

Phytoplankton diversity of a de-mineralized subtropical reservoir of Meghalaya state, northeast India

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ABSTRACT

This study monitors the spatio-temporal variations of phytoplankton of a soft-water and de-mineralized reservoir of Meghalaya state of northeast India. Phytoplankton assemblages of the littoral and limnetic regions reveal total 36 species and diverse desmids, and contribute dominantly to net plankton abundance. Our results record the quantitative importance of Charophyta > Bacillariophyta > Dinophyta and Charophyta > Dinophyta, and the 'specialist' nature of 11 and six species at the littoral and limnetic regions, respectively. *Staurostrum* spp. and *Cosmarium* spp. are notable taxa. Phytoplankton indicates moderate species diversity and depicts dominance and evenness variations. The individual abiotic factors exert differential influence on various taxa at the two regions and the canonical correspondence analysis registers 73.02 and 71.14% cumulative influence of 10 abiotic factors on the littoral and limnetic assemblages, respectively. The spatial differences of phytoplankton composition, richness, abundance, important groups and taxa, specialist species, diversity indices and the influence of individual abiotic factors are hypothesised to habitat heterogeneity amongst the sampled regions. This study records notable temporal differences of phytoplankton richness, abundance, diversity and the role of abiotic factors vis-a-vis the limited survey of November 1990–October 1991.

Keywords: Low conductivity, Primary producers, Spatio-temporal variations, Very soft-water

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Introduction

Phytoplankton deserves importance as notable contributors to primary production and integral components of aquatic food webs in inland waters. Although these primary producers have been studied from the diverse aquatic environs since the inception of the Indian limnology, a large fraction of works from this country yet represent 'routine' ecology reports because of incomplete species lists and inadequate data-analysis (Sharma and Sharma, 2021). This generalization holds valid for phytoplankton assemblages of lakes and reservoirs of India and north India in particular. The studies from the Himalayan and sub-Himalayan regions of northwest India with variable extents of useful information are from the states of Jammu and Kashmir (Zutshi and Wanganeo, 1984; Wanganeo and Wanganeo, 1991; Baba and Pandit, 2014; Ganai and Parveen, 2014), Himachal Pradesh (Thakur *et al.*, 2013; Jindal *et al.*, 2014a, 2014b; Gupta *et al.*, 2018) and Uttarakhand (Sharma and Singh, 2018; Sharma and Tiwari, 2018). Referring to northeast India (NEI), the noteworthy studies (Sharma, 2004, 2009, 2010, 2012, 2015; Sharma and Hatimuria (2017) are limited to the floodplain lakes (*beels* and *pats*) of the states of Assam and Manipur. The detailed studies on phytoplankton diversity of the sub-tropical lacustrine environs of NEI in particular are, however, limited to the works of Sharma and Pachau (2016), Sharma and Sharma (2021) from the reservoirs of Mizoram and Meghalaya states, respectively.

The present study aims at monitoring the spatio-temporal variations of phytoplankton vis-à-vis abiotic factors of a de-mineralized subtropical reservoir of Meghalaya state of NEI. The littoral and limnetic net plankton are analyzed with reference to species composition, richness, community similarities, abundance, dominant groups, important taxa, notable species, species diversity, dominance and evenness, and the individual and cumulative influence of abiotic factors on phytoplankton assemblages. The results are discussed in comparison with those from the tropical and subtropical lacustrine environs of India, and the floodplain lakes and reservoirs of NEI. Remarks are made on the spatio-temporal variations of phytoplankton diversity based on our results from the littoral and limnetic regions as well as on the temporal variations vs. our earlier preliminary survey (Sharma, 1995) undertaken at the limnetic region.

Material and Methods

The present study is based on January-December 2014 limnological survey of a small rainwater-fed reservoir (Figure 1, A-C; Latitude 25°34'N; Longitude 91°56'E, area ~10 ha; max. depth: 15m) located at a distance of about 10 km from Shillong city, the capital of Meghalaya state (referred as 'Shillong reservoir'). This warm monomictic reservoir (Sharma, 1995) serves as drinking water storage basin and lacks any aquatic vegetation and fish fauna. It is surrounded by forest cover predominated by *Plnus kesiya* with *Cassia* sp., *Cinnamomum gladuliferum*, *Rhus javanica* and *Mochilers khasyana*.

Water and the qualitative and quantitative net plankton samples were collected at monthly interval from the littoral and the limnetic regions (Figure 1C). Water temperature was noted using a centigrade thermometer and transparency was noted with a Secchi disc. pH and specific conductivity were noted with the field probes, dissolved oxygen (DO) was estimated by Winkler's method, and other abiotic factors: free carbon dioxide (CO₂), alkalinity, hardness, calcium (Ca), magnesium (Mg), chloride (Cl), dissolved organic matter (DOM), phosphate (PO₄), nitrate (NO₃) and sulphate (SO₄) were analyzed following APHA (1992). The rainfall data was collected from the local meteorological station. The qualitative net plankton samples were collected by towing nylobolt plankton net (#40 µm) and preserved in 5% formalin. All samples were screened with a Wild Stereoscopic binocular microscope; phytoplankton was observed with Leica stereoscopic microscope (DM 1000) and were identified following Islam and Haroon (1980), Fritter and Manuel (1986), Anand (1998) and John *et al.* (2002). The community similarities were calculated vide Sørensen index and the hierarchical cluster analysis was done using SPSS (version 20). The monthly quantitative samples were obtained by filtering 25 L of water each through nylobolt plankton net (#40 µm) and were preserved in 5% formalin. The quantitative enumeration of phytoplankton was done by using a Sedgewick-Rafter counting cell and abundance was expressed as ind. L⁻¹. Species diversity, dominance and evenness were computed vide Shannon-Weiner index, Berger-Parker index and E₁ index, respectively following Ludwig and Reynolds (1988). Two-way analysis of variance (ANOVA) was used to ascertain significance of variations of abiotic and biotic parameters between the sampled regions and months. Pearson correlation

coefficients for the littoral and limnetic regions (r_1 and r_2 , respectively) were calculated between abiotic and biotic parameters; p values (2-tailed) were calculated and their significance was ascertained after applying Bonferroni corrections. The canonical correspondence analysis (XLSTAT 2015) was

done to observe cumulative influence of 10 abiotic parameters namely water temperature, rainfall, transparency, specific conductivity, DO, alkalinity, hardness, Cl, DOM and PO_4 on phytoplankton assemblages.

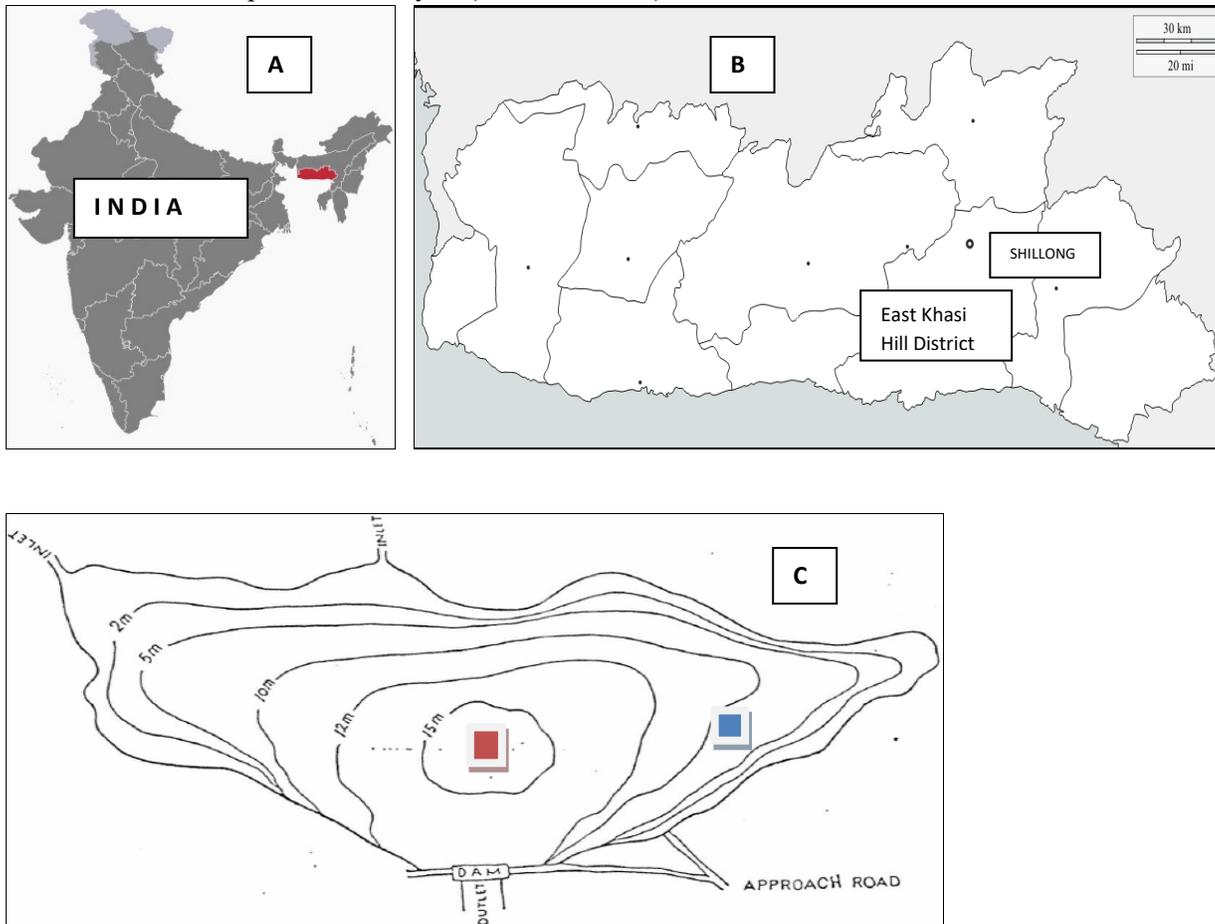


Figure 1(A-C). A, map of India showing Meghalaya state of northeast India (red color); B, map of Meghalaya indicating location of the capital city of Shillong; C, map of Shillong reservoir indicating the littoral (blue color) and limnetic (red color) regions

Results and Discussion

Our results highlight ‘very soft, acidic, highly de-mineralized and distinctly calcium poor’ nature of Shillong reservoir with oxygenated waters, low free CO_2 and nutrients, and Cl indicates the limited human impact (Table 1). We report one of the lowest specific conductivity known till date from aquatic environs of the Indian sub-continent (Hickel, 1973; Sharma and Bhattacharai, 2005; Sharma and Sharma, 2021). This notable feature is attributed to predominant effects of abundant rainfall in NEI coupled with the weathered and leached nature of rocks and soils of the catchment area and to the lowered buffering capacity of the de-mineralized waters (Sharma, 1995)

of this rain-water fed reservoir. ANOVA registers significant variations of transparency, DO, Ca, Cl and SO_4 between the regions and months, while all abiotic factors register significant monthly variations (Table 2). This study records decrease in transparency and PO_4 , and the relative increase in specific conductivity, alkalinity, hardness and Cl (Table 1) than the earlier survey (Sharma, 1995).

Total 36 species (Table 3) noted vide our study depict distinctly diverse phytoplankton than the earlier report of 16 species (Sharma, 1995), and the relatively diverse nature than the reports from lacustrine systems of Himachal Pradesh (Jindal and Thakur, 2014; Gupta *et al.*, 2018,) and Uttarakhand (Negi

and Rajput, 2015), and Meghalaya (Sharma and Lyngskor 2003), and the kingdom of Bhutan (Sharma and Bhattarai 2005). The richness broadly concurs with the reports from Assam (Devi *et al.*, 2016), Himachal Pradesh (Jindal *et al.*, 2014a), Tripura (Bharati *et al.*, 2020), Meghalaya (Sharma and Lyngdoh, 2003) and Uttarakhand (Goswami *et al.*, 2018) but is lower than known from Himachal Pradesh (Jindal *et al.*, 2013, 2014b), Meghalaya (Sharma and Sharma, 2021) and Mizoram (Sharma and Pachuau, 2016). The comparisons

highlight fairly species-rich phytoplankton assemblage of 'very soft and highly de-mineralized' waters' of the sampled reservoir in particular. Charophyta, the speciose group, records higher richness than known vide the earlier survey (Sharma, 1995), and the reports from the floodplain lakes of NEI (Sharma, 2009, 2010, 2012, 2015; Devi *et al.*, 2016) and the lakes of Kashmir (Baba and Pandit, 2014) and Uttarakhand (Negi and Rajput, 2015; Goswami *et al.*, 2018; Sharma and Singh, 2018; Sharma and Tiwari, 2018).

Table 1. Variations of abiotic factors

Factors	Present study				Nov.1990-Oct.91	
	Littoral region		Limnetic region		Limnetic region	
	Range	Average \pm S.D	Range	Average \pm S.D	Range	Average \pm S.D
Water temperature °C	11.0-21.0	17.1 \pm 3.5	11.0-20.5	16.8 \pm 3.3	12.0-21.5	17.7 \pm 3.6
Rainfall mm	0.6-780.5	211.6 \pm 223.7	0.6-780.5	211.6 \pm 223.7	1.0-652.0	196 \pm 206
Transparency m	1.6-2.2	1.88 \pm 0.16	1.6-2.2	1.93 \pm 0.16	2.0-3.25	2.55 \pm 0.35
pH	5.65-6.67	6.21 \pm 0.22	5.64-6.55	6.16 \pm 0.26	5.5-6.6	6.1 \pm 0.4
Sp. conductivity μ Scm ⁻¹	11.5-19.2	15.8 \pm 2.5	12.0-19.0	15.8 \pm 2.2	6.0-12.0	8.2 \pm 1.8
DO mg L ⁻¹	7.0-8.6	7.8 \pm 0.4	7.2-8.8	7.9 \pm 0.4	6.7-10.2	8.3 \pm 0.8
Free CO ₂ mg L ⁻¹	4.8-9.2	7.2 \pm 1.5	4.0-9.0	6.7 \pm 1.4	4.0-9.3	6.5 \pm 1.3
Alkalinity mg L ⁻¹	9.0-16.8	11.8 \pm 2.3	9.2-16.4	11.7 \pm 2.1	5.6-11.8	8.5 \pm 1.8
Hardness mg L ⁻¹	6.2-13.2	8.6 \pm 2.2	6.0-13.0	8.7 \pm 2.2	4.0-12.2	7.5 \pm 4.3
Ca mg L ⁻¹	3.8-7.6	5.3 \pm 1.2	3.6-7.0	5.0 \pm 1.3	1.6-9.5	4.7 \pm 2.5
Mg mg L ⁻¹	0.2-0.9	0.2 \pm 0.3	0.2-0.8	0.4 \pm 0.2	0.2-1.1	0.6 \pm 0.5
Cl mg L ⁻¹	19.0-42.0	30.4 \pm 6.7	18.0-40.0	29.4 \pm 6.4	4.0-8.8	5.5 \pm 1.2
PO ₄ mg L ⁻¹	0.072-0.190	0.128 \pm 0.035	0.080-0.190	0.128 \pm 0.031	0.100-0.280	0.150 \pm 0.050
SO ₄ mg L ⁻¹	1.642-2.905	2.253 \pm 0.447	1.640-2.810	2.202 \pm 0.423	1.000-3.500	2.200 \pm 0.700
NO ₃ mg L ⁻¹	0.066-0.196	0.108 \pm 0.040	0.070-0.188	0.110 \pm 0.036	0.010-0.040	0.023 \pm 0.010
DOM mg L ⁻¹	0.4-3.0	1.3 \pm 0.9	0.5-3.0	1.5 \pm 0.9	-	

Table 2. ANOVA indicating significance of abiotic factors

Parameters	Regions	Months
Water temperature	-	F _{11,23} =244.629, P < 0.0001
Transparency	F _{1,23} = 17.742, P = 0.001	F _{11,23} = 9.069, P = 0.0003
pH	-	F _{11,23} = 196.986, P < 0.0001
Specific conductivity	-	F _{11,23} = 66.715, P < 0.0001
DO	F _{1,23} = 10.632, P=0.007	F _{11,23} = 30.779, P < 0.0001
Free CO ₂	-	F _{11,23} = 6.372, P = 0.0024
Alkalinity	-	F _{11,23} = 129.223, P < 0.0001
Hardness	-	F _{11,23} = 342.936, P < 0.0001
Ca	F _{1,23} = 27.770, P=0.0002	F _{11,23} = 78.814, P < 0.0001
Mg	-	F _{11,23} = 17.551, P < 0.0001
Cl	F _{1,23} = 15.531, P=0.002	F _{11,23} = 220.202, P < 0.0001
PO ₄	-	F _{11,23} = 157.459, P < 0.0001
SO ₄	F _{1,23} = 8.302, P=0.015	F _{11,23} = 219.202, P < 0.0001
NO ₃	-	F _{11,23} = 195.429, P < 0.0001
DOM	-	F _{11,23} = 189.7048, P < 0.0001

(-) insignificant variations

The soft, calcium-poor and de-mineralized waters are known for high desmid richness (Woelkerling and Gough, 1976; Payne, 1986). This generalization is affirmed by the rich desmid diversity noted vide our study which include five species each of *Staurastrum* and *Cosmarium*, and one species each of *Arthrodesmus*, *Closterium*, *Euastrum*, *Micrasterias*, *Netrium* and *Sirogonium*. Our results concur with the richness importance of *Staurastrum* = *Cosmarium* observed from a reservoir of Meghalaya (Sharma and Sharma, 2021). This trend, however, differs from the importance of *Staurastrum* (Sharma, 1995), and high richness of *Closterium* > *Cosmarium* > *Staurastrum* > *Micrasterias* > *Gonatozygon* (Sharma, 2009), *Closterium* > *Cosmarium* > *Micrasterias* > *Gonatozygon* (Sharma, 2010), *Staurastrum* > *Cosmarium* > *Micrasterias* (Sharma and Pachau, 2016), and *Cosmarium* > *Staurastrum* > *Euastrum* (Sharma and Hatimuria, 2017) known from various aquatic environs of NEI.

Our study records higher phytoplankton monthly richness at the littoral than the limnetic region (Table 3). The differential variation, hypothesized to greater habitat heterogeneity of the former region, is affirmed by significant richness variations (Table 4) between the regions (vide ANOVA). Phytoplankton contribute to net plankton richness at the two regions ($r_1=0.746$, $p=0.013$; $r_2=0.735$, $p=0.015$). Peak richness is recorded during winter (January) and maxima during autumn-

winter (November-December) at the littoral region, and the limnetic region indicates peak in May (Figure 2). The winter peak at the former region concurs with the reports Manipur (Sharma, 2010), Meghalaya (Sharma and Sharma, 2021) and Assam (Devi *et al.*, 2016), while the peak richness at the limnetic region corresponds with the summer peaks vide Sharma (2004, 2012, 2015). A notable constellation of 30 phytoplankton species during January collection from the littoral region depicts the possibility of co-existence of a number of species in this small and relatively shallow reservoir due to high amount of niche overlap as hypothesized by MacArthur (1965). Charophyta (Table 3) contribute to phytoplankton richness ($r_1=0.688$, $p=0.028$; $r_2=0.910$, $p=0.0003$) at the two regions. Phytoplankton register 66.7-92.0% and 54.0-91.7% community similarities at the littoral and limnetic regions (Table 3), respectively and thus indicate the relatively more heterogeneity at the latter region. This generalization is endorsed by the similarity values ranging between 71-90% in ~89% instances at the littoral region as against ~77% instances with similarities ranging between 61-80% at the limnetic region. The hierarchical cluster groupings (Figures 3-4) record peak affinity between February-November and April-May collections, while July > September > June communities record maximum species divergence at the littoral region. The limnetic phytoplankton, however, indicate peak affinity between April-May and maximum divergence during July.

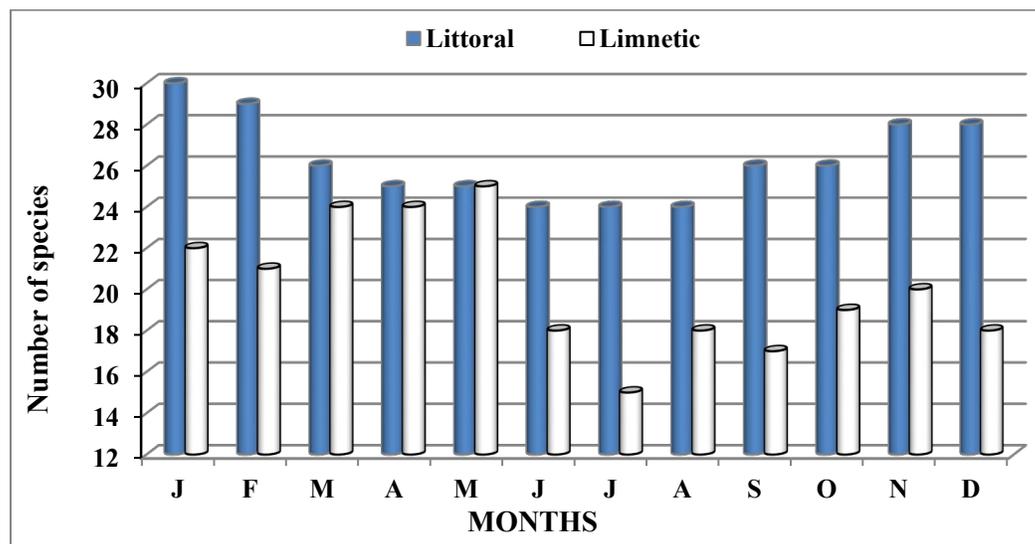


Figure 2. Monthly variations of phytoplankton richness

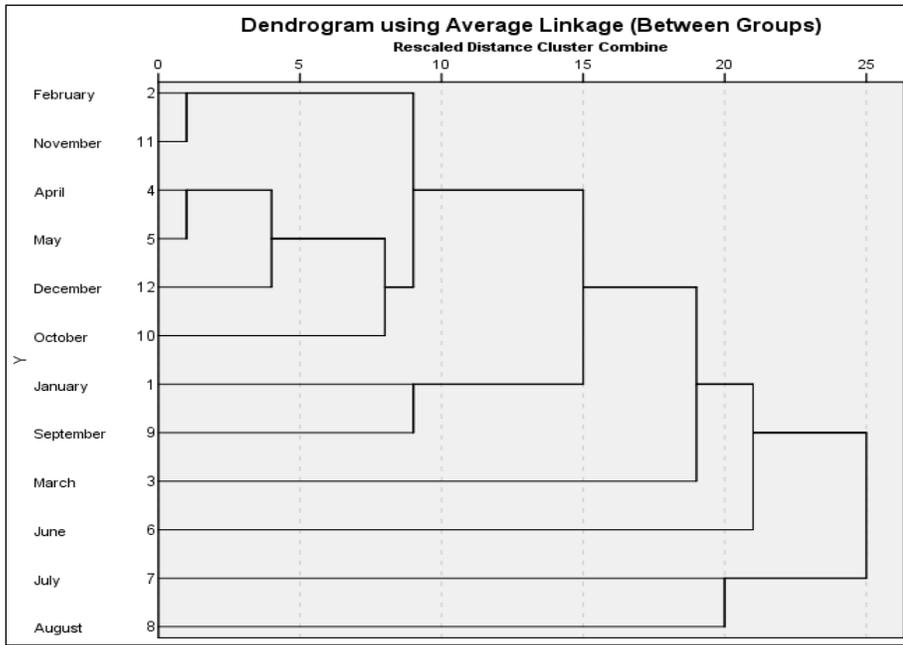


Figure 3. Hierarchical cluster analysis of phytoplankton assemblages (Littoral region)

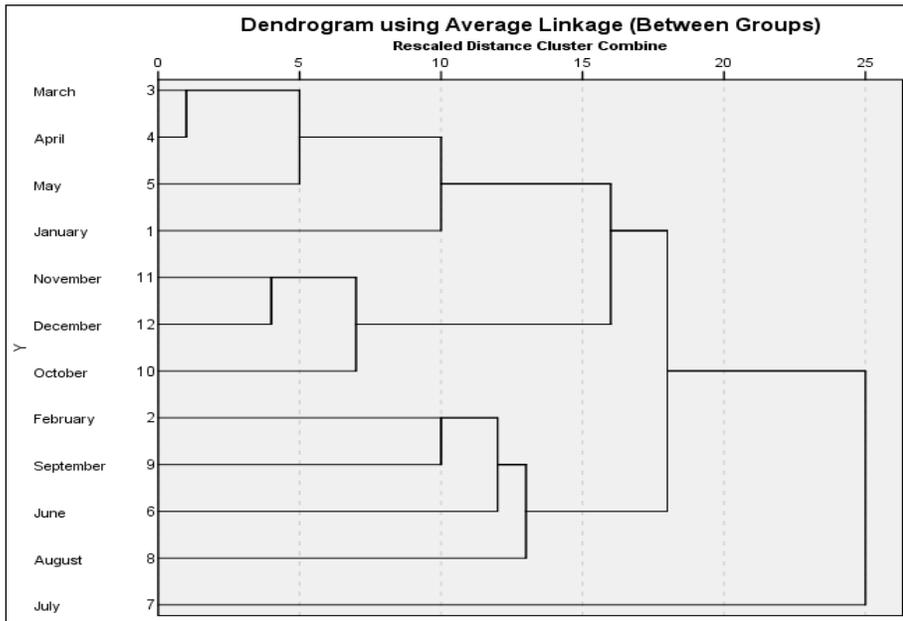


Figure 4. Hierarchical cluster analysis of phytoplankton assemblages (Limnetic region)

Table 3. Richness, abundance and diversity indices of phytoplankton assemblages

Qualitative	Present study				Nov.1990-Oct.91	
	Littoral region		Limnetic region		Limnetic region	
Net Plankton	72 species		67 species		28 species	
Phytoplankton	36 species		30 species		16 species	
Monthly richness	24-30	26 ± 2	15-25	20 ± 3	3-14	8±3
Community similarity %	66.7-92.0		54.0-91.7		-	
Charophyta	19 species		16 species		9 species	
Monthly richness	11-15	14 ± 1	7-13	11 ± 2	-	
Quantitative						
Net plankton (ind. L ⁻¹)	189-1089	551 ±239	158-430	285±87	13-400	109±104
Phytoplankton (ind. L ⁻¹)	95-887	429 ±230	74-364	216±93	7-318	98±100
Percentage	44.8-90.0	73.7 ±14.4	46.8-86.9	73.0±12.4	53.9-95.8	
Species Diversity	2.061-2.767	2.443 ±0.238	1.885-2.654	2.279±0.236	0.959-1.787	1.330±0.477
Dominance	0.156 - 0.408	0.285 ±0.099	0.187-0.464	0.278±0.093	0.265-0.883	0.542±0.212
Evenness	0.618 - 0.871	0.745 ±0.088	0.658 - 0.859	0.765±0.056	0.177-0.917	0.537±0.477
Charophyta (ind. L ⁻¹)	30-636	174 ±191	49-219	100±50	2-275	51±79
Percentage	11.8-71.7	37.4 ±16.6	46.8-86.9	47.1±11.4	2.4-85.1	
Bacillariophyta (ind. L ⁻¹)	29-312	140 ±50	8-66	34±20	1-8	2±2
Percentage	11.7-58.1	35.6 ±14.8	6.4-23.6	15.0±5.3	-	
Dinophyta (ind. L ⁻¹)	11-299	105 ±90	12-130	72±34	4-102	42±39
Percentage	10.1-39.7	24.7 ±11.6	13.3-52.3	32.8±12.8	8.5-96.0	
Chrysophyta (ind. L ⁻¹)	0-38	8 ±2	0-47	9±13	2-8	1±2
Cryptophyta (ind. L ⁻¹)	0-3	2±0	0-3	2±1	-	
Cyanobacteria (ind. L ⁻¹)	0-2	1±0	0-2	2±0	1-9	2±2
Euglenophyta (ind. L ⁻¹)	0-3	2±0	0-3	1±0	-	
Important taxa (ind. L⁻¹)						
<i>Staurastrum</i> spp.	14-570	135±150	31-204	73±45	0-90	20±28
<i>Cosmarium</i> spp.	4-38	19 ±12	2-54	15±17	-	
Important species (ind. L⁻¹)						
<i>Peridinium cinctum</i>	6-270	66±80	13-95	42±27	0-42	13±15
<i>Staurastrum freemani</i>	2-301	63±83	5-130	31±32	0-90	20±28
<i>Staurastrum arctiscon</i>	2-201	49±53	5-32	16±8	0-80	12±23
<i>Navicula radiosa</i>	6-242	61±68	2-51	21±15	-	
<i>Ceratium hirudinella</i>	5-91	38±25	2-100	30±26	2-120	29±38
<i>Tabellaria flocculosa</i>	5-60	24±18	2-18	9±5	-	
<i>Staurastrum gutwinckii</i>	2-41	17±11	8-43	24±11	0-100	16±30
<i>Cosmarium decoratum</i>	0-21	10±7	0-11	4±4	-	
<i>Pinnularia viridis</i>	0-46	12±16	0-1	1±1	-	
<i>Frustulia rhomboides</i>	2-27	11±7	0-7	2±2	-	
<i>Caloneis bacillum</i>	0-40	10±12	0-1	1±1	-	

Table 4. ANOVA indicating significance of phytoplankton assemblages

Parameters	Regions	Months
Phytoplankton richness	$F_{1,23} = 40.590, P < 0.0001$	-
Charophyta richness	$F_{1,23} = 24.267, P = 0.0004$	-
Phytoplankton abundance	$F_{1,23} = 19.260, P = 0.001$	$F_{11,23} = 3.811, P = 0.018$
Charophyta abundance	-	-
Bacillariophyta abundance	$F_{1,23} = 30.107, P = 0.0003$	-
Dinophyta abundance	-	$F_{11,23} = 5.731, P = 0.0367$
Chrysophyta abundance	-	$F_{11,23} = 5.099, P < 0.0001$
Species diversity	$F_{1,23} = 4.163, P = 0.066$	$F_{11,23} = 9.024, P = 0.0005$
Abundance of Important taxa and species		
<i>Staurastrum</i> spp.	-	$F_{11,23} = 2.934, P = 0.043$
<i>Cosmarium</i> spp.	-	-
<i>Ceratium hirudinella</i>	-	$F_{11,23} = 11.092, P = 0.0002$
<i>Cosmarium decoratum</i>	$F_{1,23} = 10.329, P = 0.008$	-
<i>Navicula radiosa</i>	$F_{1,23} = 5.638, P = 0.036$	-
<i>Peridinium cinctum</i>	-	$F_{11,23} = 3.019, P = 0.040$
<i>Staurastrum freemani</i>	-	$F_{11,23} = 4.422, P = 0.010$
<i>Staurastrum arctiscon</i>	$F_{1,23} = 5.085, P = 0.045$	-
<i>Staurastrum gutwinckii</i>	$F_{1,23} = 7.727, P = 0.018$	$F_{11,23} = 6.563, P = 0.002$
<i>Tabellaria flocculosa</i>	$F_{1,23} = 10.277, P = 0.008$	-
<i>Caloneis bacillum</i>	$F_{1,23} = 7.176, P = 0.021$	-
<i>Frustulia rhomboides</i>	$F_{1,23} = 20.502, P = 0.001$	-
<i>Pinnularia viridis</i>	$F_{1,23} = 6.538, P = 0.027$	-

(-) insignificant variations

Phytoplankton comprise dominant quantitative component and significantly influence net plankton abundance ($r_1 = 0.978, p < 0.0001$; $r_2 = 0.982, p < 0.0001$) at the littoral and limnetic regions (Table 3), and register significant density variations (Table 4) between the two regions (vide ANOVA). Phytoplankton dominance concurs with the reports from Assam (Sharma and Hatimuria, 2017), Himachal Pradesh (Jindal and Thakur, 2014), Meghalaya (Sharma, 1995; Sharma and Lyngdoh, 2003) and Mizoram (Sharma and Pachuau, 2016). The wider density variations and higher abundance (Table 3) at the littoral than the limnetic region are hypothesized to greater habitat heterogeneity of the former region. Our results depict three- and two-fold higher abundance at the two regions, respectively than the earlier survey (Sharma, 1995). This study records bimodal monthly phytoplankton density variations at the two regions (Figures 5-6) concurrent with the reports of Baba and Pandit (2014), Goswami *et al.* (2018) and (Sharma and Sharma, 2021). The peak abundance noted during October and winter maxima at the

two regions deviate from the mid-monsoon peak (Sharma and Bhattarai, 2005) and from the autumn peaks reported from Kashmir (Baba and Pandit, 2014), Meghalaya (Sharma and Sharma, 2020), Mizoram (Sharma and Pachuau, 2016) and Uttarakhand (Sharma and Singh, 2018). The winter maxima concur with the results of Wanganeo and Wanganeo (1991), Sharma (1995, 2004, 2009, 2010), Sharma and Lyngdoh (2003), Sharma and Hatimuria (2017), Goswami *et al.* (2018), Sharma and Tiwari (2018) and Sharma and Sharma (2021). Phytoplankton indicate the differential spatial quantitative importance of Charophyta > Bacillariophyta > Dinophyta and Charophyta > Dinophyta at the littoral and limnetic, respectively (Table 3). Charophyta result in late-monsoon phytoplankton peak, Bacillariophyta > Charophyta contribute to winter maxima and Charophyta > Dinophyta result in high abundance during November-December at the littoral region (Figure 5). Charophyta > Dinophyta influence late-monsoon peak and Charophyta influence winter maxima at the limnetic region (Figure 6).

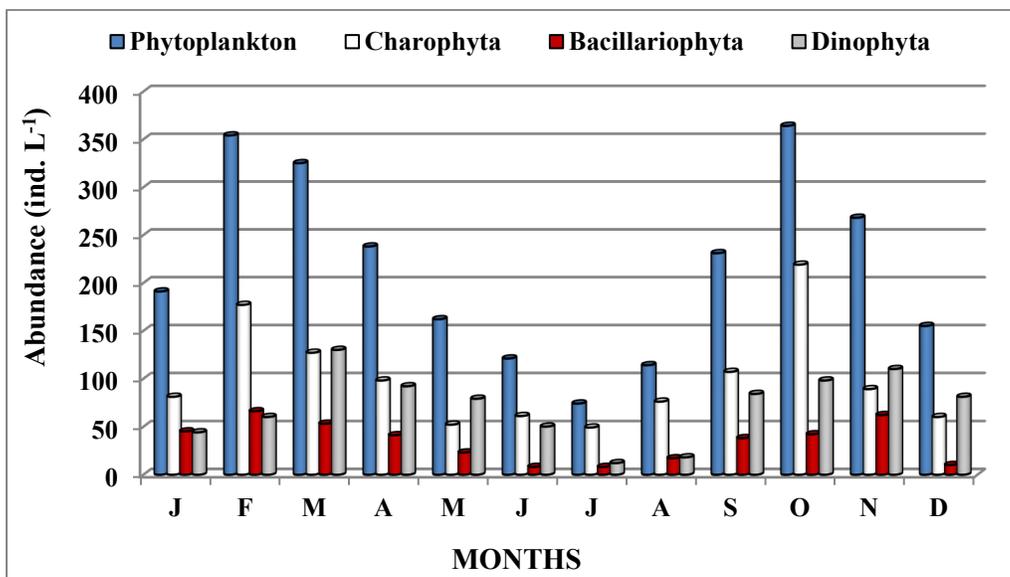


Figure 5. Monthly variations of abundance of phytoplankton and important groups (Littoral region)

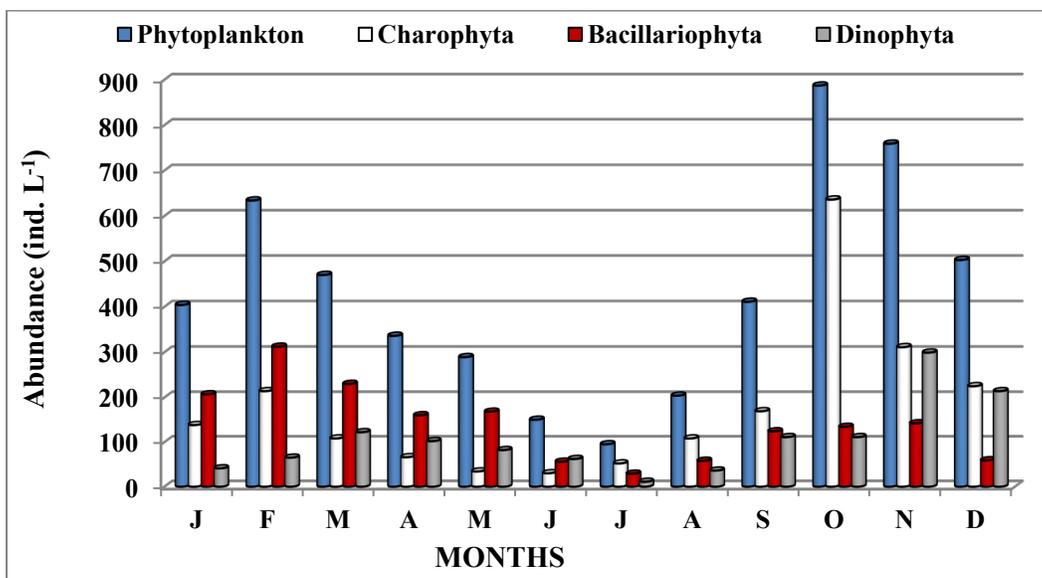


Figure 6. Monthly variations of abundance of phytoplankton and important groups (Limnetic region)

Peridinium cinctum > *Staurastrum freemani* > *S. arctiscon* > *Navicula radiosa* > *Ceratium hirudinella* > *Tabellaria flocculosa* > *S. gutwinckii* > *Cosmarium contractum* > *Pinnularia viridis* > *Frustulia rhomboides* > *Caloneis bacillum* indicate the stated order of the quantitative importance at the littoral region (Table 3). *Peridinium cinctum* > *Staurastrum freemani* > *Ceratium hirudinella* > *S. gutwinckii* > *Navicula radiosa* > *S. arctiscon* are notable at the limnetic region (Table 3). Our results categorize the ‘specialists’ nature of 11 and six species at the two regions, respectively and the ‘generalist’ nature of

the rest of species with lower densities. Following MacArthur (1965) explanation, it is hypothesized that Shillong reservoir has resources for utilization both by the ‘specialist’ and ‘generalist’ species. The ‘specialist’ species collectively (84.0 ± 8.1 , $79.8 \pm 9.3\%$) influence phytoplankton abundance ($r_1 = 0.994$, $p < 0.0001$; $r_2 = 0.941$, $p < 0.0001$) at the two regions, respectively. Of these, *Staurastrum arctiscon* ($r_1 = 0.875$, $p = 0.0009$), *S. freemanni* ($r_1 = 0.829$, $p = 0.003$) and *Cosmarium decoratum* ($r_1 = 0.846$, $p = 0.002$) individually influence phytoplankton abundance at the littoral region, while

Navicula radiosa ($r_2 = 0.840$, $p = 0.001$), *Staurastrum arctiscon* ($r_2 = 0.955$, $p < 0.0001$) and *Tabellaria flocculosa* ($r_2 = 0.716$, $p = 0.020$) exert influence at the limnetic region. *Staurastrum freemani* > *S. arctiscon* are main contributors to late-monsoon phytoplankton peak at the littoral region while the dominant *N. radiosa* contributes to winter maxima. The differential spatial importance of the ‘specialist’ species noted vide the present study concurs with the report of Sharma and Sharma (2021).

Charophyta (Table 3) contributes to the littoral and limnetic phytoplankton abundance ($r_1 = 0.763$, $p = 0.010$; $r_2 = 0.892$, $p = 0.0005$) and follows the bimodal monthly variations (Figures 5-6) identical with that of phytoplankton. The bimodal periodicity of the green algae differs from unimodal patterns reported by Baba and Pandit (2014) and Ganai and Parveen (2014). Charophyta indicates three- and two-fold higher abundance at the two regions (Table 3), respectively higher than the earlier survey (Sharma, 1995) and also records higher abundance than known from the reservoirs of Meghalaya (Sharma and Lyngskor, 2003; Sharma and Lyngdoh 2003) and Mizoram (Sharma and Pachuau, 2016) and the floodplain lakes (Sharma, 2004, 2009, 2010, 2012, 2015; Sharma and Hatimuria, 2017) of NEI. *Staurastrum freemani* > *S. arctiscon* influence late-monsoon Charophyta peak, while *Staurastrum arctiscon* > *S. freemani* contribute to the winter maxima at the littoral region. *Staurastrum freemani* > *S. gutwinckii* > *S. arctiscon* and *S. freemani* = *S. gutwinckii* > *S. arctiscon* > *Cosmarium contractum* result in late-monsoon peak and winter maxima, respectively at the limnetic region. ANOVA records (Table 4) significant variations of *C. contractum* and *S. arctiscon* abundance between the regions, *S. freemani* records significant density variations between the regions and months, and *S. gutwinckii* records significant monthly quantitative variations.

Staurastrum spp. (Table 3) contribute to Charophyta ($r_1 = 0.715$, $p = 0.020$; $r_2 = 0.918$, $p = 0.0002$) and phytoplankton ($r_1 = 0.837$, $p = 0.002$; $r_2 = 0.722$, $p = 0.018$) abundance and influence their pre-monsoon peaks and winter maxima at the two regions, respectively. *Cosmarium* spp. contribute to Charophyta ($r_1 = 0.737$, $p = 0.015$) and phytoplankton ($r_1 = 0.890$, $p = 0.001$) abundance at the littoral region (Table 3). The importance of *Staurastrum* spp. > *Cosmarium* spp. concurs with the report of Sharma and Sharma (2021) but it differs from the quantitative significance of *Staurastrum* spp. (Sharma, 1995), *Staurastrum* spp. > *Xanthidium* spp. > *Cosmarium* spp. (Sharma and Pachuau, 2016), *Closterium* spp. >

Staurastrum spp. > *Gonatozygon* spp. > *Micrasterias* spp. > *Cosmarium* spp. (Sharma, 2009); *Closterium* spp. > *Gonatozygon* spp. > *Micrasterias* spp. > *Staurastrum* spp. from Utra Pat (Sharma, 2010), and *Closterium* spp. > *Cosmarium* spp. > *Staurastrum* spp. > *Xanthidium* spp. from Waithou Pat (Sharma, 2010) known vide the different reports from NEI. *Staurastrum arctiscon* ($r_1 = 0.979$, $p < 0.0001$) and *S. freemani* ($r_1 = 0.996$, $p < 0.0001$), and *S. arctiscon* ($r_2 = 0.735$, $p = 0.015$), *S. freemani* ($r_2 = 0.968$, $p < 0.0001$) and *S. gutwinckii* ($r_2 = 0.725$, $p = 0.018$) influence *Staurastrum* spp. abundance at the two regions, respectively. *Cosmarium decoratum* ($r_1 = 0.846$, $p = 0.002$) influences *Cosmarium* spp. abundance at the littoral region.

Bacillariophyta (Table 3) comprises an important quantitative component of phytoplankton at the littoral region but records sub-dominance at the limnetic region. The differential spatial importance is affirmed by significant density variations (Table 4) of the diatoms between the two regions (vide ANOVA). Our results mark a distinct contrast to very poor diatom abundance reported vide the earlier limnetic survey (Sharma, 1995). Bacillariophyta importance at the littoral region concurs with the reports from Assam (Sharma, 2015; Sharma & Hatimuria, 2017), Himachal Pradesh (Jindal *et al.*, 2014b), Kashmir (Baba and Pandit, 2014) and Uttarakhand (Goswami *et al.*, 2018). The diatom sub-dominance at the limnetic region, however, corresponds with the reports from Manipur (Sharma, 2009) and Uttarakhand (Sharma and Singh, 2018). The diatoms record peak abundance during winter (February) and maxima during autumn (November) at the two regions (Figures 5-6). The winter peaks concur with the reports from Kashmir (Wanganeo and Wanganeo, 1991; Baba and Pandit, 2014), Meghalaya (Sharma and Lyngdoh, 2003) and Manipur (Sharma, 2009) and autumn maxima agree with the report from Meghalaya (Sharma and Sharma, 2021). *Navicula radiosa* contributes to Bacillariophyta ($r_1 = 0.699$, $p = 0.024$; $r_2 = 0.980$, $p < 0.0001$) abundance and influences winter peaks and *N. radiosa* > *Tabellaria flocculosa* influence autumn maxima at the two regions. ANOVA (Table 4) registers significant density variations of *N. radiosa*, *T. flocculosa*, *Caloneis bacillum*, *Frustulia rhomboides* and *Pinnularia viridis* between the two regions.

Dinophyta (Table 3) contributes significantly to phytoplankton abundance at the limnetic region ($r_2 = 0.709$, $p = 0.022$) and registers (Table 4) significant monthly density variations (vide ANOVA). Our results record distinctly higher Dinophyta abundance than the earlier survey (Sharma, 1995),

while it differs from poor abundance reported by Sharma and Lyngdoh (2003), Sharma and Lyngskor (2003), Sharma (2010), Sharma and Pachuau (2016) and Sharma and Hatimuria (2017) from NEI. Dinophyta abundance depicts the differential spatial patterns (Figures 5-6) with peak in autumn (November) and maxima in spring (March) at the littoral region, and it records peak in spring and maxima in autumn at the limnetic region. Peaks and maxima differ from winter peaks (Sharma, 2009) and summer maxima (Sharma and Singh, 2018). Our study records importance of *Peridinium cinctum* > *Ceratium hirudinella*; the former contributes to autumn peak and autumn maxima at the two regions, respectively; *P. cinctum* influences Dinophyta abundance ($r_2=0.667$, $p=0.035$) at the limnetic region, while *C. hirudinella* results in spring peak and autumn maxima at the two regions. ANOVA registers significant monthly density variations of the two species (Table 4).

Chrysophyta, represented by *Dinobryon sociale*, depicts limited quantitative importance (Table 3) with winter peaks at the two regions. This pattern differs from poor Chrysophyta abundance known from the floodplain lakes (Sharma, 2009, 2010, 2012, 2015) and reservoirs (Sharma, 1995; Sharma and Lyngdoh, 2003; Sharma and Lyngskor, 2003) of NEI. Amongst other phytoplankton groups, Cyanobacteria, Cryptophyta and Euglenophyta depict very poor abundance (Table 3). The present report differs from Cyanobacteria sub-dominance reported by Baba and Pandit (2014), Sharma (2015), Sharma and Pachuau (2016), Sharma and Hatimuria (2017) from the different parts of north India, while insignificance of

Cryptophyta and Euglenophyta concurs with the results of Sharma (2009), Sharma, and Pachuau (2016).

Phytoplankton record moderate species diversity (Table 3) with oscillating monthly variations at the two regions (Figure 7); ANOVA affirms its significant variations between the regions and months (Table 4). This study records $H' > 2.5$ during five (March-July) and three (January, February and April) months at two stations, respectively. The relatively higher diversity at the littoral than the limnetic region is attributed both to higher richness and abundance at the former region. The notable diversity variations recorded in the present study vis-a-vis the earlier survey (Sharma, 1995) are attributed to distinct increase in the richness and abundance of phytoplankton during the present survey. The inverse influence of phytoplankton abundance on species diversity ($r_1 = -0.723$, $p = 0.018$) at the littoral region is supported by concurrence of peak diversity during July (monsoon) with lowest abundance. The diversity is positively influenced by phytoplankton richness ($r_2 = 0.760$, $p = 0.011$) and *Cosmarium* spp. ($r_2 = 0.757$, $p = 0.011$) abundance at the limnetic region; it is inversely influenced by abundance of *Staurostrum* spp. ($r_1 = -0.738$, $p = 0.015$), *S. arcticon* ($r_1 = -0.708$, $p = 0.022$) and *S. freemani* ($r_1 = -0.736$, $p = 0.015$) at the littoral region. An inverse influence of species diversity vs. dominance ($r_1 = -0.787$, $p = 0.007$; $r_2 = -0.755$, $p = 0.012$) is affirmed by concurrence of the lower diversity with higher dominance at both regions. Further, the diversity is positively influenced by evenness ($r_1 = 0.986$, $p < 0.0001$; $r_2 = 0.891$, $p = 0.0005$) at the two regions.

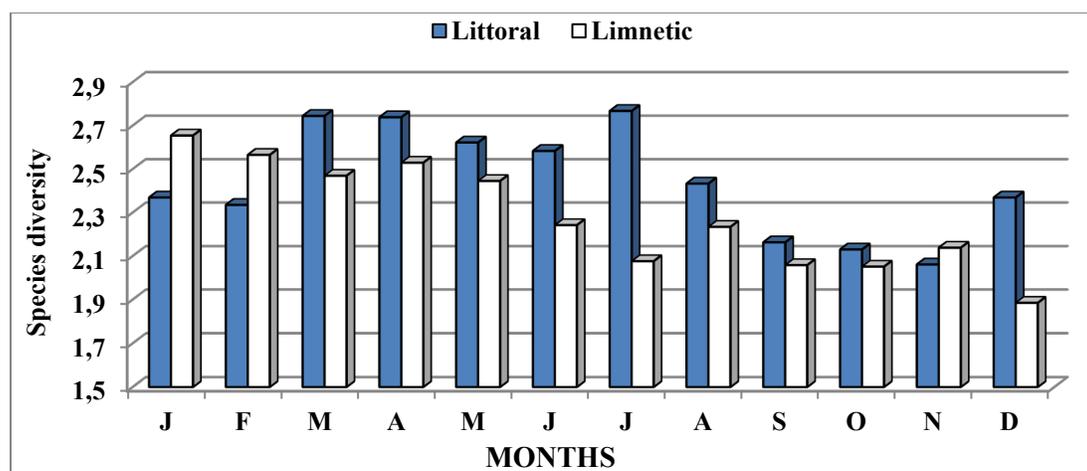


Figure 7. Monthly variations of phytoplankton species diversity

Phytoplankton dominance depicts the spatial differences at the two regions (Table 3); peak dominance and maxima at the littoral region are noted during autumn (November) and winter (February), respectively, while it records winter peak (December) and winter maxima (January) at the limnetic region. The ‘specialist’ species result in higher dominance during certain months, while low dominance during certain other months is concurrent with equitable abundance of the ‘generalist’ species. The dominance is positively correlated with abundance of *Cosmarium* spp. ($r_1=0.763$, $p=0.020$) and *C. decoratum* ($r_1=0.784$, $p=0.020$) at the littoral region. The extent of dominance variations broadly correspond with the reports of Sharma and Pachau (2016), Sharma and Hatimuria (2017) but differs from low dominance reported from the reservoirs of Meghalaya (Sharma and Lyngdoh, 2003; Sharma and Lyngskor, 2003) and the floodplains of NEI (Sharma, 2004, 2009, 2010, 2012, 2015). Our results depict the spatial differences of phytoplankton evenness at the two regions (Table 3); high evenness noticed during several months is attributed to equitable abundance of majority of taxa while dominance of certain species results in moderate evenness. These remarks are affirmed by an inverse correlation of evenness vs. dominance ($r_1=-0.846$, $p=0.002$; $r_2=-0.694$, $p=0.026$) at the two regions. Further, evenness is inversely influenced by *Staurastrum* spp. ($r_1=-0.732$, $p=0.016$), *S. arctiscon* ($r_1=-0.726$, $p=0.017$) and *S. freemani* ($r_1=-0.723$, $p=0.018$) and *Cosmarium decoratum* ($r_1=-0.651$, $p=0.041$) at the littoral region, and *Peridinium cinctum* ($r_1=-0.788$, $p=0.007$) at the limnetic region.

The present study registers the differential spatial influence of individual abiotic factors on phytoplankton assemblages. Inverse influence of water temperature ($r_1=-0.941$, $p<0.0001$), rainfall ($r_1=-0.774$, $p=0.0086$) on phytoplankton richness at the littoral region is affirmed by lower richness during warmer months and rainy season and coincides with relatively high pH ($r_1=-0.768$, $p=0.0095$), Cl ($r_1=-0.875$, $p=0.0009$) and PO_4 ($r_1=-0.797$, $p=0.0058$). The richness concurs with the periods of high alkalinity ($r_2=0.732$, $p=0.0161$), hardness ($r_2=0.713$, $p=0.0206$), Ca ($r_2=0.789$, $p=0.0067$) and DOM ($r_2=0.805$, $p=0.0050$) at the limnetic region. Higher phytoplankton abundance observed during January-March and again during October to December concurs with the relatively high transparency ($r_1=0.696$, $p=0.0026$) and photosynthetic activity of the primary producers resulting in high DO ($r_1=0.696$, $p=0.0254$), while lower abundance during monsoon season affirms inverse influence of rainfall ($r_1=-$

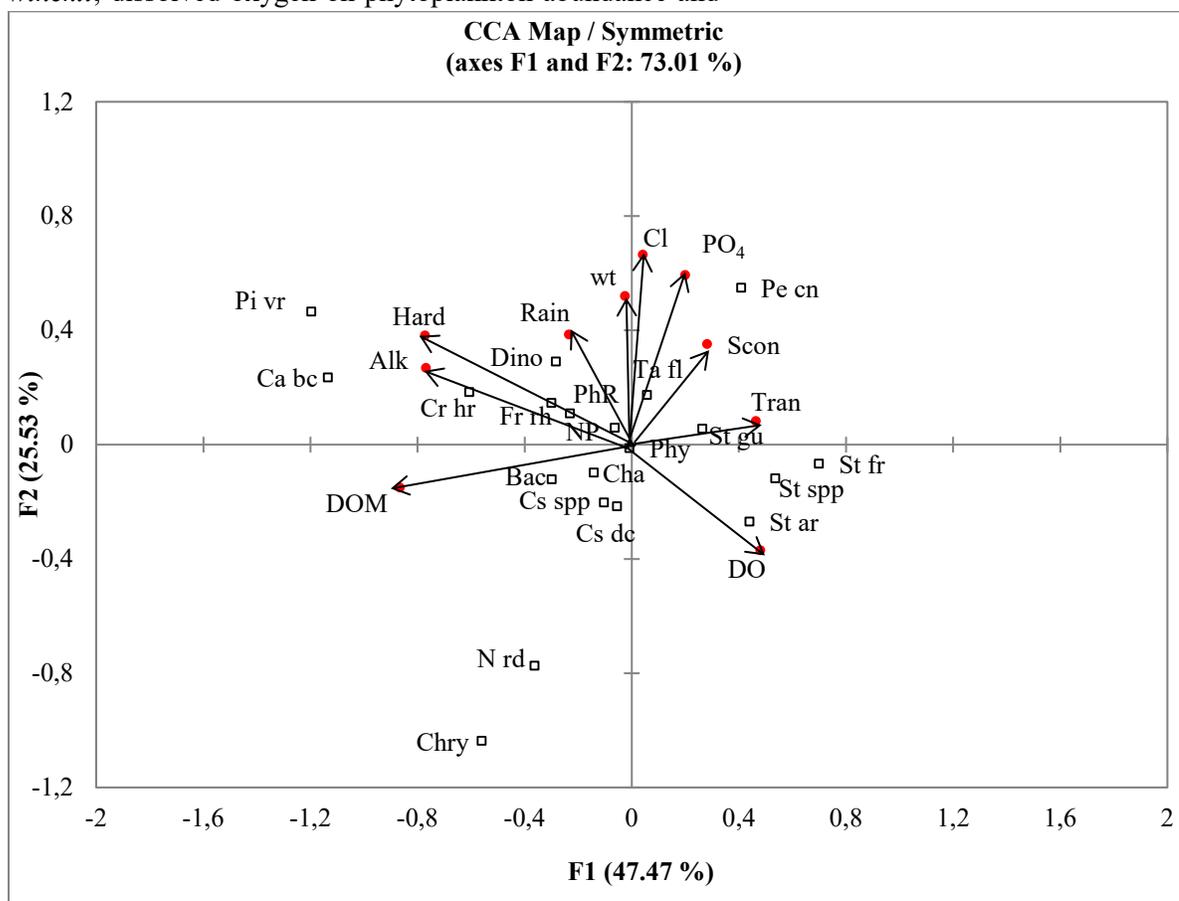
0.695 , $p=0.0257$) at the littoral region. The periods of high phytoplankton abundance result in increased DO ($r_2=0.759$, $p=0.0109$) at the limnetic region. This conclusion also holds valid for the positive correlations of Charophyta ($r_1=0.808$, $p=0.0047$; $r_2=0.818$, $p=0.0038$) and *Staurastrum* spp. ($r_1=0.718$, $p=0.0194$; $r_2=0.825$, $p=0.0033$) abundance with DO at the two regions, and with Bacillariophyta ($r_2=0.856$, $p=0.0047$) at the limnetic region. High Dinophyta abundance concurs with high specific conductivity ($r_1=0.803$, $p=0.0052$) at the littoral region. Bacillariophyta abundance concurs with months of high Cl contents ($r_2=0.856$, $p=0.0047$) at the two regions; Chrysophyta abundance corresponds with high specific conductivity ($r_2=0.727$, $p=0.0172$) and Dinophyta indicate low abundance during periods of high DOM ($r_2=-0.679$, $p=0.0251$) at the limnetic region. Overall importance of the individual abiotic factors is concurrent with the reports of Sharma and Sharma (2021) but deviates from the importance of only a few factors (Sharma and Lyngskor, 2003; Sharma and Lyngdoh, 2003; Sharma, 2010) and much limited role of the individual factors reported vide the various works from NEI (Sharma, 1995, 2012, 2015; Sharma and Pachau, 2016).

Referring to important species, lower alkalinity ($r_1=-0.723$, $p=0.0181$), hardness ($r_1=-0.730$, $p=0.0165$), Ca ($r_1=-0.812$, $p=0.0043$) and DOM ($r_1=-0.821$, $p=0.0036$) favor *Staurastrum gutwinckii* abundance at the littoral region, while this desmid is inversely influenced only by Ca ($r_2=-0.718$, $p=0.0194$) at the limnetic region. *Cosmarium decoratum* indicates lower densities concurrent with the periods of high temperature ($r_1=-0.792$, $p=0.0063$), rainfall ($r_1=-0.813$, $p=0.0042$), pH ($r_1=-0.747$, $p=0.0130$) and Cl ($r_1=-0.819$, $p=0.0038$) at the littoral region. *Navicula radiosa* is inversely influenced by water temperature ($r_1=-0.718$, $p=0.0194$) and Cl ($r_1=-0.725$, $p=0.0177$); *Tabellaria flocculosa* is positively influenced by DO ($r_1=0.694$, $p=0.0181$) and NO_3 ($r_1=0.880$, $p=0.0008$); and *Ceratium hirudinella* is positively influenced by alkalinity ($r_2=0.771$, $p=0.0090$), hardness ($r_2=0.705$, $p=0.0228$), Ca ($r_2=0.719$, $p=0.0191$) and DOM ($r_2=0.817$, $p=0.0040$) at the limnetic region. *Peridinium cinctum* is positively influenced by NO_3 ($r_2=0.684$, $p=0.0292$) and *Staurastrum arctiscon* is positively influenced by DO ($r_2=0.794$, $p=0.0061$) at the limnetic region. Our results thus endorse the differential spatial influence of the individual abiotic factors on notable phytoplankton species broadly concurrent with the report of Sharma and Sharma (2021). This generalization, however, marks departure from the results of

Sharma (1995, 2009, 2010, 2012, 2015), Sharma and Lyngdoh (2003) Sharma and Pachuau (2016) and Sharma and Hatimuria (2017) yielding little insight on influence of individual abiotic factors on important species.

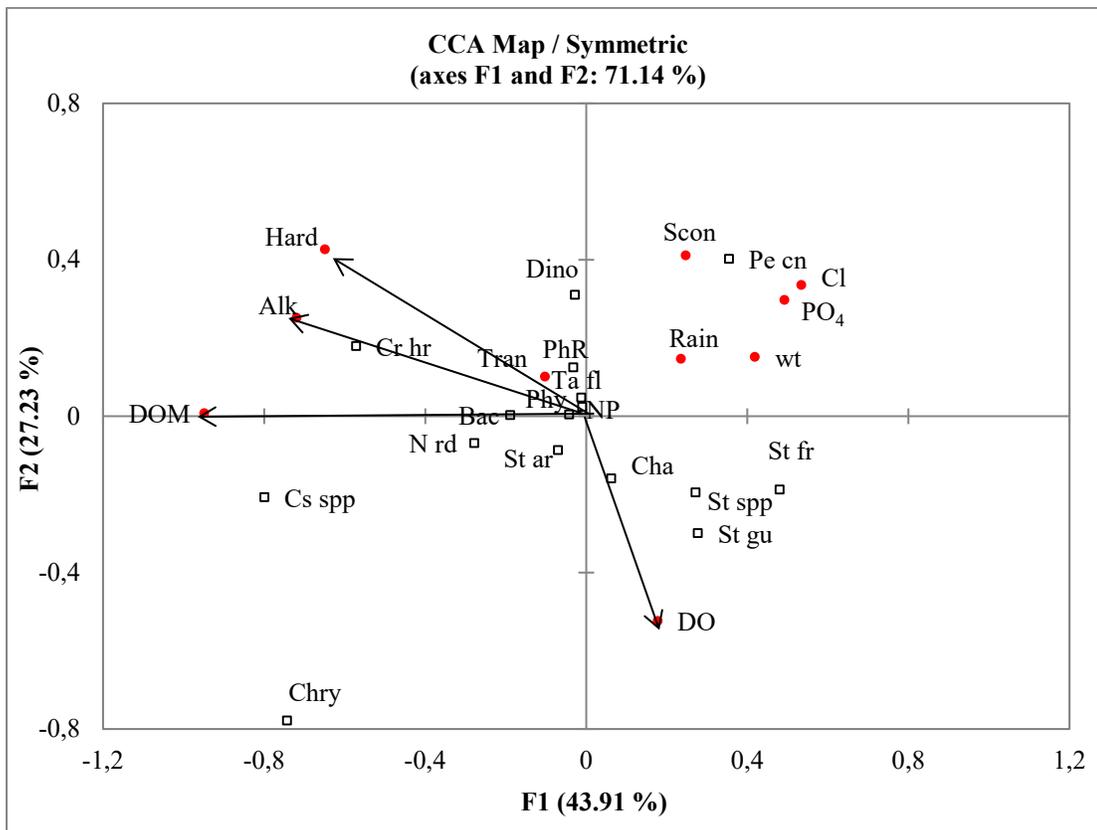
The CCA registers high and broadly identical cumulative influence (73.01 and 71.14%) of 10 abiotic factors, along 1 and 2 axes, on the littoral and limnetic phytoplankton assemblages, respectively (Figures 8-9). The CCA co-ordination biplot indicates influence of alkalinity and hardness on abundance of *Ceratium hirudinella* and *Frustulia rhomboides*; rainfall on richness of phytoplankton and limited influence on Dinophyta abundance; PO₄ on *Tabellaria flocculosa* density; specific conductivity and transparency on *Staurastrum gutwinckii*; dissolved oxygen on phytoplankton abundance and

limited influence on *Staurastrum* spp., *S. arctiscon* and *S. freemani*; and DOM on Charophyta and Bacillariophyta, and limited influence on *Cosmarium* spp. and *C. decoratum* at the littoral region (Figure 8). The CCA biplot registers influence of alkalinity and hardness on *Ceratium hirudinella*; alkalinity and DOM phytoplankton and Bacillariophyta abundance; DO on Charophyta abundance and limited influence on *Staurastrum* spp., *S. arctiscon* and *S. freemani* at the limnetic region (Figure 9). Higher overall cumulative influence of abiotic factors reported vide this study is concurrent with the reports from Khawiva reservoir of Mizoram (Sharma and Pachuau, 2016); Bhareki and Holmari beels (Sharma and Hatimuria, 2017) of the Majuli floodplains, and Deepor beel (Sharma, 2015) of Assam.



Abbreviations: Abiotic factors: Alk (alkalinity), Cl (chloride), Cond (specific conductivity), DO (dissolved oxygen), DOM (dissolved organic matter), hard (hardness), rain (rainfall), Trans (transparency), PO₄ (phosphate), wt (water temperature). **Biotic factors:** Bac (Bacillariophyta abundance), Ca sp. (*Caloneis bacillum*), Cha (Charophyta abundance), Chry (Chrysophyta abundance), Cs spp (*Cosmarium* species abundance), Cr hr (*Ceratium hirudinella* abundance), Cs dc (*Cosmarium decoratum* abundance), Dino (Dinophyta abundance), Fr rh (*Frustulia rhomboides*), NP (net plankton abundance), N rd (*Navicula radiosa* abundance), Pe cn (*Peridinium cinctum* abundance), Pi vr (*Pinnularia viridis* abundance), PhR (phytoplankton richness), Phy (phytoplankton abundance), St spp (*Staurastrum* species.), St ar (*Staurastrum arctiscon*), St fr (*Staurastrum formosum* abundance), St gu (*Staurastrum gutwinckii* abundance), Tb fl (*Tabellaria flocculosa* abundance)

Figure 8. CCA coordination biplot of phytoplankton assemblages and abiotic factors (Littoral region)



Abbreviations: Abiotic factors: Alk (alkalinity), Cl (chloride), Cond (specific conductivity), DO (dissolved oxygen), DOM (dissolved organic matter), hard (hardness), rain (rainfall), Trans (transparency), PO₄ (phosphate), wt (water temperature). **Biotic factors:** Bac (Bacillariophyta abundance), Cha (Charophyta abundance), Chry (Chrysophyta abundance), Cs spp (*Cosmarium* species abundance), Cr hr (*Ceratium hirudinella* abundance), Dino (Dinophyta abundance), NP (net plankton abundance), N rd (*Navicula radiosa* abundance), Pe cn (*Peridinium cinctum* abundance), PhR (phytoplankton richness), Phy (phytoplankton abundance), St spp (*Staurastrum* species.), St ar (*Staurastrum arcticon*), St fr (*Staurastrum formosum* abundance), St gu (*Staurastrum gutwinckii* abundance). Tb fl (*Tabellaria flocculosa* abundance)

Figure 9. CCA coordination biplot of phytoplankton assemblages and abiotic factors (Limnetic region)

Conclusion

The fairly diverse phytoplankton, rich Charophyta with diverse desmids, and peak constellation per sample of 30 species are notable features of very soft, acidic, highly calcium poor and one of the most de-mineralized waters of this small subtropical reservoir in particular. Phytoplankton dominance vs. net plankton abundance, the spatial differences of dominance of important groups, the reports 11 and 6 ‘specialist’ species and *Staurastrum* spp. > *Cosmarium* spp. importance at the littoral and the limnetic regions are noteworthy. The differential spatio-temporal variations of species composition, richness, abundance, diversity, dominance, evenness and influence of the individual abiotic factors are hypothesised to habitat heterogeneity amongst the sampled regions. The CCA registers high cumulative influence of 10 abiotic

factors on phytoplankton assemblages. Our results highlight distinct temporal differences of phytoplankton richness, abundance and species diversity vis-a-vis the limited survey of November 1990–October 1991. This study is an important contribution to the reservoir limnology and phytoplankton diversity of India and the subtropical reservoirs of NEI in particular.

Compliance with Ethical Standard

Conflict of interests: The authors declare that for this article they have no actual, potential or perceived conflict of interests.

Ethics committee approval: -

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