), and nutrient inputs influenced by local hydrology and land use. The dominance of diatoms suggests mesotrophic to oligotrophic conditions and a relatively balanced ecological state. These findings highlight the critical role of seasonal processes in structuring phytoplankton communities and underscore the utility of phytoplankton diversity as an indicator of freshwater lake ecosystem health. The study provides baseline data for monitoring and managing freshwater resources in the semi-arid region of Karnataka, emphasising the need for continued assessment of phytoplankton dynamics in relation to environmental variability and anthropogenic pressures.

Keywords: Planktonic algae, Lakes, Seasons, Diversity indices, Species richness.

Introduction

Phytoplanktons, is a term used to denote the ecological group of unicellular or colonial photosynthetic organisms adapted to live freely or suspended in water [1], 49% of the global net primary production (≈108 Pg C year^{-1}) and of atmospheric oxygen are derived from the photosynthetic activity of phytoplankton [2]. Phytoplankton's provide a fundamental supporting service to the biosphere: nutrient (re-)cycling and redistribution. Phytoplankton interacts with microbes in the biosphere that influence the global cycling of micro and macronutrients [3]. Phytoplankton diversity reflects the interplay between environmental forcing and biological interactions within aquatic systems. Factors such as light availability, temperature, nutrient concentrations, hydrological regime, and grazing pressure strongly influence phytoplankton composition, abundance, and succession [4, 5]. Functional and taxonomic diversity of phytoplankton has been shown to enhance ecosystem stability and productivity, while shifts toward low-diversity assemblages may indicate ecological stress or eutrophication [6]. Understanding phytoplankton diversity and its seasonal variation is pivotal to aquatic ecology, as these patterns serve as sensitive indicators of environmental change and ecosystem health. Long-term and seasonal assessments of phytoplankton communities provide valuable insights into the effects of climate variability, anthropogenic nutrient enrichment, and altered hydrological regimes on aquatic ecosystems [7].

Kundavada Lake (length ~0.93 km^2) and Hadadi Lake (length ~4.28 km) are two freshwater rain-fed, shallow lentic ecosystems in the Davanagere district of Karnataka, India. Kundavada Lake, located within the urban periphery of Davanagere city, and Hadadi Lake situated near Hadadi village, contributes to primary production, nutrient cycling, and local livelihoods through water supply, fisheries, and habitat provisioning. Both lakes are increasingly influenced by agricultural runoff, domestic effluents, and seasonal hydrological fluctuations, which can strongly influence aquatic community structure. Phytoplankton responds sensitively to such changes and are widely used as indicators of ecosystem health and trophic dynamics. However, comparative baseline information on phytoplankton diversity and seasonal succession in these lakes is limited, particularly with respect to hydrological seasonality and environmental drivers in an aquatic ecological context. This knowledge gap limits effective assessment of trophic status and ecosystem functioning. In India, phytoplankton diversity and seasonal variation in freshwater lakes has been studied [8, 9]. However, despite numerous studies on phytoplankton dynamics in freshwater ecosystems, information on seasonal variation in phytoplankton composition in the present study area remains limited. Therefore, this study investigates the seasonal variation in phytoplankton diversity and composition of algal communities in Kundavada and Hadadi lakes within an aquatic ecological framework.

Materials and methods

Study Site

The study was conducted in two freshwater lakes in Davanagere, Karnataka. Kunduvada Lake, also known as Kunduvada Kere (14.4425° N, 75.9111° E) is at an elevation of 602 m above sea level and is a prominent freshwater lake located in the central semi-arid dry agro-climatic belt of Davanagere (Fig. 1). Geographically positioned near National Highway-4, the lake spans approximately 250 acres and serves as a crucial ecological and socio-economic resource. It receives inflow primarily from the Tungabhadra canal and functions as a significant source of irrigation in the region. The region experiences hot summers with mean annual temperatures ranging from approximately 20º to 33ºC and average annual rainfall of 640-680mm, most of which occurs between June and September. Ecologically, Kunduvada Lake is rich in biodiversity and supports a variety of aquatic flora and fauna.

Hadadi Lake exhibits similar tropical inland climate conditions with annual precipitation of 530-540mm and generally warm temperatures, with average pre-monsoon highs exceeding 35ºC and high relative humidity during the peak monsoon period. This lake lies approximately 7 kilometres southeast of Davanagere city (Fig. 2). Geographically, the lake is located at 14°26'57"N and 75°58'12"E, with an average elevation of around 602 meters above mean sea level. The lake is a natural lentic water body whose surface area and depth vary seasonally, primarily receiving water from local runoff and groundwater inputs. The surrounding landscape is characterised by agricultural and rural land use, which influences nutrient and sediment inputs into the lake.

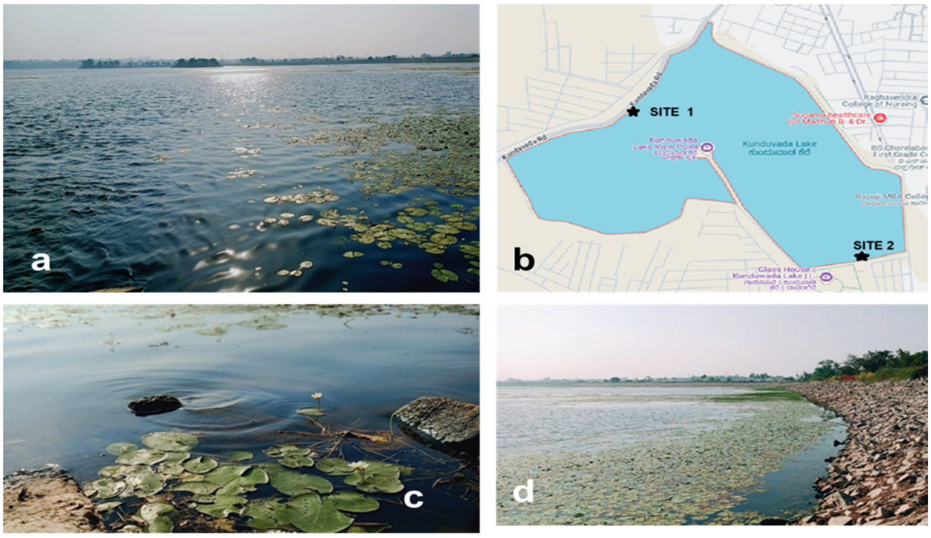

Figure 1. Kunduvada lake situated in Davanagere city; a. View; b. Google location; c. Site 1; d. Site 2.

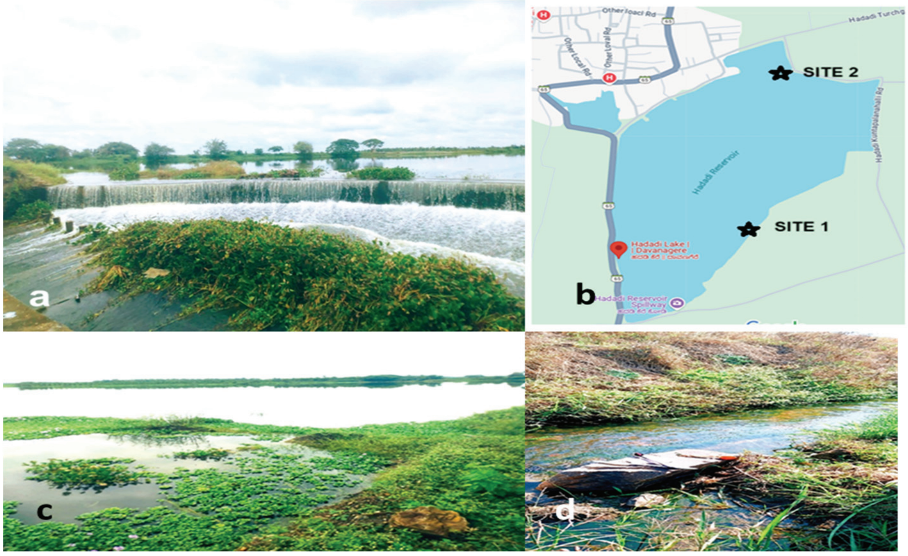

Figure 2. Hadadi lake situated at the outskirts of Davanagere city.; a. View; b. Google location; c. Site 1; d. Site 2.

Collection of samples and preservation

Sampling was carried out from both lakes, selecting two sites from each lake, i.e., from Kunduvada Lake – Site K1, Site K2 (Fig. 1c & 1d) and from Hadadi Lake – Site H3, Site H4 (Fig. 2c & 2d) to analyse phytoplankton seasonal diversity, assessment of algal biodiversity indices and water quality during the winter and summer seasons (December 2024 – April 2025). The samples were drawn in the mornings between 9 am to 10 am. Sampling was conducted in Kunduvada Lake and Hadadi Lake at four predetermined sites representing distinct ecological zones of the two lakes, namely the inlet and outlet. Littoral surface water samples were collected and transferred into well-labelled 500ml plastic bottles (Fig. 3). The sample bottles were cleaned with distilled water before collecting the sample. The samples were preserved immediately with formaldehyde solution (4%, v/v) and Lugol's Iodine to prevent cellular degradation and microbial decomposition. The preservatives were added in sufficient quantity to ensure long-term storage and viability of algal morphology for microscopic analysis.

Figure 3. Lake water samples collected and preserved in sample bottles

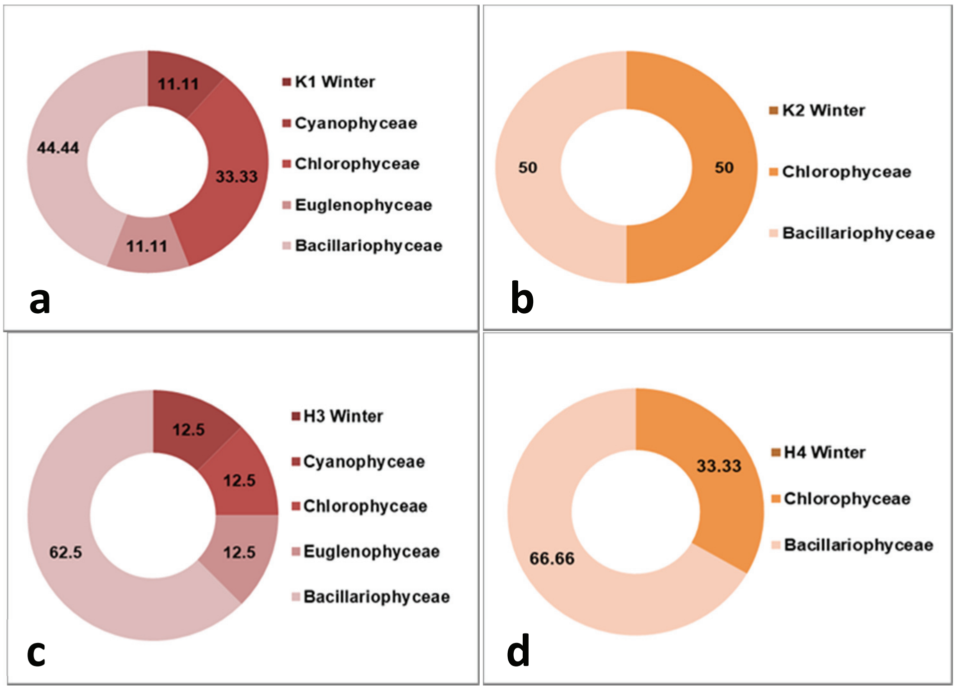

Figure 4a. Pie chart representing the occurrence of algal classes in the four sites of lake samples during the winter season

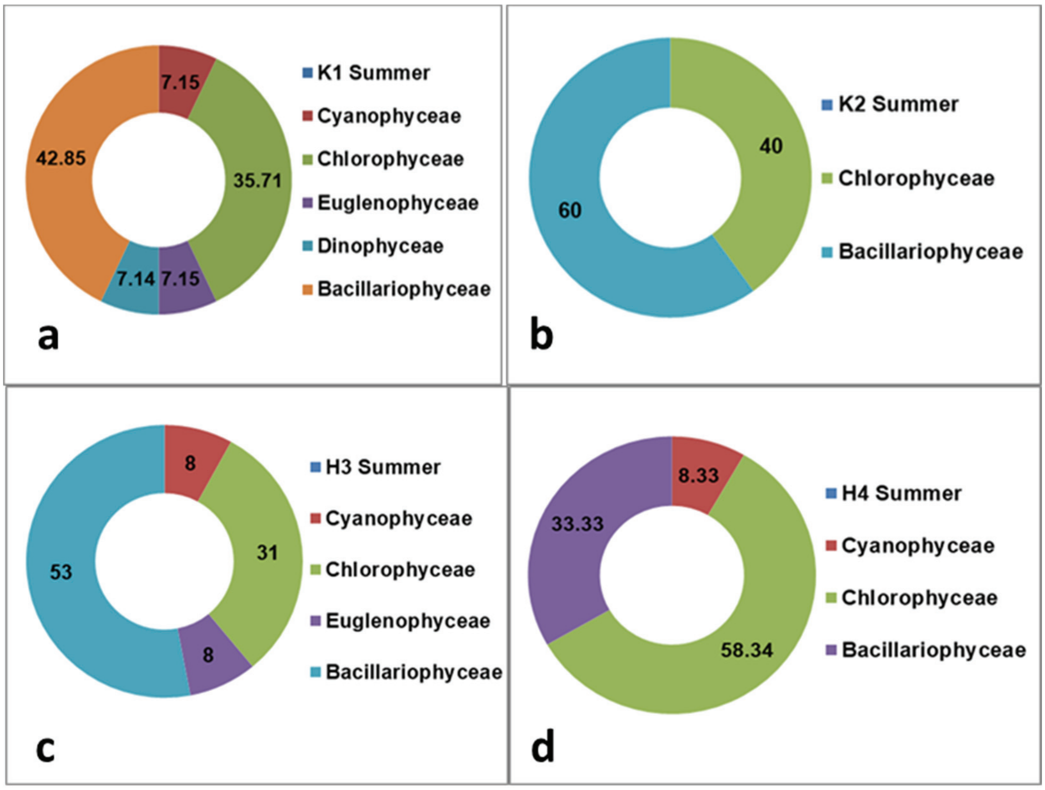

Figure 4a. Pie chart representing the occurrence of algal classes in the four sites of lake samples during the summer season

Observation and identification of algal phytoplankton

The water samples from four sites (K1, K2, H3 & H4) of two lakes were immediately processed for microscopic observation and identification. Three drops of thoroughly mixed solution were taken on a clean glass slide (Blue Star®, 75X25mm) with a coverslip placed over the solution and placed on the stage of Light microscope (OPTIcx, Labomed). The slide was observed for the presence of phytoplanktonic algae at 4X, 10X, and 40X magnifications, photographed and documented. The algal forms were identified according to the identification guide [10].

Assessment of algal diversity and community structure in two seasons

The algal diversity of two lakes was assessed by tabulating the presence/absence of particular algal species in four sites of two lakes during two seasons (winter and summer). The presence or absence of a species was indicated as ‘1’ and ‘0’ respectively. The data was analysed by PAleontological STatistics (PAST statistical) software version 4.035. Freshwater phytoplankton community structure was assessed using standard diversity indices. Species diversity was calculated using Shannon-Wiener index (H’), while dominance was evaluated using Simpson’s index (1-D) [11, 12]. Species richness was estimated using Margalef’s and Menhinick’s indices [13, 14]. Evenness of species distribution was determined using Pielou’s evenness index (J) [15]. Dominance of individual taxa was further examined using the Berger–Parker dominance index [16]. Phytoplankton diversity was quantified at multiple spatial scales following Whittaker’s framework [17, 18]. Alpha diversity (α-diversity), representing local phytoplankton diversity, was calculated for each sampling site using species richness and the Shannon–Wiener diversity index. Gamma diversity (γ-diversity) was defined as the total phytoplankton species richness recorded across all sampling sites within the study area. Beta diversity (β-diversity), which reflects spatial turnover in species composition among sites, was estimated as the ratio of gamma to mean alpha diversity (β = γ/α□).

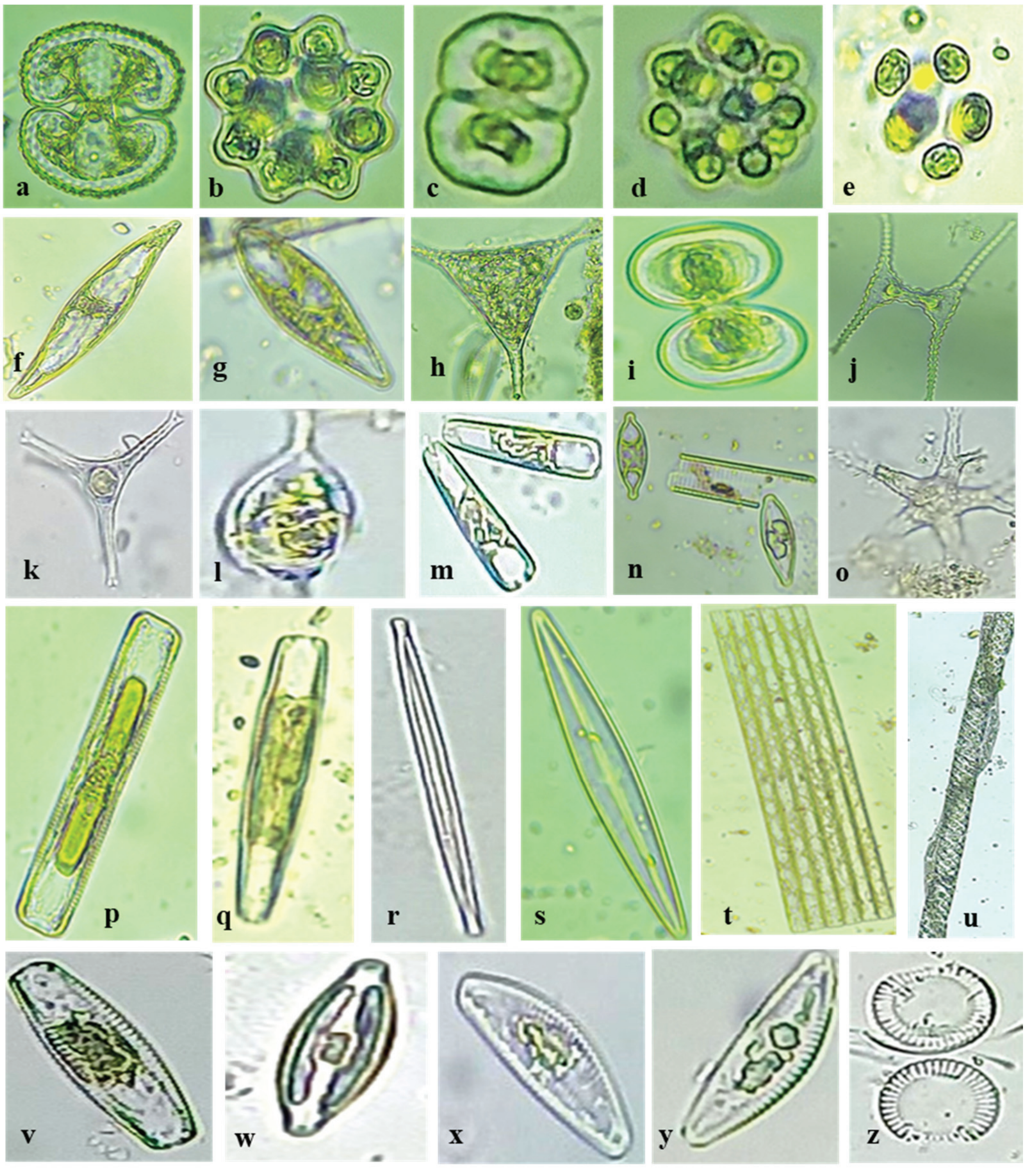

Figure 5. Microphotographs of algae observed in water samples from Kunduvada and Hadadi lakes during winter**.**

a) *Cosmarium tetraphthalmum* Bréb. ex Ralfs. b) *Coelastrum proboscideum* Bohlin. c) *Cosmarium difficile* Lütkm. d) *Coelastrum cambricum* W. Archer. e) *Oocystis* Nägeli ex A.Braun. f) *Pleurosigma* W.Smith. g) *Euglena viridis* Ehrenb. h) *Tetraedon* Kütz. i) *Cosmarium contractum* Kirchn. j) *Staurastrum* sp. Ehrenb. k) *Staurastrum gracile* Ralfs l) *Phacus* Duj. m) *Gomphonema* C. Ag. n) *Gomphonema parvulum* Kütz. o) *Staurastrum spongiosum* Bréb. ex Ralfs. p) *Pinnularia* Ehr. q) *Gomphonema* spp. r) *Synedra acus* (Kütz.)Ehrenb. s) *Frustulia rhomboides* (Ehr.)Ral. t) *Fragilaria* Lyngb. u) *Spirogyra* Link. v) *Rhizosphenia abbreviata* (Kütz) Grunow. w) *Navicula salinarum* Cleve. x) *Cymbopleura inequalis* (Krasske) Krammer. y) *Cymbella* C. Agardh. z) *Cyclotella* Kütz.

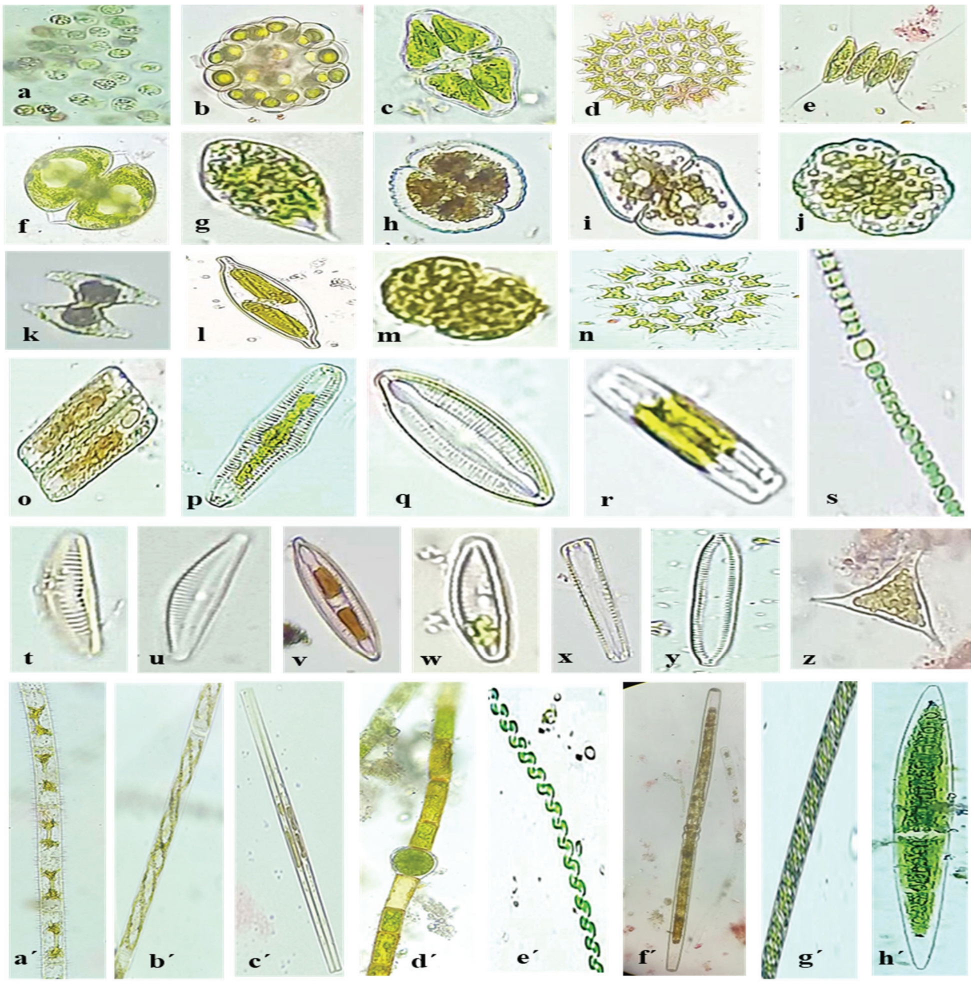

Figure 6. Microphotographs of algae observed in Kunduvada and Hadadi lakes during summer.

a) *Microcystis* Kütz. b) *Coelastrum sphaericum* Nägeli. c) *Euastrum* Ehrenb. d) *Pediastrum* Meyen. e) *Scenedesmus* Meyen. f) *Cosmarium connatum* Bréb. g) *Phacus* Duj. h) *Cosmarium tetrapthalmum* Bréb. ex Ralfs. i) *Euastrum ansatum* Ehrenb. j) *Cosmarium abbreviatum* Bréb. k) *Stauastrum bicorne* W. Sm. l) *Navicula* Bory de St. Vincent sp. m) *Gymnodinium* Stein. n) *Pediastrum* Meyen sp. o) *Diatoma vulgaris* Bory. p) *Pinnularia biceps* Ehrenb. q) *Cocconeis* Ehrenb. sp. r) *Achnanthes coarctata var. parallela* (Grunow.) Hustedt s) *Dolichospermum planctonium* (Gomont.) Wacklin, L. Hoffmann & Komarek. t) *Encyonema minutum* (Hilse) D.G. Mann. u) *Cymbella tumida* (Bréb.) W. Sm. v) *Navicula* spp. w) *Craticula cuspidata* (Kütz.) D.G. Mann x) *Denticula subtilis* Kütz. y) *Nitzschia dissipata* (Kütz.)W. Sm. *z) Tetraedron* Ehrenb. *a´) Zygnema* C. Agardh b´) *Spirogyra* sp. Link. c´) *Synedra ulna* (Nitzsch) Ehrenb. d´) *Oedogonium* Link. e´) *Spirulina* Turpin. f´) *Scytonema crispnum* C. Ag. g´) *Spirogyra* sp. h´) *Closterium acerosum* Ehrenberg.

Results

In the current investigation, the diversity of algae, such as phytoplanktons, was studied by sampling lake water in two seasons from ‘Kunduvada’ and ‘Hadadi’ lakes of Davanagere, Karnataka. The samples were collected from lakes, which is source of water for Site 1, Site 2 (Kunduvada lake) and Site 3, Site 4 (Hadadi lake) respectively. Phytoplankton identification across the studied freshwater lakes revealed the presence of four major algal classes belonging to Bacillariophyceae, Chlorophyceae, Cyanophyceae, and Euglenophyceae, with marked spatial and seasonal variations.

Seasonal composition of algal taxa

During winter season, Bacillariophyceae was the dominant group at all sites with K1 and K2 representing 44.45% and 50% respectively, while greater dominance of 62.5% and 66% was recorded in H3 and H4 sites (Fig. 4a). Common diatom genera included *Fragilaria, Frustulia, Cyclotella, Cymbella, Gomphonema, Navicula, Pinnularia,* and *Synedra*. Chlorophyceae showed moderate representation of 33.33% to 50% in K1 and K2 sites followed by low and moderate representation of 12.5% and 33.3% in H3 and H4 sites. Chlorophycean genera included *Coelastrum, Cosmarium, Oocystis, Spirogyra, Staurastrum,* and *Tetraedron*. Euglenophyceae (*Euglena, Phacus*) and Cyanophyceae (*Oscillatoria, Microcystis*) occurred in lower abundance (Fig. 4b). In the summer season, a shift in phytoplankton composition was observed, particularly at Kunduvada Lake sites K1 and K2, where Chlorophyceae (35.7% and 44%) and Bacillariophyceae (42.8% and 60%) increased in dominance. Chlorophycean taxa such as *Pediastrum, Coelastrum, Closterium* sp., *Spirogyra* sp., *Zygnema* sp., *Scenedesmus, Sphaerocystis* and *Cosmarium* were abundant, along with bloom-forming cyanobacteria (*Microcystis*). Diatoms persisted but showed reduced dominance compared to winter. The genera identified are *Navicula, Gomphonema, Diatoma, Pinnularia, Cocconeis, Achnanthes, Cymbella, Denticula* and *Nitzschia* (Fig. 6). Overall, the phytoplankton community exhibited a clear seasonal succession, characterised by diatom dominance during winter and increased abundance of green algae and cyanobacteria during summer.

Assessment of algal diversity indices during winter and summer seasons

Simpson and Shannon alpha biodiversity indices were used to measure the distribution and richness of the algal during two seasons, in the lake water sites. The analysis showed relative differences among the four sampling sites (Table 1). In the winter season, the Shannon diversity (*H*) indices for the four sites of two lakes showed a maximum diversity index (*H*max) for Kunduvada Lake (Site 2) sample (*H*max = 2.197) and a lower value for Hadadi Lake (Site 3), i.e. (*H*max = 1.079) respectively (Table 2). In the Simpson 1-D values of the summer season, at Site 1 showed the highest value (0.9231) and the other three sites showed values of 0.9, 0.9121 and 0.9167. In the winter season, the Site 2 showed the highest value (0.8889), and the other three sites showed values of 0.857, 0.875 and 0.8333, respectively. Shannon index (*H*) values were moderate than three indices of Simpson (1-D), Evenness and Dominance (D), indicating higher diversity and good water quality. The Site 2 (Kunduvada Lake) and Site 3 (Hadadi Lake) during the summer season showed alpha diversity indices, particularly the Shannon index (*H*), as the highest value of the index (2.565), and the other two sites showed 2.303 and 2.485, respectively (Table 2).

The species richness curves for phytoplanktons exhibited clear seasonal and spatial variations across the four sampling sites. During winter and summer seasons, the expected number of species ($E_{(s)}$) increased progressively with increase in algal taxa at all sites, indicating consistent species accumulation and adequate sampling effort. In the winter season (Fig. 7), Site 4 recorded the highest species richness, followed by Site 2, Site 1, and Site 3, which showed lowest richness. The winter richness curves approached asymptotic levels at relatively lower taxon numbers, suggesting stable phytoplankton assemblages under cooler seasonal conditions. In contrast, during summer season, overall species richness was comparatively higher in Site 3 exhibiting highest richness, followed by Site 4. Site 1 showed moderate richness, whereas Site 2 consistently recorded the lowest species richness. The summer species accumulation curves displayed steeper slopes and higher asymptotic values, reflecting enhanced phytoplankton diversity and greater species turnover under warm-season conditions. Comparatively, summer season richness curves were more elevated than those of winter at all sites (Fig. 8), indicating a seasonal increase in phytoplankton diversity. The observed seasonal shift in dominant richness patterns highlights the influence of temperature, nutrient dynamics, and hydrological conditions on phytoplankton community structure in the aquatic ecosystem.

Table 1. Algal diversity indices of lake water samples collected in winter and summer seasons of 2024-2025.

	Winter season				**Summer season**			
	Alpha Diversity Indices				**Alpha Diversity Indices**			
	Kunduvada lake		**Hadadi lake**		**Kunduvada lake**		**Hadadi lake**	
Indices	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Taxa_S	8	9	8	6	13	10	13	12
Individuals	8	9	8	6	13	10	13	12
Dominance_D	0.125	0.1111	0.123	0.1667	0.07692	0.1	0.082	0.08333
Simpson_1-D	0.875	0.8889	0.857	0.8333	0.9231	0.9	0.9121	0.9167
Shannon_H	2.079	2.197	1.079	1.792	2.565	2.303	2.565	2.485
Evenness_e^H/S	1	1	1	1	1	1	1	1
Brillouin	1.326	1.422	1.026	1.097	1.735	1.51	1.735	1.666
Menhinick	2.828	3	2.528	2.449	3.606	3.162	3.606	3.464
Margalef	3.366	3.641	3.376	2.791	4.678	3.909	4.678	4.427
Equitability_J	1	1	1	1	1	1	1	1
Fisher_alpha	0	0	0	0	0	0	0	0
Berger-Parker	0.125	0.1111	0.135	0.1667	0.07692	0.1	0.07692	0.08333
Chao-1	36	45	36	21	91	55	91	78

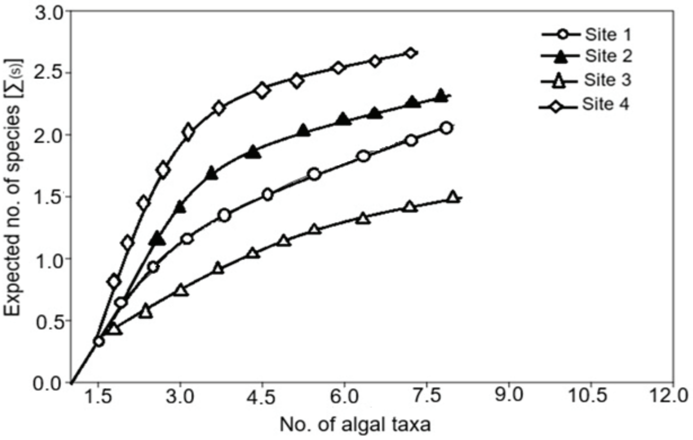

Figure 7. Rarefaction species richness curve of algal phytoplankton in the winter season.

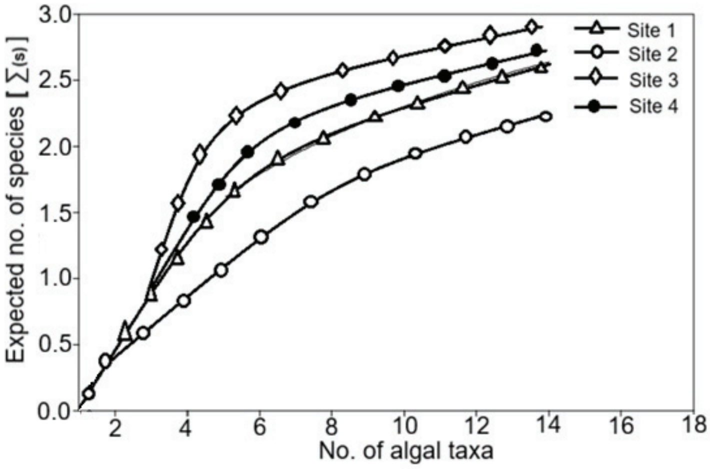

Figure 8. Rarefaction species richness curve of algal phytoplankton in the summer season.

During the winter season, global beta diversity indices revealed clear spatial variation in phytoplankton community composition among the sampled freshwater lakes (Table. 2). Whittaker's beta diversity value was 3.0, while the Wilson–Shmida index showed a comparable value (3.0968), indicating substantial species turnover between sites. Cody's index exhibited a markedly high value (24), reflecting pronounced species replacement across locations. In contrast, Routledge (0.5976), Harrison (1.0), Harrison 2 (0.8148), Mourelle (1.0323), and Williams (0.7097) indices displayed relatively lower values, suggesting moderate levels of compositional dissimilarity during winter.

During the summer season, global beta diversity indices indicated pronounced spatial variation in phytoplankton community composition among the studied freshwater lakes (Table 2). Whittaker's beta diversity remained at 3.0, while the Wilson–Shmida index was slightly lower (2.9583), suggesting continued species turnover across sites. Cody's index showed a high value (35.5), indicating increased species replacement during summer compared to winter. Routledge (0.5997), Harrison (1.0), Harrison 2 (0.8974), Mourelle (0.9861), and Williams (0.7292) indices displayed moderate values, reflecting intermediate levels of compositional dissimilarity among sites in summer.

Table 2. Beta diversity indices of lake samples in two seasons

Global Beta Diversity Indices		
Season:	**Winter**	**Summer**
Whittaker	3.0	3.0
Harrison	1.0	1.0
Cody	24	35.5
Routledge	0.5976	0.59973
Wilson-Shmida	3.0968	2.9583
Mourelle	1.0323	0.98611
Harrison 2	0.81481	0.89744
Williams	0.70968	0.72917

Discussion

Seasonal variation is a key driver of phytoplankton dynamics in aquatic ecosystems. Seasonal changes in irradiance, water temperature, mixing patterns, and nutrient inputs regulate phytoplankton growth and succession, often resulting in predictable temporal patterns in community structure [19]. In temperate systems, phytoplankton succession is commonly characterised by spring diatom blooms, followed by summer dominance of flagellates or cyanobacteria, and reduced biomass during winter [5]. In tropical and subtropical ecosystems, seasonal variability is frequently governed by monsoonal rainfall, hydrological fluctuations, and nutrient loading rather than temperature alone [20]. The present study shows pronounced seasonal variation in phytoplankton community structure, diversity, and spatial turnover in Kunduvada and Hadadi lakes, reflecting ecological responses to changes in environmental conditions such as temperature, water quality, and nutrient gradients. Similar seasonal patterns have been documented in recent freshwater and coastal systems, demonstrating that phytoplankton communities are sensitive indicators of limnological change [21]. Among phytoplankton species significant variability exist in their growing rates [1]. As an example, green algae and diatoms can grow much faster than toxin-producing cyanobacteria under adequate light and nutrient conditions [22].

During winter sampling, diatom taxa (Bacillariophyceae) were prevalent, consistent with other recent freshwater studies showing diatoms dominate under cooler, well-mixed conditions conducive to efficient nutrient uptake. Similar patterns of diatom prevalence under stable environmental regimes have been reported in reservoirs and freshwater lakes in India, where diatom diversity peaked under favourable physico-chemical conditions [23]. In contrast, summer assemblages in this study showed increased proportions of chlorophytes and cyanobacteria, highlighting a shift in community structure under warmer conditions and possibly stratified water columns. Such seasonal transitions toward Chlorophyceae and Cyanophyceae during warmer periods are consistent with dynamics observed in recent phytoplankton studies across tropical and subtropical systems, where environmental drivers like higher temperature, light availability, and nutrient fluctuations shape community composition. For example, high-salinity lakes in northwest China showed dominance of both diatoms and cyanobacteria driven by water temperature and salinity gradients [24].

The dominance of Bacillariophyceae in the phytoplankton community of the studied freshwater lakes reflects their ecological adaptability and efficiency in utilising available resources. Diatoms such as *Fragilaria, Cymbella*, and *Synedra* were recorded in high abundance, suggesting favourable environmental conditions, particularly sufficient silica concentrations and moderate nutrient availability. Their siliceous frustules confer buoyancy control and protection from grazers, enhancing their survival and persistence in the planktonic phase [25]. Seasonal stratification and mixing events may further influence diatom proliferation by suspending benthic nutrients into the photic zone, thereby enhancing growth [1]. The presence of Bacillariophyceae as a dominant group indicated a mesotrophic to oligotrophic status in this study, aligning with previous studies that emphasise their prevalence in relatively unpolluted freshwater systems [26]. Their role in primary production is crucial, as they contribute significantly to biogeochemical cycling and form the foundational trophic level for higher aquatic organisms [27]. This pattern resonates with broader evidence that phytoplankton succession is tightly linked to seasonal drivers—with diatoms often dominating under mixing and cooler periods and opportunistic chlorophytes and cyanobacteria increasing with warming and nutrient shifts. Similar seasonal fluctuation patterns were also reported in tropical-mountain lakes, underscoring how climate and local limnological conditions jointly influence phytoplankton dynamics [28].

In our study, the Shannon index (*H*) value was higher, which is less than three and the Simpson index (1-D) value was less than one. The abundance of algal species belonging to four classes was recorded in all four sites. These indices illustrate the structural and functional aspects of phytoplankton communities in the studied freshwater ecosystem. The observed diversity pattern reflects a balanced ecological state with seasonal variability and anthropogenic influence. These indices show species richness and evenness and also serve as reliable indicators of ecosystem health. Higher Shannon diversity and species richness observed in summer suggest that niche heterogeneity increases under warmer seasonal regimes, allowing a broader array of taxa to coexist. In principle, Shannon's *H* takes into account the proportion of each species in an ecosystem studied; hence, it gives a better description of an ecosystem's diversity than a plain number of species. When the number of species is equal in two locations, the index is capable of distinguishing between sites dominated by a single or only a few predominant species and those where each species has comparable input to the whole biodiversity [13]. Recent investigations of phytoplankton biodiversity have shown that environmental heterogeneity and multiple interacting drivers, such as temperature, nutrient availability, and water quality, can enhance species richness and evenness, particularly in transitional seasons or under more variable habitat conditions [23].

However, the increased representation of opportunistic taxa such as cyanobacteria in richness metrics may signal potential early responses to nutrient enrichment or ecosystem stress, a trend highlighted in recent studies examining functional and beta diversity loss associated with eutrophication gradients in tropical aquatic environments [29].

Beta diversity in this study indicated substantial species turnover among sites, with slightly higher values in summer. Such patterns point to spatial environmental heterogeneity driven by localised differences in habitat conditions, nutrients, and water movement, which shape phytoplankton assemblages. Observations from recent work in coastal and inland lakes show that environmental gradients in multi-site systems contribute significantly to species turnover and compositional differentiation, particularly in seasonally dynamic conditions [30]. Seasonal shifts toward variable chlorophyte and cyanobacterial assemblages may influence food web dynamics, water quality, and ecosystem resilience, echoing broader concerns in recent freshwater ecology research about how seasonal change and anthropogenic pressures shape aquatic biodiversity. Consequently, studies addressing phytoplankton diversity and seasonal dynamics contribute to improved ecosystem monitoring, management, and conservation strategies in aquatic environments.

Conclusions

The present study demonstrates clear spatial and seasonal variation in phytoplankton community composition across freshwater lakes, as reflected by multiple global beta diversity indices. Substantial species turnover was evident among sampling sites in both winter and summer, with consistently high Whittaker and Wilson–Shimida values. The marked increase in Cody's index during summer indicates enhanced species replacement relative to winter, highlighting the influence of seasonal dynamics on community heterogeneity. The combined use of different beta diversity indices indicates a robust assessment of phytoplankton compositional variation, underscoring the importance of seasonality in structuring freshwater phytoplankton assemblages.

Conflicts of interest

The authors declare that no conflict of interest exists in the present study.

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