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INTEGRATING PHYTOPLANKTON FUNCTIONAL GROUPS AND WATER QUALITY INDICES TO ASSESS TROPICAL SWAMP FOREST ECOLOGY

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Abstract

Tropical swamp forests are dynamic ecosystems where water quality is closely linked to ecological integrity. The Ratargul Swamp Forest in Bangladesh faces increasing anthropogenic and environmental pressures, but a comprehensive ecological assessment integrating biological and physicochemical indicators is lacking. The present study was conducted to evaluate its ecological status, identify key environmental drivers, and assess the utility of financial groups (FGs) as bioindicators for conservation. In the present study, the ecological condition of the forest was assessed by integrating phytoplankton FGs with the water quality index (WQI) and the chlorophyll-based trophic state index [TSI (Chl)] during the pre-monsoon and post-monsoon seasons. A total of 54 phytoplankton species were identified from the swamp forest, with Euglenophyta dominating the assemblage**.** Functional group W1 **(***Euglena* sp*., Euglena mutabilis, E. rostrifera, E. viridis, E. oblonga, E.acus, E. polymorpha, E. chordata, E. allorgei, E. deses, Phacus* sp*., Phacus longicaudus. Strombomonas* sp*., Synura* sp. and *Astasia* sp.) associated with organic pollution and high biological oxygen demand (BOD), were the most abundant in both seasons, with a marked increase post-monsoon. Redundancy analysis (RDA) revealed that soluble reactive phosphorus (SRP), soluble reactive silicate (SRS), and conductivity were the key environmental drivers influencing the composition of FGs. The water quality of the swamp forest was poor, as indicated by the WQI, which was based on the selection of water quality parameters (R^2 = 0.85). The TSI (Chl) supported the WQI result, indicating the eutrophic status of the forest. The present research findings showed that phytoplankton functional groups, when integrated with water quality indices, offer a robust and sensitive approach to ecological monitoring and planning conservation strategies for tropical swamp forest wetland ecology.

Introduction

Freshwater swamp forests are unique wetland systems that contribute to global water ecology by maintaining the local water balance (Manhas *et al*., 2009; Teixeira *et al*., 2008). Tropical swamp forests play key hydrological roles in water storage, optimising flood peaks, maintaining underground water levels, recharging runoff, mitigating degradation and pollution, and improving water quality (Xu and Chunjing, 2015; Clews *et al*., 2018). The formation of forest swamps

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depends on specific climatic and physiognomic conditions (Yongxing, 2003). Due to topographical variation, discrete floristic diversity, including flora and fauna, was found in the surrounding areas of swamp forests (King, 1871; Van Andel, 2003). Special edaphic conditions that support different vegetation characteristics are influenced by seasonal water accumulation (Gupta *et al*., 2006; Manhas *et al*., 2009). Swamp forests provide necessary sustenance as habitats and nursery grounds for various aquatic organisms, hydrophytes and woody perennials (Xu and Chunjing, 2015; Chen *et al*., 2016).

Among aquatic organisms, the phytoplankton community structure is commonly used as a reliable tool to assess water quality (Hu *et al*., 2021; Stevenson and Smol, 2015; Singh *et al*., 2013). They can withstand extreme conditions and are the only suitable organisms for monitoring environmental variations over short periods (Gao *et al*., 2013; Chen *et al*., 2016). Apart from their role as primary producers in the aquatic food chain, the species richness, diversity, abundance, and seasonal succession of these organisms are key indicators of water quality (Gao *et al*., 2008; Wang *et al*., 2011; Chen *et al*., 2016). Among aquatic organisms, phytoplankton maintain their cosmopolitan nature and sensitivity to various environmental factors, making them excellent indicators for bio-monitoring to assess water quality, pollution status and ecological changes (Walker, 1992; Katsiapi *et al*., 2012).

Phytoplankton functional groups have been widely used to study phytoplankton ecology in lakes, reservoirs, and rivers (Devercelli, 2006; Piirsoo *et al*., 2008; Becker *et al*. 2010). The distribution of functional groups varies across environmental factors, enabling inference of functional species diversity. In the traditional taxonomic approach, the functional classification of phytoplankton describes several species with similar seasonal sequences, including functionally related phytoplankton taxa that occur under similar environmental conditions. This approach has been widely used to explore the relationships between phytoplankton species and ecological variables (Reynolds *et al*., 2002). The dynamic relationship between phytoplankton and nutrients has long been of great interest in aquatic ecology (Chattopadhyay *et al*., 2003). Seasonal accumulation of nutrients in water can lead to the formation of algal blooms and degrade water quality (Donglin *et al*., 2022; Lin-lin *et al*., 2012). Environmental variables can cause significant alterations in the existing phytoplankton composition, abundance, and distribution; as a result, phytoplankton community structure is altered (Swain and Kearsley, 2001; Van Andel, 2003). Such conditions are reflected by various phytoplankton functional groups in the aquatic ecosystem (Abonyi *et al*., 2012; Salmaso and Padisák, 2007).

Ratargul is the only swamp forest categorised as a special biodiversity-protected area in northeastern Bangladesh. In this subtropical region, monsoon rains are responsible for the seasonal inundation of these swamp forests. During the monsoon, the forest receives the maximum amount of water to replenish its ecosystem through rainfall or adjacent river flushing (Choudhury *et al*., 2004). Water quality parameters varied significantly between the pre-monsoon and post-monsoon seasons (Nahian *et al*., 2018). The rich diversity of flora and fauna in the swamp forest can be influenced by seasonal fluctuations in water quality (IUCN, 2004; Islam *et al*., 2016). In addition, ecosystem destruction, including biodiversity and vegetation degradation, has become a regular phenomenon in recent years due to anthropogenic interventions and inadequate environmental regulations (Humayun-Bin-Akram and Masum, 2020). To understand the current ecological condition and develop new tools for building ecosystem restoration strategies in the Ratargul Swamp Forest, it is necessary to observe the dynamics of phytoplankton and its seasonal succession in relation to various environmental factors (Ma *et al*., 2014). So far, such studies are long overdue. The present study investigated (i) to find the relation of physicochemical parameters with phytoplankton and its FGs, (ii) to determine the ecological status of the Ratargul Swamp Forest based on FGs, and (iii) to examine the relationship between phytoplankton functional groups and water quality indices, identifying potential bioindicators for ecological monitoring. This investigation can provide researchers with insights into the importance of considering FGs for conservation and management strategies by identifying critical factors that influence swamp forest health and sustainability.

Materials and Methods

Study area:

Ratargul Swamp Forest is a freshwater subtropical forest located on the bank of the Goyain River, about 26 km from Sylhet town in Bangladesh (Fig. 1). It is the largest swamp forest in Bangladesh. This forest covers approximately 30,325 acres. The existing ecosystem of this area comprises several different types of habitats, including a river, lowland areas with vegetation, and depressions (Choudhury *et al*., 2004). The Goyain River originates in the mountain ranges of Meghalaya (India) and is the primary source of water and nutrients for the forest through which it flows (Islam *et al*., 2016). The forest is renowned for its evergreen nature. The segments fill with freshwater during the rainy season, and in winter, the forest receives thousands of migratory birds, creating an excellent scenario. As a typical subtropical wetland ecosystem, the forest has a high potential for biodiversity and other intangible values. In addition, riverine swamp forests contain almost permanently waterlogged soils in depressions, lowlands, headwaters and watercourse margins. Many individuals represent only a few flood-tolerant plant species in these forests (Nahian *et al*., 2018; Scarano, 2002; Koponen *et al*., 2004; Allen *et al*., 2005). Plenty of inundated trees stand in the Ratargul Swamp forest, and it is so dense that even sunlight cannot penetrate the inner side of the forest through the leaves to reach the water.

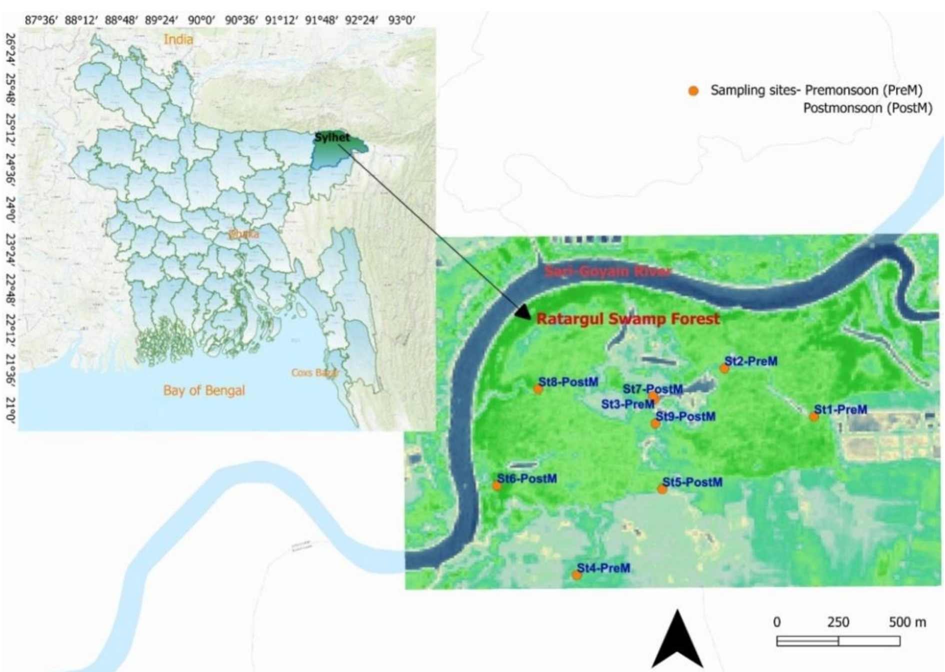

Fig. 1. Map showing sampling sites (orange dots) during pre-monsoon and post-monsoon in the Ratargul Swamp Forest, Bangladesh (Source: Copernicus Data Space Ecosystem, ESRI Topo, and GeoDASH).

Field sampling and lab analysis:

In the present study, water and phytoplankton samples were collected from different locations of the forest during May and November 2016, which were termed pre-monsoon (rising waters) and post-monsoon (falling waters), according to Pramanik *et al.*, (2016). Due to heavy and continuous rainfall, sampling during the monsoon was not conducted. After collection, 1 L phytoplankton samples from each sampling site were preserved with Lugol's solution. For further analysis, water and preserved phytoplankton samples were transported to the National Professor A. K. M. Nurul Islam Laboratory at the Department of Botany, University of Dhaka, and the Research Laboratory at the Department of Botany, Jagannath University. Air temperature, water temperature, pH, dissolved oxygen (DO), total dissolved solids (TDS) and conductivity were measured in *situ* using portable devices. Alkalinity, soluble reactive silicate (SRS), soluble reactive phosphorus (SRP), nitrate-nitrogen (NO_3-N), Chl *a*, and pheophytin were determined following the procedures of Mackereth *et al.*, (1978), Wetzel and Likens, (1979), Murphy and Riley, (1962), Müller and Wiedemann, (1955) and Marker *et al*. (1980), respectively, as described by Gani *et al*., (2011). In the laboratory, phytoplankton samples were sedimented and then concentrated, discarding the liquid portion that did not contain phytoplankton. Finally, quantification was done with the help of a Helber bacterial counting chamber (Z30000, Helber Bacteria 1 cell Thoma) under a compound microscope, Optika (Model B-500POL-1) fitted with a camera (Gani *et al*., 2011; Nancucheo and Barrie, 2012; Haberkorn *et al*., 2020). Magnification of ×400 was used for the identification and counting of phytoplankton. The phytoplankton species contributing more than 5% to the total abundance at least one sampling site were assigned to functional groups, using the criteria of Reynolds *et al*., (2002) and Padisák *et al*., (2009).

Statistical analysis:

Redundancy analysis (RDA) was applied to determine the relationship between phytoplankton functional groups and environmental variables using CANOCO v 4.5. Before RDA analysis, some ecological variables were standardised (pH, air and water temperature), and others were log (x+1) transformed. The relative abundances of phytoplankton FGs were Arcsine transformed. Using the Bray-Curtis index, a hierarchical clustering analysis (Primer v6; Clarke and Gorley 2001) was performed on phytoplankton FGs from different sampling sites to examine their similarities and dissimilarities. For determining the relation of environmental parameters (obtained from RDA) on phytoplankton FGs (obtained from the Bray-Curtis similarity index), different linear models (individual or combined) were used using R version 4.1.2 (R Core Team, 2021).

Application of the water quality and trophic state index:

The water quality index (WQI) was used to assess swamp forest quality, based on selected parameters from RDA and regression models. The WQI and quality class calculations were based on the weighted arithmetic index method (Brown *et al*., 1970, 1972; Gani *et al*., 2024), as shown in Eq. I.

$$WQI = \sum WiQi/Wi \text{-----------------------} \quad (I)$$

The quality rating scale for each parameter Qi was calculated by using this expression:

$$Quality\ rating,\ Qi = 100\left[\frac{Vn-Vi}{Vs-Vi}\right]$$

Where *Vn*= the actual amount of the nth parameter; *Vi*= the ideal value of this parameter. *Vi*= 0, except for DO.Vi = 14.6 mg/l; *Vs*= recommended surface water value for the corresponding parameters according to (ECR, 2023).

The weight values (Wi) for the selected parameters in WQI calculation were assigned using regression models.

To compare the WQI result with trophic status, the chlorophyll-based trophic state index [TSI(Chl)] proposed by Lamparelli (2004) was used (eq II).

$$TSI(Chl) = 10\left(6 - \left(0.92 - 0.34\left(\frac{lnChl}{ln2}\right)\right)\right) \text{-------------------(II)}$$

This index follows the six trophic statuses in aquatic systems in tropical regions (Molisani *et al.*, 2010).

Results and Discussion

A total of 54 phytoplankton species were identified during the present study. The species composition showed that Euglenophyta was the dominant group, followed by Heterokontophyta, Chlorophyta, Cryptophyta, and Cyanophyta in both the pre-monsoon and post-monsoon periods. However, the abundance (%) of Heterokontophyta was increased, and Chlorophyta was decreased post-monsoon (Fig. 2). Among the Heterokontophytes, all of them are diatoms. The total density of phytoplankton during pre-monsoon and post-monsoon was 25.97×10^3 ind/l and 61.76×10^3 ind/l, respectively. The increase was mainly due to the appearance of new diatom species during the post-monsoon period, with a twofold increase in abundance. A similar pattern was observed in Chl a concentration: during the post-monsoon period (11.84 µg/l), it was higher than during the pre-monsoon period (6.22 µg/l, Fig. 3). This finding is also supported by the individual phytoplankton density when common phytoplankton species were considered. The abundance of *Synura* sp., *Trachelomonas volvocina*, *Trachelomonas crevia*, *Euglena viridis*, *Euglena oblonga*, *Phacus longicaudus*, *Astasia* sp., *Strombomonas* sp., *Euglena* sp., *Navicula pupula*, *Navicula bacillum*, *Navicula delicatula* and *Peridinium* sp. were increased from pre-monsoon to post-monsoon without *Cryptomonas erosa* (Table 1). Almost all environmental variables showed higher values during the pre-monsoon period than during the post-monsoon period, except for SRP and Chl *a* (Fig. 3).

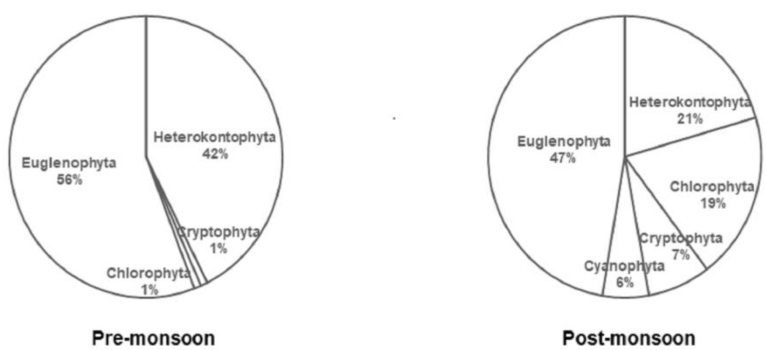

Fig. 2. Comparison of the relative abundance of phytoplankton groups in two seasons of Ratargul Swamp Forest, Bangladesh.

The phytoplankton species of Ratargul Swamp Forest were divided into ten functional groups: A, D, E, J, Lo, Lm, W1, W2, X1, and Y. Based on Reynolds *et al.*, (2002), relative abundance greater than 5% was considered as a representative functional group. During the pre-monsoon and post-monsoon periods, the representative functional groups were W1 > J > X1 > Y > W2 > D and W1 > A > W2 > E, respectively. The relative abundance of different representative functional groups showed that W1 is the dominant functional group in both seasons, with a higher quantity post-monsoon than pre-monsoon. A similar pattern was observed for W2 and A functional groups, where relative abundance increased from pre-monsoon to post-monsoon. The opposite phenomenon was observed in the Lo and Y functional groups, i.e., a decrease in relative abundance from pre-monsoon to post-monsoon. The appearance and disappearance occurred in other functional groups (D, E, J, L_m, and X1) during the pre-monsoon and post-monsoon seasons. The spatial distribution of functional groups showed that W1 and X1 were present in all pre-monsoon sampling stations, and E, W1, and W2 were present in all post-monsoon sampling stations (Table 2). The assigned functional groups of Ratargul Swamp Forest mainly followed environmental characteristics (Table 3).

Table 1. List of common phytoplankton species of both seasons with abundance ($\times 10^3$ind/l) in Ratargul Swamp Forest, Bangladesh.

Phytoplankton species	Sampling period	
	Pre-monsoon	Post-monsoon
Cryptomonas erosa	1.83	1.38
Synura sp.	1.36	9.48
Trachelomonas volvocina	1.34	3.45
Trachelomonas crevia	1.06	4.74
Euglena viridis	0.26	2.22
Strombomonas sp.	1.59	9.82
Euglena sp.	4.68	7.69
Navicula pupula	0.26	2.88
Navicula bacillum	0.26	2.99
Peridinium sp.	1.04	2.57
Phacus longicaudus	0.27	1.34
Astasia sp.	0.27	3.41
Navicula delicatula	0.27	3.83
Euglena oblonga	0.56	3.25

Table 2. Relative abundance (%) of phytoplankton functional groups in Ratargul Swamp Forest, Bangladesh.

Sampling sites	A	D	E	J	L_0	L_m	W1	W2	X1	Y
St1-PreM	5.26	10.53		10.53	5.26		28.95	10.53	13.16	7.89
St2-PreM		10.00		30.00	10.00		20.00		10.00	20.00
St3-PreM	4.55	4.55			4.55		36.36	22.73	9.09	9.09
St4-PreM				8.33		8.33	75.00		8.33	
PreM	**2.45**	**6.27**		**12.21**	**4.95**	**2.08**	**40.08**	**8.31**	**10.15**	**9.25**
St5-PostM	70.59		2.94		2.94		14.71	8.82		
St6-PostM	29.63		22.22				33.33	14.81		
St7-PostM	3.51		3.51		7.02		77.17	5.29		1.75
St8-PostM			8.57		2.86		68.56	20.01		
St9-PostM	5.56		5.56		2.78		66.61	19.48		
PostM	**21.86**		**8.56**		**3.12**		**52.08**	**13.68**		**0.35**

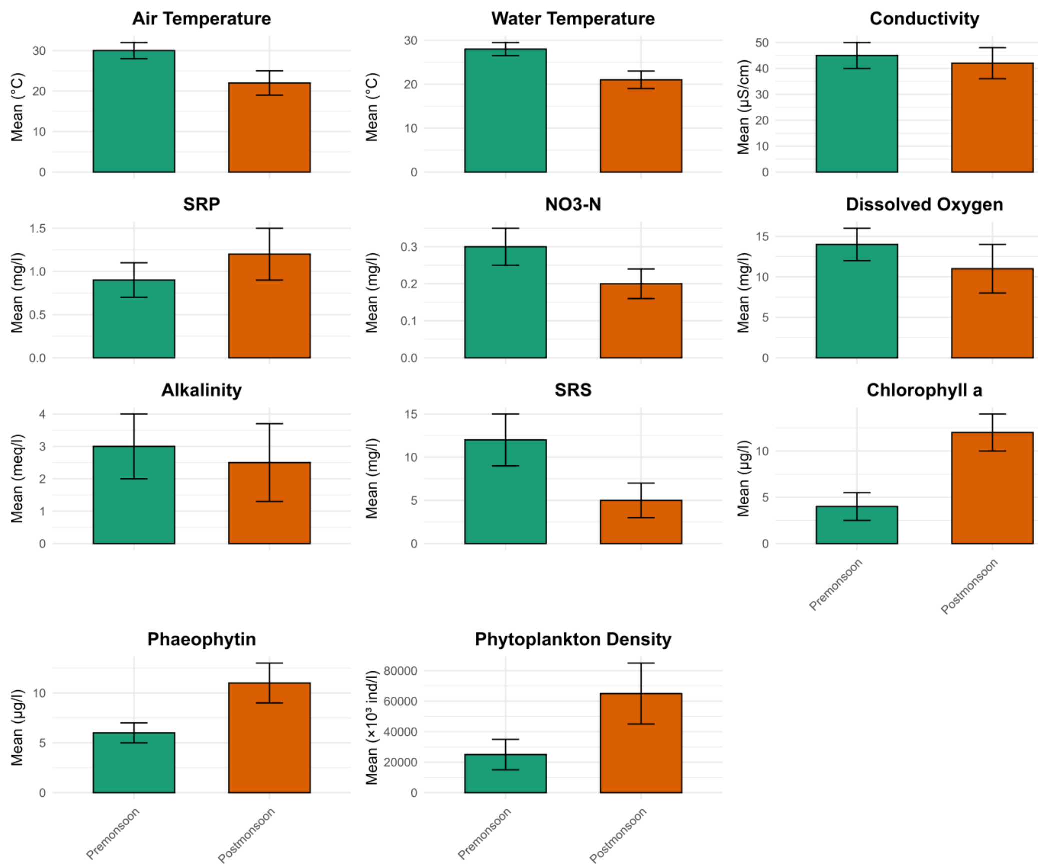

Fig. 3. Seasonal variation of environmental parameters (air temperature, water temperature, conductivity, alkalinity, DO, SRS, SRP, NO_3-N, TDS, Chl *a*, phaeophytin and phytoplankton density) in Ratargul Swamp Forest (mean value with standard deviation).

Only three environmental variables were selected in RDA based on the Monte Carlo test and the inflation factor (which had to be ≤20). The first two ordination axes explained 98.8% of the variance of the species (functional groups)-environment relation and 82.3% of the variance of species data (Fig. 4). Axis I (eigenvalue = 0.57) was mainly related to conductivity (r = 0.84). In contrast, axis II (eigenvalue = 0.26) was related primarily for DO (r=0.82) and SRP (r=-0.79) (Fig. 4). Functional groups W1 and W2 negatively correlated with conductivity and DO, respectively. A strong negative correlation was observed between SRP and functional groups J, Y, and D, which were the representative pre-monsoon groups.

The Bray-Curtis similarity index among the sampling sites showed that FGs were primarily divided into two groups, Gr1 and Gr2, with less than 35% similarity between them. Gr1 comprised FGs A, D, W1, and W2, and Gr2 comprised the rest of the FGs except Lm, which was excluded due to its low contribution (Fig. 5).

Table 3. Phytoplankton functional groups and their characteristics of Ratargul Swamp Forest, Bangladesh.

Phytoplankton species	Functional group	Environmental characteristics
Euglena sp., *Euglena mutabilis, Euglena rostrifera, Euglena viridis, Euglena oblonga, Euglena acus, Euglena polymorpha, Euglena chordata, Euglena allorgei, Euglena deses, Phacus* sp., *Phacus longicaudus. Strombomonas* sp., *Synura* sp. and *Astasia* sp.	W1	tolerant to high BOD, grazing sensitive and adapts to organic pollution
Trachelomonas volvocina, *Trachelomonas crevia*)	W2	inhabited to a moreshallow mesotrophic environment
Navicula pupula, Navicula cuspidate, Navicula bacillum, Navicula delicatula, Pinnularia gibba, Pinnularia sp., *Pinnularia stauroptera, Surirella ovata* and *Surirella* sp.	A	represented clean, often well-mixed base poor, nutrient deficit condition
Nitzchia sp., *Eunotia monodon*, *Synedra acus*, *Amphicampa eruca*	D	sensitive to nutrient depletion and can adaptto river flushing and turbid water
Mallomonas sp.	E	sensitive to CO_2 deficiency but can survive a low-nutrient environment
Scenedesmus quadricauda, *Hyaloraphidium* sp., *Ankistrodesmus spiralis*, *Crucigenia lauterbornii*	J	have a strong tolerance to shallow-water habitats but are sensitive to low light
Monoraphidium convolutum, *Monoraphidium griffithii*, *Nephrocytium* sp.	X1	have a strong tolerance to shallow water habitats but are sensitive to low nutrient conditions
Peridinium sp.	L_0	considered as summer epilimnia, usually inhabited to the mesotrophic environment and sensitive to water mixing
Microsystis sp.	L_m	considered as summer epilimnia, usually inhabited to the eutrophic environment and sensitive to water mixing

Table 4. Regression models between phytoplankton groups (derived from the Bray-Curtis similarity index) and environmental parameters (selected from RDA analysis).

Model	Term	Coefficients:	Std. Error	Sig, Level	R^2	p-value
Gr1~Cond+DO+SRP	Intercept	436.3	120	*	0.88	0.009
	Cond	-17.6	42.4			
	DO	-347.8	91.6	*		
	SRP	191	74.6	.		
Gr2~Cond+DO+SRP	Intercept	-5.76	77.7		0.93	0.002
	Cond	-180.8	27.4	**		
	DO	346.7	59.2	**		
	SRP	-23.9	48.2			
(Gr1+Gr2)~Cond+DO+SRP	Intercept	430.5	128.2	*	0.85	0.01
	Cond	-198.3	45.2	**		
	DO	-1.08	97.7			
	SRP	167.1	79.6	.		

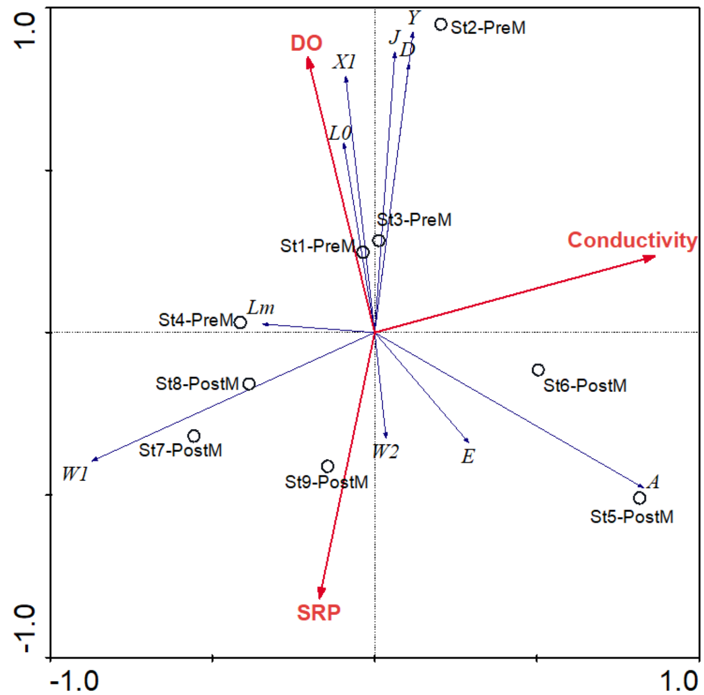

Fig. 4. RDA ordination plot of phytoplankton functional groups concerning environmental variables and sampling sites in pre-monsoon and post-monsoon.

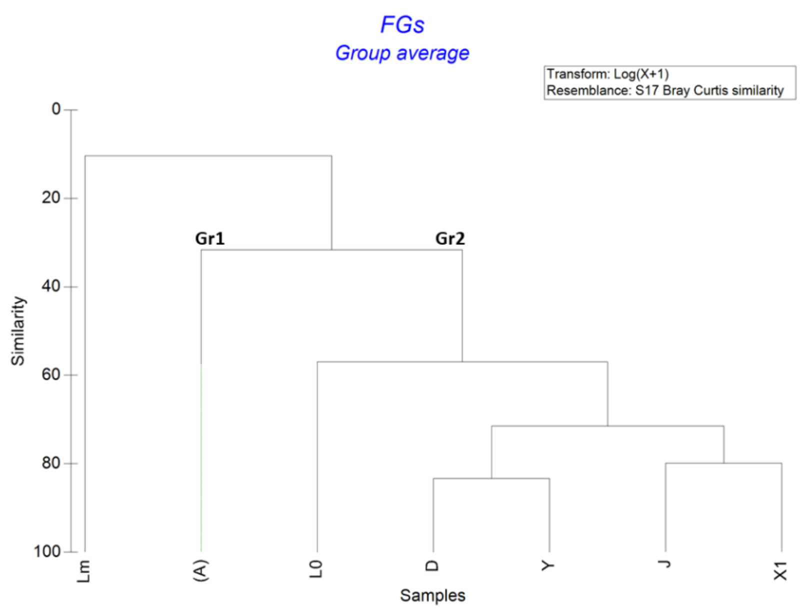

Fig. 5. Bray-Curtis similarity dendrogram of functional groups (FGs) of phytoplankton found during pre-monsoon and post-monsoon sampling periods. The assigned groups Gr1 (A)=A, E, W1 and W2and Gr2=L0, D, Y, J and X1showed similarity <35%. FG Lm, represented by only one species, was excluded due to low contributions (<20%).

The regression models for the groups (Gr1 and Gr2) and environmental parameters (DO, conductivity, and SRP) revealed significant relationships between the groups and the environmental parameters, with R^2 values of 0.88 and 0.93, respectively. The relationship between these parameters, when combined with Gr1 and Gr2, was also significant at $p < 0.01$, with an R^2 of 0.85 (Table 4). This suggested that the water quality index (WQI) using these parameters might effectively explain the water quality status of the swamp forest, considering phytoplankton FGs.

The WQI values of the swamp forest varied from 34 to 94, with the maximum limit being 100 (Supplementary Table S1 a-i). Thus, the water quality status of the sampling sites ranged from good to very poor. In the pre-monsoon period, water quality was poor, and in the post-monsoon period, it reached the maximum poor-quality limit (>75, which is very poor). Overall, the water quality in the Ratargul Swamp Forest was poor (Fig. 6).

Fig. 6. Water quality index (WQI) of different sampling sites during pre-monsoon and post-monsoon, showing water quality class, which varied from "good" to "very poor" in the Ratergul Swamp Forest, Bangladesh. The orange line indicates the boundary between "good" and "poor," and the red line indicates the boundary between "poor" and "very poor.".

The TSI (Chl) showed that the trophic status of the swamp forest varied from mesotrophic to supereutrophic (TSI value: 52-68). In the pre-monsoon period, the trophic status was mesotrophic; in the post-monsoon period, the status was eutrophic. So, overall, the trophic status of the Ratargul Swamp Forest was eutrophic (Fig. 7).

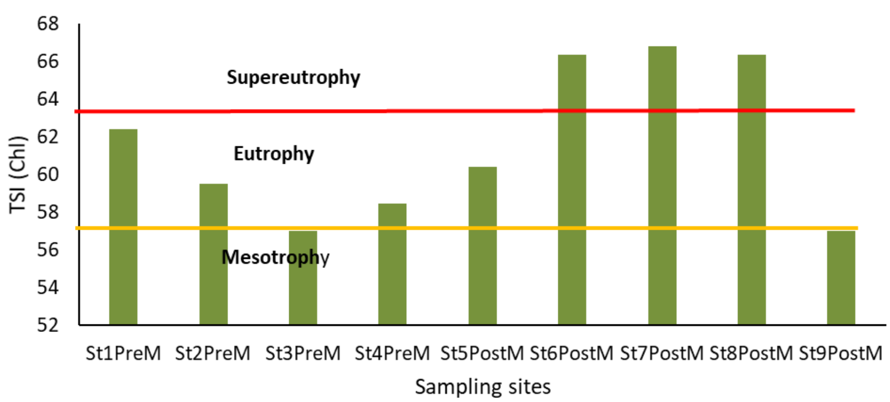

Fig. 7. Trophic state index based on chl *a* [TSI (Chl)] of different sampling sites during pre-monsoon and post-monsoon, showing that trophic status varied from "mesotrophy" to "supereutrophy" in the Ratergul Swamp Forest, Bangladesh. The orange line indicates the boundary between "mesotrophy" and "eutrophy", and the red line indicates the boundary between "eutrophy" and "supereutrophy".

In Ratargul Swamp Forest, flooding occurs seasonally, depending on changes in water flow and depth profiles. This feature is quite common in the freshwater swamp forests of Southeast Asia (Clews *et al.*, 2018). Water flow velocity can alter various environmental variables in different aquatic habitats, thereby affecting phytoplankton assemblages (Plata-Díaz *et al.*, 2011). The results supported this: when inundation began, water velocity increased, and alterations in the above environmental variable occurred, leading to changes in phytoplankton abundance. Extensive flooding occurs beyond the forest during the monsoon, washing away the grazing land and some residential areas. So, when water starts falling during the post-monsoon, some nutrients remain in the water. So, the present research findings confirm that phytoplankton FGs are sensitive indicators of the ecological condition of the forest, aligning with global evidence that FG approaches outperform traditional metrics in flood-pulsed systems (Abonyi *et al.*, 2012; Becker et al. 2010). The dominance of W1 (e.g., *Euglena* spp.) post-monsoon reflects its tolerance to organic loading, mirroring the elevated BOD observed by Nahian *et al.*, (2018) and underscoring the role of monsoon-driven nutrient flushing. Notably, the correlation between SRP and phytoplankton in the pre-monsoon ($r = 0.9$) and the influence of SRS during the post-monsoon period suggest seasonal shifts in limiting nutrients-a pattern likely driven by sediment scouring during floods and subsequent silicate release. Some new diatom species characterised the phytoplankton composition during the post-monsoon period. Several studies have established a correlation between SRS concentration and diatom abundance (Gogoi *et al.*, 2019; Murulidhar and Murthy 2015; Yang *et al.*, 2008).

A majority of phytoplankton species belonging to the phyla Euglenophyta and Heterokontophyta were present in both seasons, and the DO range (1.7-2.7 mg/l) indicated a mesotrophic state of the swamp forest (Tavernier *et al.*, 2009). Phytoplankton succession was observed from the pre-monsoon to the post-monsoon period, leading to changes in the composition and abundance of euglenophytes and heterokontophytes. In both seasons, a nearly identical abundance of *Cryptomonas erosa* was found, which reproduces and grows in low light intensities (Steward and Wetzel, 1986). During the investigation, low light was observed due to the presence of various aquatic angiosperms, which provided a canopy cover, typically characteristic of swamp forests (Clews *et al*., 2018; Choudhury *et al*., 2004).

Significant differences were observed in a few environmental variables between seasons, and the pytoplankton functional groups reflected the ecological status of the forest, both spatially (inundated area) and seasonally (water flow). The RDA ordination plot differentiated pre-monsoon and post-monsoon sampling sites based on functional groups and environmental variables (Fig. 4). The W1 and W2 functional groups were representative groups of both seasons. The W1 functional group prefers to live in organic-rich conditions and can tolerate high BOD. As a result, the occurrence of this group is higher in the post-monsoon season, although it is not representative of the pre-monsoon season. In the RDA ordination plot, conductivity was negatively correlated with these sampling sites and W1 functional groups (Fig. 6). During the pre-monsoon period, water flow began to increase. The members of this group are fast-growing, grazing-sensitive species that are adapting to organic pollution—this is a crucial phytoplankton compositional pattern in this forest system, which increases as the monsoon begins to play a role in gradually carrying large amounts of sediment on the forest floor. Similarly, the W2 functional group showed a negative correlation with DO, with higher values in some pre-monsoon sampling sites than in post-monsoon sites. Functional group D was sensitive to nutrient depletion and showed a negative correlation with SRP concentration, which was lower during the pre-monsoon season. So, it was negatively correlated with some of the pre-monsoon sites. The functional group A, dispersed between SRP and conductivity, exhibits a high affinity with St5-PostM, indicating a clean and nutrient-deficient condition. This sampling site, situated at the periphery of the forest, consists of different diatom species not observed during the pre-monsoon period. This illustrates the seasonal variation in phytoplankton species exhibited by functional groups.

In the present study, it was observed that phytoplankton FGs were effective in assessing water quality in the forest. This was mainly supported by the regression results for the reduced FGs (Gr1 and Gr2) on selected environmental parameters. Later, TSI (Chl) also supported the result by showing the trophic status of the forest. The findings suggested that phytoplankton functional groups may be a key element in assessing the ecological status to support management of this type of aquatic habitat. Our results support the integration of FGs into the management of the swamp forest. The association of the W1 group with poor water quality (WQI > 75) signals eutrophication risks, while diatom-dominated FGs (e.g., A) could serve as recovery indicators. To mitigate monsoon-driven nutrient loading, we recommend buffer zones to reduce sediment inflow and real-time FG monitoring during floods.

Conclusion

The present study bridges a critical gap in wetland ecological assessment by demonstrating that phytoplankton FGs capture ecological shifts imperceptible to conventional methods. The following key findings support this:

- Monsoon inundation drove FGs succession, favouring organic-pollution-tolerant W1 post-monsoon.
- Nutrient correlations shifted seasonally, with SRP and SRS emerging as key drivers of change.
- FG-based indices (WQI, TSI) confirmed trophic status, aligning with physicochemical data but offering an earlier warning.

In addition, WQI indicated poor water quality, resulting in an eutrophic status based on TSI (Chl) or vice versa. This finding suggests that assessing ecological conditions is more practical when environmental factors correlate with biological factors; such a phenomenon was observed in the Ratargul Swamp Forest, where the dynamics of phytoplankton FGs serve as a representative of the biological quality elements of the ecosystem. So, for Ratargul and similar wetlands, we urge policymakers to (i) adopt FGs-based monitoring to detect degradation before physicochemical thresholds are exceeded, (ii) prioritise SRP control post-monsoon through sediment retention measures, and (iii) future studies should expand FG applications to other tropical swamps, validating their global utility.

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