



The Potential Role of Phytoplankton Functional Groups Under Anthropogenic Stressed Wetlands: Characterizing The Environmental Sensitivity

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Abstract

Anthropogenic and climatic changes are continuously altering the freshwater plankton, necessitating an evaluation of the complex structure of plankton communities to understand and mitigate these impacts. In this context, the present study focuses on evaluating the structure of plankton communities, specifically Phytoplankton Functional Groups (FGs) for assessing the environmental sensitivity of wetlands under changing scenario. These FGs are defined by shared adaptive features rather than taxonomic traits. Over the period from 2016 to 2018, two ecologically distinct wetlands were examined, analysing their phytoplankton FGs and their relationship with water quality parameters. Ecohydrological data revealed significant seasonal variations ($p \leq 0.05$) in key parameters such as water depth, temperature, pH, electrical conductivity, dissolved oxygen, total alkalinity, total hardness, $\text{NO}_3\text{-N}$, and $\text{PO}_4\text{-P}$. Notably, there were no significant differences observed among the sampling stations within each wetland. A total of 125 phytoplankton genera/species were classified into 23 FGs in the open wetland and 22 FGs in the closed wetland. Spatial and seasonal analyses of dominant FGs suggested both wetlands were experiencing pollution pressures. This study highlights the powerful role of phytoplankton functional groups (FGs) as bioindicators of wetland health, uncovering pollution pressures. In open wetlands, 15 phytoplankton FGs with 36 key taxa (Indicator Value $\geq 40\%$) emerged as critical indicators, while in closed wetlands, only 10 FGs with 17 taxa were identified. To assess eutrophication, the occurrence of these indicator species was evaluated using BVSTEP function analysis. The study recommends pollution reduction in catchment areas and restoration of riverine connectivity to enhance FG diversity. Phytoplankton FG methodologies are deemed effective for assessing the environmental sensitivity of wetlands significantly impacted by human activities. This research offers a scientific foundation for the evaluation and restoration of wetland ecosystems.

Keywords Phytoplankton · Functional group · Ecohydrology · Ecological indicator · Wetland

Highlights

- Phytoplankton functional groups (FGs) serve as precise bioindicators of wetland environmental sensitivity and pollution pressures.
- Seasonal and spatial assessments of water quality reveal insights into wetland ecological health.
- The response of phytoplankton FGs to environmental factors effectively indicates water quality.
- Key plankton species were identified as indicators of wetland ecological sensitivity.

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Introduction

Inland freshwater ecosystems and their finite resources are increasingly affected by climatic and anthropogenic factors. Ecology plays a crucial role in understanding the distribution and interactions of organisms within their environment. Rapid environmental changes, including reduced water

depth, extreme events, pollution, eutrophication, and ecological degradation (Sarkar et al. 2020; Zhang et al. 2019; Zhu et al. 2021; Kumari et al. 2023), are growing concerns. Wetlands, as primary renewable water resources, provide diverse services that enhance livelihoods (Sarkar et al. 2020). Shallow lakes, dynamic aquatic ecosystems, are significantly impacted by rising temperatures and nutrient fluctuations, leading to rapid phytoplankton succession (Allende et al. 2019; Poniewozik & Lenard 2022). Phytoplankton abundance and diversity are highly responsive indicators of ecological changes in aquatic environments (Gogoi et al., 2021; Mohanty et al. 2021). While traditional research has focused on phytoplankton assemblages and diversity for monitoring various aquatic ecosystems (Sarkar et al. 2020; Gogoi et al., 2021; Mohanty et al. 2021), these methods do not fully capture ecosystem functions. Understanding the functional roles and structural adaptations of phytoplankton is crucial for comprehending their ecological interactions (Reynolds et al. 2002). Taxonomic classification provides morphological and genetic information but falls short in understanding ecological functional similarities.

The categorization of phytoplankton based on functional roles and morphology has been explored by ecologists in freshwater (Salmaso et al. 2015; Allende et al. 2019; Wang et al. 2021; Abonyi et al. 2021) and marine ecosystems (Xu et al. 2016). For instance, within Bacillariophyta, various cell forms and life strategies from unicellular to colonial and filamentous—are documented. Ecologists have sought to address this complexity by grouping organisms based on functional characteristics such as size, form, nutrient requirements, life strategies, distribution patterns, and common structural and functional features.

The FG classification of phytoplankton has been primarily fostered to understand how environmental factors shape the functional composition of phytoplankton (Reynolds et al. 2002). This FG approach allows for the distinction between “natural constraints” and “human impacts” on phytoplankton, facilitating the evaluation of a river’s ecological status (Yan et al. 2023). The concept gained traction as ecological understanding of phytoplankton species’ functional qualities improved. Today, the approach proves effective in understanding seasonal changes in phytoplankton communities and assessing the ecological status of aquatic ecosystems based on physiological, morphological, and environmental distinctiveness (Dochin, 2019; Latinopoulos et al. 2020). Initially, identified 14 phytoplankton functional groups, later expanded to 31 (Reynolds et al., 2002), and further to over 40 groups (Padisak et al. 2009). Methods for classifying functional groups based on shared ecological features and functional connectivity have since been refined (Reynolds et al. 2002; Padisak et al. 2009; Salmaso et al. 2015; Wang et al. 2021).

The concept of phytoplankton functional groups (FGs) has been widely applied to assess the ecological status of diverse aquatic habitats (Borics et al., 2014; Toporowska et al. 2018; Varol, 2019; Allende et al. 2019; Latinopoulos et al. 2020; Wang et al. 2021).

This study focused on two shallow oxbow lakes in eastern India, each with distinct morphological features and significant human impact. These lakes serve multiple purposes beyond fisheries enhancement, making them ideal for examining phytoplankton and identifying key phytoplankton functional groups (FGs). Anthropogenic and climatic changes are driving significant alterations in freshwater plankton diversity, specifically within phytoplankton Functional Groups (FGs). These changes are reflected in the spatial and seasonal variations in phytoplankton community structure, which are closely linked to water quality parameters. By analyzing phytoplankton FGs as bioindicators, it is possible to detect pollution pressures and assess the ecological health of wetland ecosystems. This study hypothesizes that the diversity and composition of phytoplankton FGs are sensitive indicators of environmental changes in wetlands, and that effective management strategies can mitigate these impacts by enhancing FG diversity through pollution reduction and restoration efforts. By gathering ecological data on these lakes, this study contributes to the understanding of their environmental sensitivity and provides essential insights for informing government policies on aquatic ecosystem health management. The findings establish a foundation for further ecological assessments and efforts to improve and restore these unique shallow lakes.

Materials and Methods

Study Area and Sampling Sites

The wetlands 25°59'54.02"N 88°03'27"E (Khalsi) and 23°05'14.14"N 88°04'56.22"E (Akaipur) located in West Bengal, are two distinct wetlands and productive in terms of fisheries (Fig. 1). The water spread area of Khalsi ranges from 36 to 65 hectares, while Akaipur varies between 20 and 28 hectares. Our study spanned from March 2016 to February 2018, with seasonal sampling across three stations in each wetland: pre-monsoon, monsoon, post-monsoon, and winter. These ecosystems are nestled among farmlands and residential areas. They support capture-based and culture-based fisheries, sustaining approximately 300 families in Akaipur and 500 in Khalsi (Meena et al., 2019). Both wetlands lie within the lower Ganga basin and are affected by agricultural runoff, domestic waste, jute retting, silt from monsoon floods, and other human activities. Akaipur is a closed wetland with no river connection, while

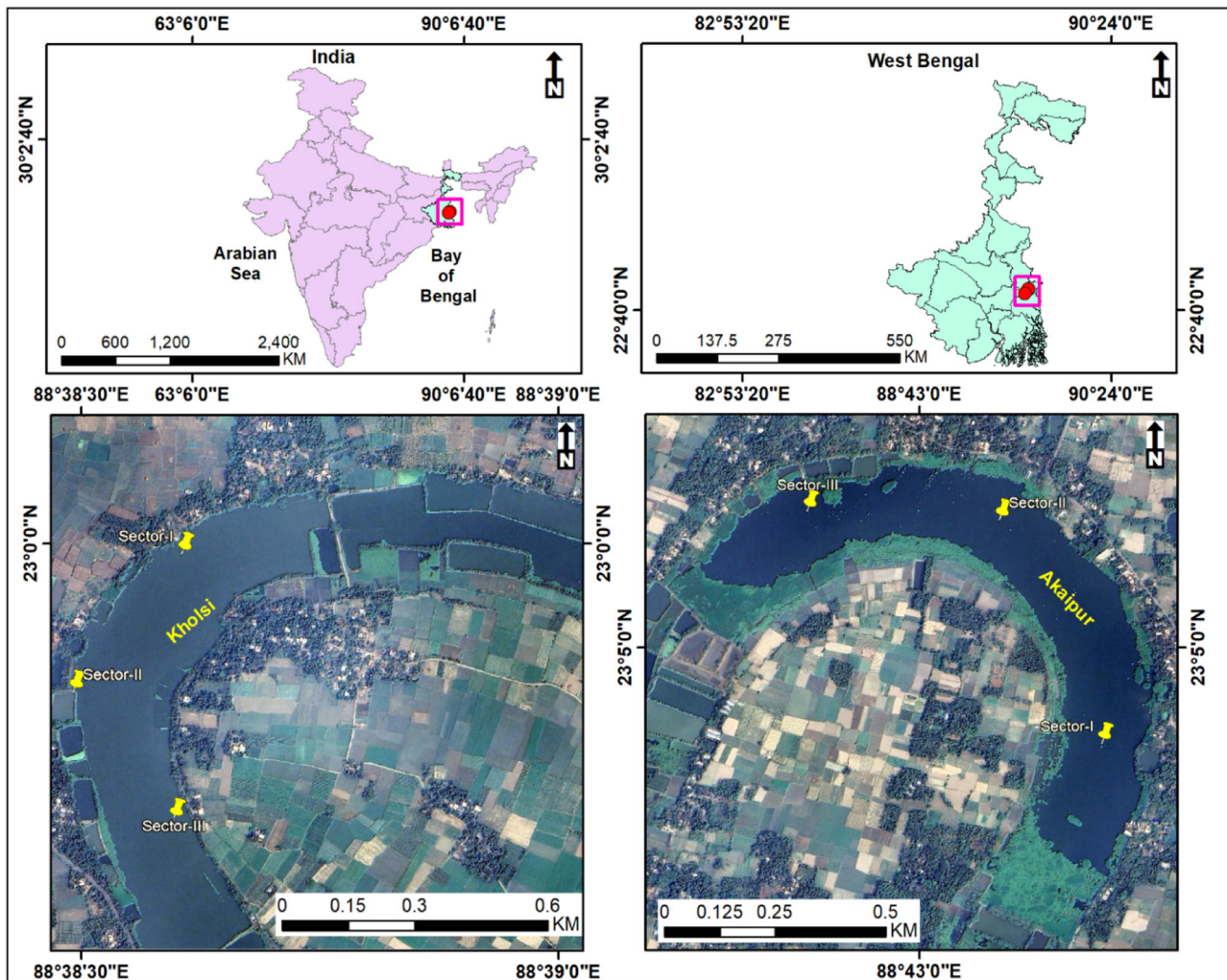


Fig. 1 Map showing three sampling sites of each wetland: seasonally open (Khalsi) and closed (Akaipur)

Khalsi reconnects to its parent river during the monsoon. Their abundant macrophytes provide refuge and breeding grounds for various indigenous fish species. The determination of sampling sites in both lakes was done in such a way that the sample has a possible resemblance to the present ecological status of the lakes. Khalsi (seasonally open wetland) Sector I is the middle zone (free from macrophytes), Sector II is open with a river channel and infested with *Eichhornia* hyacinth, and Sector III is dominated by *Nymphaea*. In the closed wetlands wetland (Akaipur), station 1 surroundings are dominated by human habitation Station II clear zone free from macrophytes, and Station 3 is dominated by macrophytes and surrounding agricultural crop fields.

Water Sampling

Water samples were collected from each sampling site to assess various water quality parameters. Water temperature

(Temp.), pH, and electrical conductivity (EC) were measured in the field using a multi-parameter probe (Eutech PCS Test 35). Transparency (SD) was determined using a Secchi disc. Dissolved oxygen levels were measured on-site using the modified Winkler titrimetric method (Strickland and Parsons, 1972). Additionally, total alkalinity (TA), total hardness (TH), and nutrient parameters such as nitrate-nitrogen ($\text{NO}_3\text{-N}$) and phosphate-phosphorus ($\text{PO}_4\text{-P}$) were analyzed following standard methodologies outlined by the American Public Health Association (APHA, 2012). Chlorophyll a (Chl a) concentration was determined using the standard spectrophotometric method with a HACH Spectrophotometer (DR 2800, Germany) in accordance with APHA (2012) guidelines. In addition, the WQI was calculated based on the estimated water quality parameters (water temperature, pH, electrical conductivity, dissolved oxygen, total alkalinity, total hardness, $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$) to understand the grade of water suitability for human use and aquatic biodiversity and propagation. Here, we

followed the Weighted Arithmetic Water Quality Index (WAWQI) (Brown et al., 1972) for WQI calculation. The degree of purity or potability of the water variables was specified by the Bureau of Indian Standards (BIS, 2012). The WAWQI rating is 0–25: Excellent; 26–50: Good; 51–75: Poor; 76–100: Very poor and >100: unfit for consumption.

Phytoplankton Sampling

Subsurface phytoplankton samples (0.5 meters below the surface) were collected seasonally across four distinct period: pre-monsoon (March–June), monsoon (July–September), post-monsoon (October–November), and winter (December–February) from April 2016 to March 2018. For qualitative and quantitative study of phytoplankton, water samples were collected by using a hand-held plankton net of mesh size 20 μm mesh size bolting silk cloth. 50 L volume of sub-surface water was filtered from each sampling location and the concentrated sample was transferred to a 50 ml plastic container and stabilized in situ with Lugol's iodine solution (1.5% v/v). fixed into 4% buffered formalin. The algal cell count was enumerated using the Sedgwick–Rafter counting cell method by using a trinocular light microscope 'Axiostar plus – Carl Zeiss' (Zeiss 37081). Taxa were identified and classified following standard literature (Prescott, 1962; Ward and Whipple, 1992; Cox, 1996; Belinger and Sigeo, 2010). The updated algal taxonomic nomenclature was reaffirmed by following the Algae Base (Guiry and Guiry 2020). Phytoplankton biomass was assessed following the geometric approximation of each taxon (Hillebrand et al. 1999) and converted into biomass (1 $\text{mm}^3 \approx 1 \text{ mg}$ fresh weight). Phytoplankton biomass was assessed using geometric approximations for each taxon (Hillebrand et al. 1999) and converted into biomass (1 $\text{mm}^3 \approx 1 \text{ mg}$ fresh weight). Phytoplankton taxa were classified into functional groups (FGs) based on criteria established by Reynolds et al. (2002), Padisak et al. (2009), and Borics et al. (2020).

Statistical Analysis

The summary statistics (mean and standard deviation) of the abiotic and biotic data were performed in MS Excel 2010. The hydro chemical parameters in different seasons for both wetlands were subjected to one-way analysis of variance (ANOVA) and post hoc test (Duncan's) using SPSS v.21. To comprehend the major water variables in the studied wetlands, principal component analysis (PCA) was performed. In addition, we performed permutational MANOVA (PERMANOVA) to test the differences ($p \leq 0.05$) between the phytoplankton FGs (biomass value) with respect to seasons and stations for both wetlands. To

examine the similarity of community structure between FGs, non-metric multidimensional scaling (with the distance-based trajectory) was carried-out using 'Bray-Curtis' similarity measures. Pre-treatment of all biological data was done by square root transformation before analysis. Canonical correspondence analysis (CCA) between biotic (FGs) and the abiotic variables (10 water variables) was performed to examine their relationship for open and closed wetlands. In addition, distance-based linear model (DistLM) was performed using the distance-based redundancy analysis constrained ordination (dbrDA). Then we obtained the model using the AICc selection criteria and the stepwise selection procedure. The indicator species analysis was carried-out to identify the potential indicator species of phytoplankton in the seasonally open and closed wetland environment in each season. An indicator value (*IndVal*) of $\geq 25\%$ can be considered the threshold to identify the indicator taxa in this method, meaning that a taxon is present in $\geq 50\%$ of the samples in a group and that its relative abundance in each group is $\geq 50\%$ (Hunt and Hosie, 2006). All multivariate analyses were performed using statistical tools such as PRIMER version 6.1.6 and PAST version 4.08.

Result

Water Quality Parameters

The water quality parameters of open and closed wetlands are presented in Table 1, revealing significant variations between them, as indicated by PERMANOVA analysis ($F = 5.673$; $p = 0.01$). Maximum water depth was observed during the monsoon season in open wetlands and during winter in closed ones, with significant seasonal differences ($p < 0.05$) in both. Transparency was lower in closed wetlands but not significantly ($p > 0.05$), while temperature variations were significant across seasons, especially in closed wetlands. Water remained alkaline in both wetlands with pH values between 7.7 and 8.7, and electrical conductivity (EC) was significantly higher during pre-monsoon in open wetlands. Nutrient concentrations varied significantly between seasons, with nitrate-nitrogen ($\text{NO}_3\text{-N}$) highest during the monsoon in open wetlands and during pre-monsoon in closed ones, and phosphate-phosphorus ($\text{PO}_4\text{-P}$) levels highest in winter for open wetlands and monsoon for closed ones. Principal Component Analysis (PCA) revealed that axes 1 and 2 explained 61.8% of the seasonal variation in open wetlands and 58.0% in closed wetlands, with pH, temperature, EC, TA, $\text{NO}_3\text{-N}$, and water depth being key variables (Fig. 2a, b). Based on the calculated value of Water Quality Index (WQI), the water quality was found to be 'good' and ranged from 24.92–31.65 and 29.77–35.54 for Khalsi and Akaiapur

Table 1 Mean values and standard error (in parenthesis) of water quality parameters in the studied wetlands

Variables	Khalsi/Open wetland				Akaipur/Closed wetland			
	PRM	MON	POM	WIN	PRM	MON	POM	WIN
Depth (cm)	77.50 ^a	257.17 ^b	200.8 ^c	172.17 ^a	141.66 ^a	117.33 ^a	167.25 ^{ab}	214 ^b
SD (cm)	77.50 ^a	85.83 ^a	116.16 ^a	79.0 ^a	33.16 ^a	53.58 ^a	48 ^a	44.91 ^a
Temp. (°C)	31.58 ^a	28.75 ^b	28.58 ^b	22.50 ^c	29.58 ^a	26.33 ^{ab}	31 ^a	24.41 ^b
pH	7.96 ^a	8.02 ^a	7.76 ^a	8.26 ^b	8.15 ^a	8.53 ^a	8.39 ^{ab}	8.73 ^b
EC (μS/cm)	348.16 ^a	214.73 ^b	273.0 ^b	224.50 ^b	124.16 ^a	120.66 ^a	155.18 ^a	120.56 ^a
DO (mg l ⁻¹)	6.75 ^a	5.30 ^a	6.03 ^a	7.41 ^b	6.27 ^a	8.73 ^b	7.0 ^{ab}	8.83 ^b
TA (mg l ⁻¹)	163.66 ^a	99.75 ^b	87.33 ^b	140.50 ^a	86.83 ^a	45.83 ^b	63.91 ^a	64.66 ^c
TH (mg l ⁻¹)	133.50 ^a	123.58 ^{ab}	86.33 ^b	131.66 ^a	63.66 ^a	41.83 ^{ab}	55.83 ^a	54.66 ^a
NO ³ -N (mg l ⁻¹)	0.19 ^a	0.44 ^b	0.195 ^a	0.16 ^a	0.311 ^a	0.225 ^b	0.163 ^b	0.134 ^c
PO ⁴ -P (mg l ⁻¹)	0.035 ^a	0.087 ^{ab}	0.099 ^{ab}	0.107 ^b	0.023 ^a	0.291 ^a	0.114 ^b	0.09 ^b

Values with the same letters are not significantly different in seasons (PRM Pre-monsoon, MON Monsoon, POM Post-monsoon, WIN Winter)

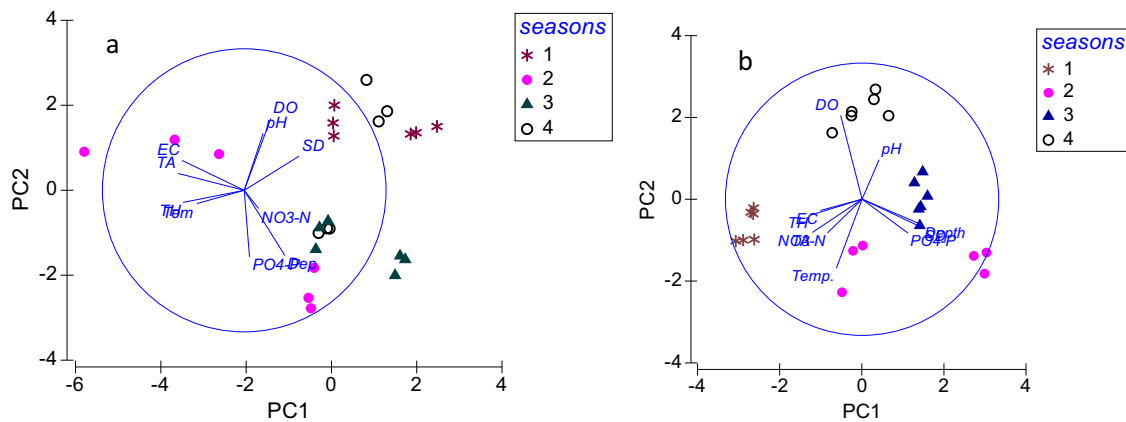


Fig. 2 Principal component analysis of water variables in Open (a) and closed wetland (b) 1: pre-monsoon, 2: monsoon, 3: post-monsoon and 4: winter season

wetlands, respectively. While comparing both wetlands, the index value was comparatively higher in the closed wetland, indicating that the closed wetland had slightly low water quality than the open one.

Phytoplankton FGs Biomass Composition

In the present study, a total number of 125 phytoplankton genera/species was classified into 23 phytoplankton FGs – TB, P, G, X1, T, S3, J, X2, N, H2, H1, M, S2, K, Lo, MP, TD, S1, W1, W2, C, D, F of which 22 FGs from the closed wetland. W2 FG is absent from the closed wetland (Supplementary file: Table S2). Single species *Trachelomonas* sp. of functional group W2 was dominant during the post-monsoon season in open wetland. Phytoplankton FGs biomass (mgL⁻¹) of seasonally open wetland was calculated highest (90.92 ± 19.56) in the post-monsoon season and lowest (26.38 ± 8.63) in the monsoon season. The average biomass of FGs was higher in open wetlands than the closed ones. In the closed wetland, phytoplankton FGs biomass

(mgL⁻¹) was slightly higher (29.52 ± 16.23) in winter season than post-monsoon season (29.21 ± 14.86) and lowest (15.11 ± 6.78) in pre-monsoon season (Fig. 3). We have also studied the assemblage pattern of FGs in the different sampling sites in both closed and open wetlands to know the intra variations of wetlands. The finding is very interesting, among the 22 FGs recorded from closed wetland dominance of Functional group M (more than 40% contribution) followed by K (more than 20% contribution) in all three sectors. Whereas in seasonally open wetland, more homogeneous distribution of FGs, but dominance of M (more than 20%) contribution in Sector III and I but in the clear zone (Sector II) dominance of J followed by P (Fig. 4). PERMANOVA analysis exhibited a significant variation of phytoplankton composition between seasons (Open: $F = 2.116$; $p = 0.016$; Closed: $F = 2.1331$; $p = 0.022$) and insignificant between stations in both the wetlands.

FGs-wise seasonal distribution pattern was assessed for both open and closed wetlands. In open wetland, 23 FGs have been recorded throughout the study. Their contribution

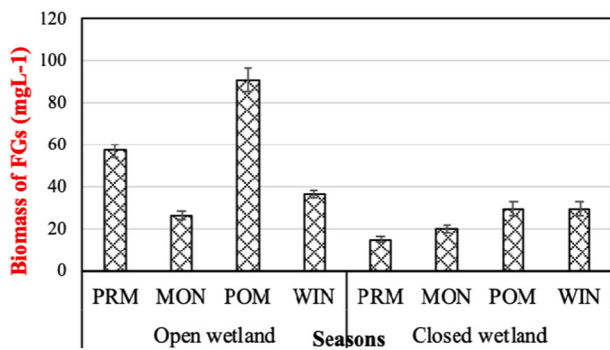


Fig. 3 Seasonal variation in phytoplankton FGs biomass/ biovolume (mg L^{-1}) in both the wetlands (error bars showing the standard deviation); PRM pre-monsoon, MON monsoon, POM post-monsoon and WIN winter season

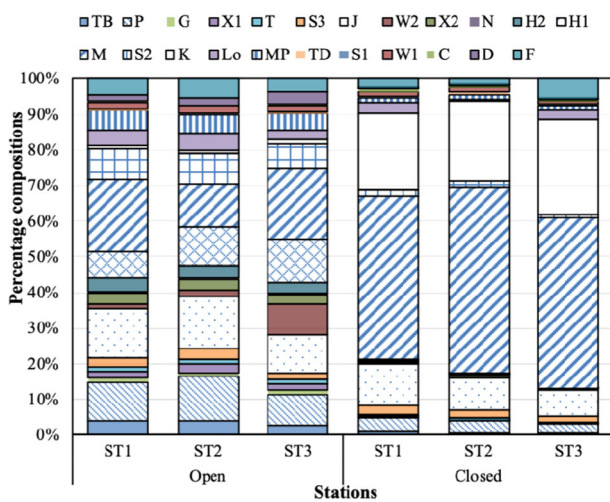


Fig. 4 Spatial variation in phytoplankton biomass/ biovolume (mg L^{-1}) of FGs for both the wetlands

to each season has been given in Fig. 5. TD was the most dominant FG during Pre-monsoon followed by X2 and H2. Twenty-one FGs have been recorded from post-monsoon except S1 and X1. The lowest contribution (<2%) was made by F during the post-monsoon season. Biomass of FGs – T and F (more than 70%) was contributed during the winter season followed by S1, C, and N. Except for these two FGs–TD and S3 rest were recorded during the winter season. FG–TD was found to be most dominant throughout the study period in open wetland.

In closed wetlands, the dominance of FGs–S1, S2, S3, H2, X1, MP in pre-monsoon season. The contribution of FGs–G, N, H1, and Lo were almost negligible in pre-monsoon. Single FG S1 was found to be most dominant in the pre-monsoon season. The FGs such as N and TD were found to be the most prevailing Group (contributing more than 95%) followed by T and D in the post-monsoon season. H2 is the only FG that has not been recorded during the post-monsoon season. FGs–Lo, X2, and G were found

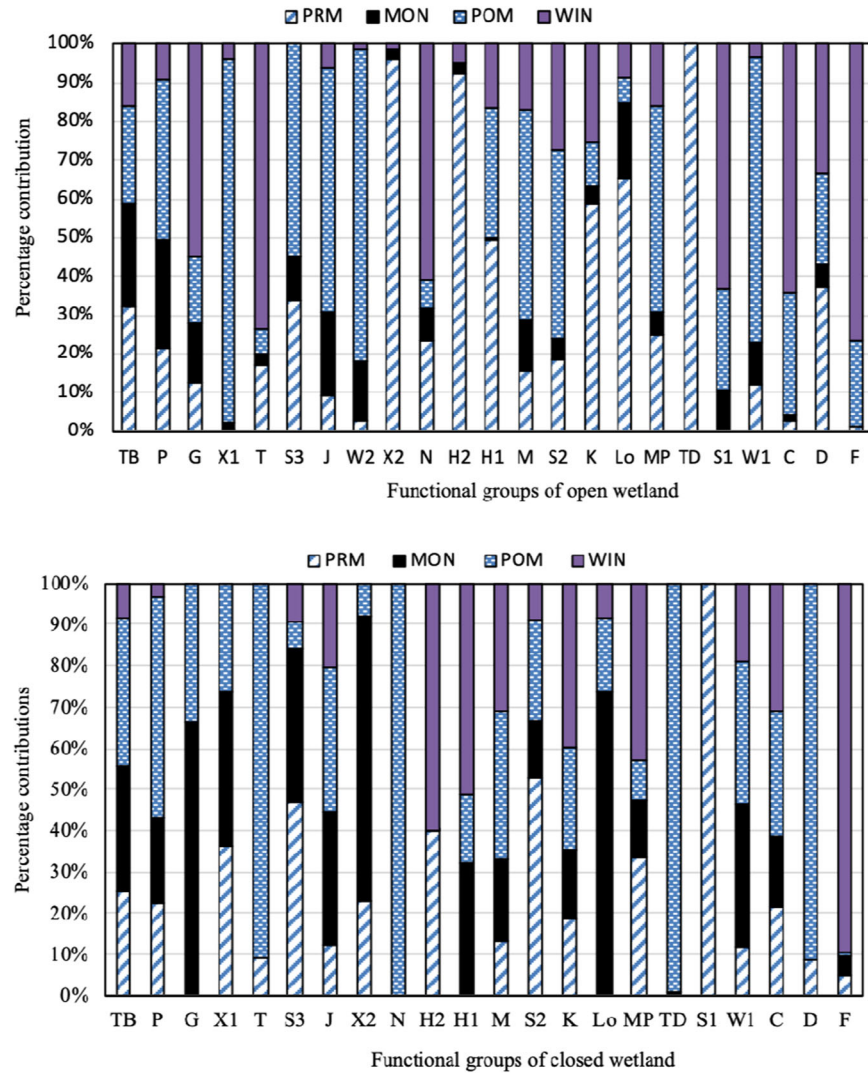
to be dominating during the monsoon season while F was in the winter season. The FGs–G, X1, T, X2, N, TD, S1 and D were least or not contributing to the biomass of winter seasons (Fig. 5).

Non-metric multidimensional scaling based on Bray-Curtis similarity matrix for the FGs in open wetland showed overall 54% similarity of the phytoplankton FG (biomass) and their resemblance increased steadily from monsoon to winter and pre-monsoon (Fig. 6a). Likewise, the overall similarity of phytoplankton biomass in the closed wetland was slightly lower at 43% (Fig. 6b). In addition, the FGs biomass in the studied wetlands was multimodal as samples in both the wetlands were widely separated in the same season. The cumulative dominance curve (k – dominance curve) extracted for the seasonally open wetland reflected that the biomass of phytoplankton functional groups was noticeably higher during the monsoon than in other seasons (Fig. 7a). However, in the closed wetland, the plotted curves indicate similar pattern of dominance (biomass) with their overlapping nature (Fig. 7b). In addition, the nature of phytoplankton biomass between post-monsoon and winter period is closely resembles than the seasons between pre-monsoon and monsoon. In winter, the biomass of the phytoplankton functional groups in the closed wetland increased substantially.

Relations of the Phytoplankton FGs to Environmental Factors

Canonical Correspondence analysis was performed between water variables (depth, transparency, SD, pH, EC, DO, TA, TH, $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$) and phytoplankton functional groups (biomass value) to comprehend the interactions between the factors. The eigen value and percent variation were calculated, and the scaler explained 0.17616 and 40.04% correlations in axis 1 and 0.10613 and 24.73% correlations in axis 2 in the data set. The variables TA, Temp., depth, SD and nutrients ($\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$) had close affinity with all the functional groups in the open wetland. Water variables such as TA, TH, pH and depth were positively associated in Axis 1 and SD, Temp., pH, $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$ in axis 2. Axis 1 scores 10 functional groups (G, X2, N, H2, H1, K, Lo, TD, S1 and F) and is more closely related to TA, TH, EC, pH and $\text{NO}_3\text{-N}$. Similarly, axis 2 scores six groups (S3, W2, X2, Lo, TD and W1) and showed strong affinity for depth, SD, Temp. and $\text{PO}_4\text{-P}$. Functional groups (TB and X1) showed a negative correlation in both axes. Overall, water depth and transparency showed a strong negative affinity with all functional groups in the open wetland (Fig. 8). In the close wetland, CCA revealed 35.13% and 20.76% variation of the data set with the eigen value 0.1488 and 0.0879 in axis 1 and 2, respectively. Axis 2 achieves higher number of functional groups (TB, C, D, MP, T, H2, S1 and H) and

Fig. 5 Seasonal relative contribution of functional groups biomass (mg l^{-1}) in open and closed wetlands



shows a correlation with Temp., depth, TH, EC and SD. The functional groups – W, J, TB, C, D and T exhibited positive correlation in both the axis unlike F and K. Water variables Temp. and total alkalinity acted as effective factors for functional groups TB, J, T, D and C. Similarly, TD, X1, and S3 showed a strong positive correlation with depth. It was also shown that nutrient parameters ($\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$) had an overall negative influence on all functional groups in the closed wetland (Fig. 8). The NMDS trajectory showed at the similarity of samples biomass increased from winter to pre-monsoon for both the wetlands (Fig. 8). In addition, to quantify the explained variables, distance based linear model (DistLM) was performed to obtain a significant correlation between the phytoplankton functional groups and each of the environmental variables. The linear model explained 72.11% (axes 1 and 2) with the predictor variables TA ($F=4.4111$, $p=0.001$), Temp. ($F=3.2371$, $p=0.008$), PO_4P ($F=3.4139$; $p=0.009$) and NO_3N ($F=2.8967$, $p=0.043$) with the AICc (= 170.34) and

$R^2=0.47$ in the open wetland. Similarly, in the closed wetland also explained 67.42% variation with 6 environmental variables (step-wise selection) viz., depth, SD, Temp. EC, TH and $\text{PO}_4\text{-P}$ could explain the discrepancies in phytoplankton biomass in the studied stations. The fitted model explained AICc value of 138.78 with R^2 (= 0.80675).

Seasonal Occurrence of Indicator FGS

The seasonal occurrence of indicator species among different FGS (*IndVal*) for wetland sensitivity was analyzed and species contributing more than 30% were considered as Indicator species for both the ecosystem (open and closed wetland). The best set of 70 phytoplankton species found to be near a perfect match in the seasonally open wetland. Likewise, a set of 38 species of phytoplankton were found in the closed wetland, which could be potential indicator species. Based on the *IndVal* analysis (>30% threshold value), a total of 92

Fig. 6 Non-metric multidimensional scaling based on Bray-Curtis similarity matrix for the FGs in open (a) and closed wetland (b) PRM pre-monsoon, MON monsoon, POM post-monsoon and WIN winter season (six sampling station for each seasons)

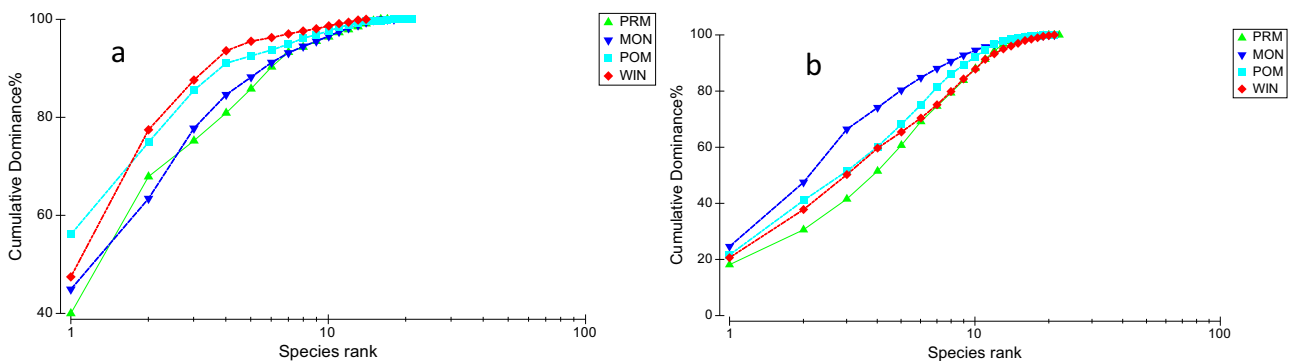
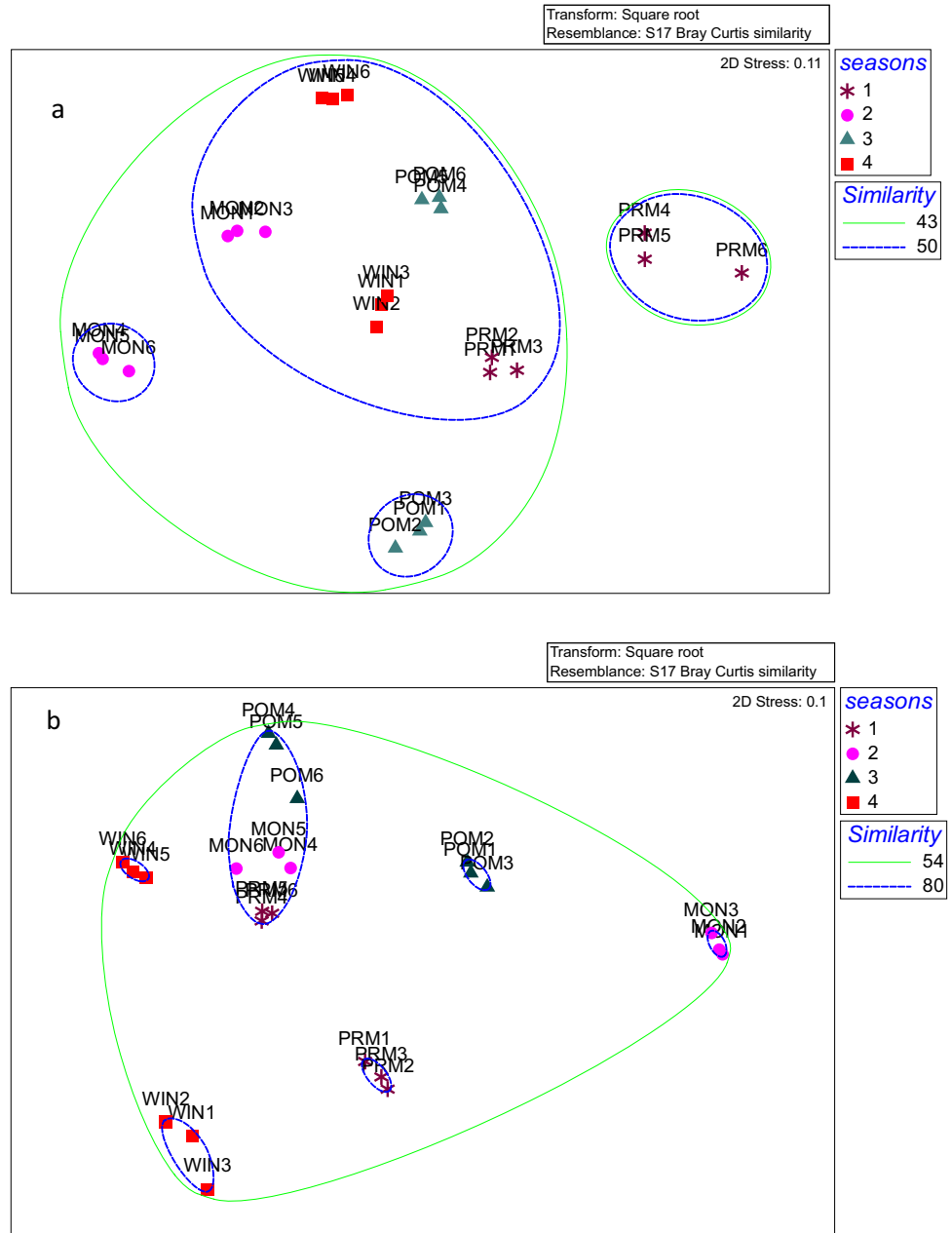
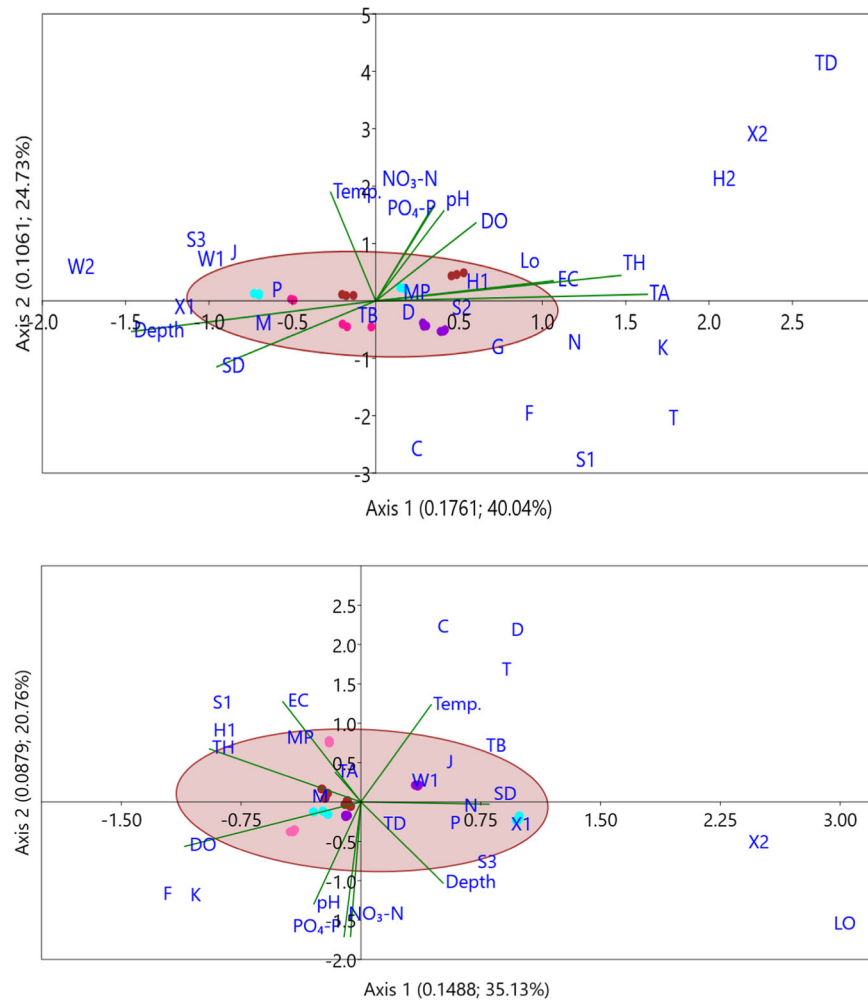


Fig. 7 k-dominance curve showing the dominance pattern of FGs biomass in open (a) and closed (b) wetlands

Fig. 8 CCA plot between water variables and FGs in open (top) and closed wetland (bottom). Dark brown: pre-monsoon; Green: monsoon; pink: post-monsoon; violet: winter



phytoplankton species were recognized as key indicators across seasons, considering both wetlands (Table 2).

In the open wetland, a total of 9 (J, H1, T_B, H2, T_D, X2, K, T, D) phytoplankton FGs were represented as indicators during the pre-monsoon period followed by 8 in post-monsoon. The maximum number of phytoplankton species (36 taxa) was marked as indicator species (*IndVal* \geq 40%) for open wetland. However, the lowest FGs were found in winter with 2 Phytoplankton FGs (F and T_B). In the closed wetland, the FGs indicator was 10 Phytoplankton FGs, comparatively lower than in the open wetland 15 FGs with *IndVal* (\geq 40%). In contrast to open wetland, maximum FGs (9 FGs–J, S2, T_B, TD, X2, G, W1, T, D) during the post-monsoon period. The indicator species that reached *IndVal* (\geq 40%) were *Aphanothece* sp., *Caloneis* sp., *Centrtractus* sp., *Fragilaria* sp., *Mougeotia* sp. *Phacus* sp., *Pinnularia* sp., *Scenedesmus longus*, and *Synedra* sp. While in the monsoon season, only 2 FGs characterized as *IndVal* (\geq 40%) represented by two taxa *Coelastrum reticulatum* (FG-J) and *Gomphospheria* sp. (FG-K). The indicator species were somewhat lower in both the wetlands during winter

season. The *IndVal* ($>$ 40%) was characterized by 2 taxa *i.e.*, *Rhopalodia* sp. (T_B) and *Westella* sp. (F) in the open wetland and only one species occurs in the closed wetland under FGs (F) during winter. Quantitatively several phytoplankton species characterized by *IndVal* (\geq 30%) as indicator species *Caloneis* sp., *Coelastrum* sp., *Coscinodiscus* sp., *Dictyosphaerium* sp., *Euastrum* sp., *Euglena elongate*, *Penium* sp., *Rhodomonas* sp., *Synedra* sp., *Synedra ulna*, *Tetrastrum* sp., *Ulothrix* sp. are common in both wetlands. The FGs for common indicators are depicted in Table 2.

Discussion

The human activities such as agricultural runoff, urbanization, industrial discharges, and aquaculture practices significantly affect the water quality and planktonic algae in the wetlands of West Bengal's wetlands. The wetlands in West Bengal often bordered by agricultural lands, where the use of fertilizers causes nutrient-rich runoff (particularly nitrogen and phosphorus) to enter these wetlands. These

Table 2 Indicator species (*IndVal*) observed for the open and closed wetland in the four seasons (bold: value > 30% is considered as indicator value)

FGs	Indicator Species	Open wetland				Closed wetland			
		PRM	MON	POM	WIN	PRM	MON	POM	WIN
1	<i>J</i>	<i>Ankistodesmus spiralis</i>	50	0	0	0	0	0	0
2		<i>Chroococcus</i> sp.	9.07	9.04	31.89	0	0	0	0
3		<i>Coelastrum reticulatum</i>	0	18.15	0	31.85	0	50	0
4		<i>Coelastrum</i> sp.	0	11.57	33.34	5.09	0	3.79	13.02
5		<i>Pediastrum obtusum</i>	0	0	0	0	11.64	32.02	5.39
6		<i>Pediastrum tetras</i> var. <i>Tetraodon</i>	11.73	8.24	0	30.03	0	0	0
7		<i>Pediastrum simplex</i> var. <i>Duodenarium</i>	0	0	0	0	34.08	0	15.91
8		<i>Scenedesmus abundance</i>	0	9.38	34.41	6.2	0	0	0
9		<i>Scenedesmus abundance</i> var. <i>asymmetrica</i>	0	2.68	47.32	0	0	0	0
10		<i>Scenedesmus abundance</i> var. <i>brevicauda</i>	0	8.64	41.36	0	0	0	0
11		<i>Scenedesmus acuminatus</i>	0	11.98	38.02	0	0	0	0
12		<i>Scenedesmus arcuatus</i>	0	17.91	32.09	0	0	0	0
13		<i>Scenedesmus armatus</i> var. <i>Bicaudatus</i>	0	2.92	47.08	0	0	0	0
14		<i>Scenedesmus bijuga</i>	0	3.24	46.76	0	0	0	0
15		<i>Scenedesmus dimorphus</i>	0	33.86	16.14	0	0	0	0
16		<i>Scenedesmus longus</i>	0	0	0	0	1.912	44.26	0
17		<i>Tetraedron caudatum</i>	0	16.78	33.22	0	0	0	0
18		<i>Tetraedron minimum</i>	0	14	36	0	0	0	0
19		<i>Tetraedron regulare</i>	0	36.9	13.1	0	0	0	0
20		<i>Tetrapedia</i> sp.	0	0	50	0	0	0	0
21		<i>Tetrastrum</i> sp.	0	0	50	0	0	11.85	31.6
22	<i>S2</i>	<i>Aphanothece</i> sp.	0	0	0	0	0	50	0
23		<i>Spirulina</i>	18.48	31.52	0	0	0	0	0
24	<i>H1</i>	<i>Asterionella</i> sp.	0	0	12.61	37.39	0	0	0
25		<i>Dictyosphaerium</i> sp.	0	0	50	0	5.974	3.13	8.41
26		<i>Rivularia</i> sp.	49.49	0	0.51	0	0	0	0
27	<i>T_B</i>	<i>Caloneis</i> sp.	18.51	0	0	31.49	0	0	50
28		<i>Coscinodiscus</i> sp.	50	0	0	0	0	33.33	0
29		<i>Eunotia pectinalis</i>	13.01	0	3.21	32.18	0	0	0
30		<i>Fragillaria</i> sp.	0	0	0	0	0	0	50
31		<i>Gomphonema costrictum</i>	34.53	15.47	0	0	0	0	0
32		<i>Mastogloia</i> sp.	0	50	0	0	0	0	0
33		<i>Navicula</i> sp.	0	0	0	0	35.82	4.24	2.32
34		<i>Nitzschia linearis</i>	6.55	5.99	34.19	0	0	0	0
35		<i>Pinnularia</i> sp.	0	0	0	0	0	0	50
36		<i>Rhopalodia</i> sp.	0	0	4.04	43.93	0	0	50
37		<i>Surirella</i> sp.	50	0	0	0	0	0	0
38	<i>H2</i>	<i>Calothrix</i> sp.	50	0	0	0	0	0	0
39		<i>Gleotrichia natans</i>	50	0	0	0	0	0	0
40		<i>Hormodium</i> sp.	17.01	0	0	32.99	0	0	0
41	<i>TD</i>	<i>Centritractus</i> sp.	0	0	0	0	0	0.58	49.11
42		<i>Coelosphaerium</i> sp.	50	0	0	0	0	0	0

Table 2 (continued)

	FGs	Indicator Species	Open wetland				Closed wetland			
			PRM	MON	POM	WIN	PRM	MON	POM	WIN
43	X2	<i>Chlamydomonas</i> sp.	31.64	12.63	0	5.73	0	0	0	0
44		<i>Microchaete</i>	50	0	0	0	0	0	0	0
45		<i>Rhodomonas</i> sp.	0	50	0	0	8.23	38.2	3.55	0
46		<i>Cryptomonas</i> sp.	0	0	0	0	0	0	50	0
47	X1	<i>Chlorella</i> sp.	0	0	47.11	2.89	0	0	0	0
48		<i>Schroederia indica</i>	0	10.24	39.76	0	0	0	0	0
49		<i>Schroederia</i> sp.	0	50	0	0	0	0	0	0
50		<i>Schroederia</i> sp.	0	0	0	0	5.45	4.06	4.66	34.69
51	P	<i>Closterium</i> sp.	1.27	0.82	35.59	12.01	0	0	0	0
52		<i>Treubaria</i> sp.	33.33	0	0	0	0	0	0	0
53		<i>Ulothrix</i> sp.	13.99	0	36.01	0	50	0	0	0
54		<i>Ulothrix tenuissima</i>	30.15	19.85	0	0	0	0	0	0
55	N	<i>Cosmarium</i> sp.	0	0	0	0	0	0	33.33	0
56		<i>Euastrum</i> sp.	0	0	50	0	0	0	33.33	0
57		<i>Euastrum verrucosum</i>	0	0	0	0	0	0	33.33	0
58		<i>Mellomonas</i> sp.	0	0	0	0	0	0	33.33	0
59		<i>Penium</i> sp.	33.33	0	0	0	5.5	31.84	6.6	0
60	F	<i>Crucigenia crucifera</i>	0	8.8	41.2	0	0	0	0	0
61		<i>Kirchneriella</i> sp.	0	0	50	0	0	0	0	0
62		<i>Oocystis</i> sp.	2.69	0	47.31	0	0	0	0	0
63		<i>Westella</i> sp.	0.83	0	7.2	41.97	4.03	3.45	0	42.51
64	G	<i>Eudorina</i> sp.	0	0	0	0	0	32.71	17.28	0
65		<i>Lagerheimia</i> sp.	0	0	0	0	0	0	50	0
66		<i>Pandorina</i> sp.	7.37	9.62	0	33.01	0	0	0	0
67		<i>Eudorina</i> sp.	0	0	0	0	0	12.03	31.94	0
68		<i>Volvox</i> sp.	0	50	0	0	0	0	0	0
69	W1	<i>Euglena acus</i>	3.97	3.44	40.87	0	0	0	0	0
70		<i>Euglena elongata</i>	1.26	0	48.1	0	0	0	0	33.33
71		<i>Microspora</i> sp.	0	50	0	0	0	0	0	0
72		<i>Phacus acuminatus</i>	0	0	0	0	0	33.33	0	0
73		<i>Phacus caudata</i>	5.22	8.27	30.66	5.84	0	0	0	0
74		<i>Phacus nordstedtii</i>	0	0	0	0	0	33.33	0	0
75		<i>Phacus</i> sp.	0	0	0	0	3.71	2.47	42.56	0
76	K	<i>Gloeocapsa</i> sp.	50	0	0	0	0	0	0	0
77		<i>Gomphosphaeria</i> sp.	0	0	0	0	0	50	0	0
78		<i>Strombomonas</i>	0	0	0	0	11.57	32.63	0	0
79	SI	<i>Lyngbya contorta</i>	0	6.8	4.28	38.92	0	0	0	0
80	Lo	<i>Merismopedia elegans</i>	32.98	7.27	4.39	5.36	0	0	0	0
81		<i>Merismopedia glauca</i>	0	0	0	0	0	38.67	9.14	2.18
82	M	<i>Microcystis aeruginosa</i>	7.2	4.37	30.7	7.72	0	0	0	0
83		<i>Microcystis aeruginosa</i>	0	0	0	0	0	19.56	30.43	0
84	T	<i>Mougeotia</i> sp.	0	0	0	0	8.45	0	41.54	0
85		<i>Netrium digitus</i>	50	0	0	0	0	0	0	0
86	D	<i>Nitzschia acicularis</i>	0	0	0	0	4.67	42.98	0	0
87		<i>Spirogyra vandalurensis</i>	50	0	0	0	0	0	0	0

Table 2 (continued)

FGs	Indicator Species	Open wetland				Closed wetland			
		PRM	MON	POM	WIN	PRM	MON	POM	WIN
88	<i>Synedra acus</i>	30.65	19.35	0	0	0	0	0	0
89	<i>Synedra</i> sp.	0	7.97	42.03	0	6.62	0	40.05	0
90	<i>Synedra ulna</i>	0	44.31	5.69	0	16.59	33.4	0	0
91	<i>Zygema</i> sp.	50	0	0	0	0	0	0	0
92	W2 <i>Trachelomonas</i> sp.	1.15	3.75	44.6	0.5	0	0	0	0

activities contribute to nutrient loading, pollution, and habitat alteration, leading to issues like eutrophication, toxic algal blooms, and changes in species composition (Bera et al. 2021). The study revealed that nutrient parameters such as $\text{NO}_3\text{-N}$ were highest in both wetlands during the monsoon season. However, the concentration was greater in open wetlands compared to closed ones. In contrast, $\text{PO}_4\text{-P}$ levels peaked in open wetlands during the post-monsoon period but were subsequently lower than in closed wetlands. This difference is attributed to the increased decomposition process in open wetlands during the post-monsoon season, which is due to reduction in water outflow. Meanwhile, continuous decay of organic matter in closed wetlands resulted in higher $\text{PO}_4\text{-P}$ concentrations throughout the seasons (Bao et al. 2023).

Electrical conductivity in wetlands tends to increase during both pre-monsoon and post-monsoon periods due to higher water saturation. Following the monsoon, the geochemical characteristics of surface water in these wetlands change, resulting in higher electrical conductivity, indicating shifts in ion concentrations and overall water quality (Baruah and Baruah 2024). Additionally, pH in wetlands often rise during the winter season, further affecting electrical conductivity (Gerla 2013). Interestingly, dissolved oxygen levels are lower in open wetlands compared to closed ones, likely due to higher DO consumption for decomposition of debris and organic matter, which is replenished during seasonal restoration of connectivity with the main river channel. In contrast, closed wetlands, due to their isolated nature, receive less debris. However, the lowest DO levels in closed wetlands are observed during the pre-monsoon period when water saturation is high and organic decomposition is intensified. WQI was comparatively higher in closed wetland than in open one, fall within the range of scale 'good' (BIS, 2012) as evident in our study.

Understanding the spatial distribution of phytoplankton functional groups is a key focus in ecology, and its importance is heightened by the current challenges of habitat alteration, fragmentation, wetland shrinkage, and ongoing biodiversity loss (Pinel-Alloul et al. 2013; Tinnevelt et al. 2022). The present study broadly contributes to

understanding the diversity of phytoplankton functional groups and their ecohydrological interactions in two ecologically district wetlands. A large number of species based on similar taxonomic traits but having different ecological characteristics, their linkage and ecological functions are different in both the wetlands. Phytoplankton species were grouped based on their similarity in ecological adaptation and classified into 23 FGs for open and 22 FGs for closed wetlands for assessing ecological status. High fluctuation in water level and variation in water spread area are natural phenomena of the wetlands, seasonally open with parent River channel (Md. Aftabuddin et al. 2017). Flood riparian connection in wetlands is a prime factor for infusing lots of nutrients into the seasonally open wetland (Gogoi et al., 2021). Ecohydrological changes become drivers for changes in phytoplankton FGs diversity and increasing their biomass in post-monsoon (Townsend and Douglas 2017). The average annual biomass of phytoplankton functional groups was higher in seasonally open than closed wetland. The spatial pattern of phytoplankton functional groups did not depict significant differences between the wetlands. However, ecohydrological spatial variation between wetlands is significant. In contrast, to the river ecosystem, Yang et al. (2017) water quality parameters become more favorable in late monsoon than the onset of monsoon in wetland ecosystem. This was due to the residential period of influx water from the catchment is higher in wetland than river ecosystem. FG biomass in monsoon was lowest in seasonally open wetland but comparatively higher in closed wetlands. This could be related to the connectivity of the main river channel and the mixing of nutrients leads to higher plankton diversity and biomass in open than closed wetlands (Gogoi et al., 2021). FG biomass was recorded highest during the post-monsoon season in open wetlands due to the increased growth of a few phytoplankton functional groups in the presence of favorable temperatures and availability of organic nutrients (Padisak et al. 2009; Reinl et al. 2022).

In terms of FG composition, TB was the most diverse group composition of 22 species. Generally, TB prefers clear lotic environment, low nutrient and considerably good, oxygenated water, representative species mostly

diatoms include *Mastogloia* sp., *Cymbella* sp., *Navicula radiosa*, *Navicula rhynchocephala*, *Navicula* sp., *Gomphonema gracile*, *Gomphonema costrictum*, *Amphipleura* sp., *Nitzschia* sp. etc. Wang et al. (2021) has studied in estuarine river delta, reported TB dominates during the dry seasons. In the present finding, similarly, TB dominates during premonsoon season in open wetland, in contrast to closed wetland during post-monsoon season. The recent application of the Reynolds FG system to the middle Danube River has demonstrated its utility in identifying long-term compositional changes and potential regime shifts, but future advancements depend on developing quantitative parameters to model and quantify the effects of global warming and human impacts on river phytoplankton and ecosystem functioning (Abonyi et al. 2021). However, TB dominates during pre-monsoon in open wetland and post-monsoon in closed wetland but lower contribution in biomass. Occurrences of several FGs such as X1, H1, C, F, and X2 are reasonably higher but have less contribution in biomass. Gogoi et al., (2021) reported a lower contribution of Bacillariophyceae and Chlorophyceae during the monsoon season. The FGs such as G, X2, and Lo species *Chlamydomonas* sp., *Volvox* sp., *Eudorina* sp., *Pandorina* sp., *Merismopedia* sp. were contributing higher in closed wetland compared to open wetland. These species are an indicator of the stagnant organic pollution-rich ecological status of water (Cardoso et al. 2017; Reinl et al. 2022). The FG term W2, dominance of single species *Trachelomonas* spp. during the post-monsoon season in open wetland. This is one of the species that flourish in certain environmental conditions such as pH closer to neutral and organically rich conditions (Grabowska and Wołowski 2013). In open wetland, pH was most suitable for their growth, and it was no longer supported by changes in environmental factors, hence was absent in closed wetland. The dominance in biomass of Functional group TD in the pre-monsoon season was influenced by the rise in temperature and reduction in depth in the open wetland and S1 in the closed wetland due to higher organic nutrients (Wanganeo and Wanganeo 1991). The biomass of functional groups TD, N, T, and D associated with Chlorophyceae and Bacillariophyceae was comparatively higher during the post-monsoon season in closed wetlands due to benign environmental water quality parameters and bioavailability of silica content in water (Sharma 2015; Gogoi et al., 2021). Biomass of functional groups of W1, W2, X1, J, S2, S3, and M contributes to individual peaks in post-monsoon season in open wetland due to higher individual biomass and abundance of species associated with the functional groups. In contrast to the finding of dominance of Euglenophyceae such as *Trachelomonas* sp. and *Euglena* sp. in closed wetlands, their abundance increased due to the presence of labile organic load in combination with seasonal alteration especially

physical water quality parameters (Li et al. 2018). Non-motile green algae associated with F is dominant in both closed and open wetlands during the winter season due to more stable water and moderate nutrient concentration (Padisak et al. 2009). This implies that the diversity of functional groups is a potential indicator of spatial and temporal changes in aquatic ecosystems.

Phytoplankton species appeared as indicator species that vary seasonally in two different ecohydrological scenarios. There were no common taxa that appeared as indicator species during pre-monsoon with IndVal ($\geq 30\%$). Therefore, it indicated that taxa present during this period are influenced by light intensity with higher temperature and bottom visible conditions in open wetlands as transparency equal to water depth. The abundance of taxa such as *Ankistodesmus spiralis*, *Calothrix* sp., *Coelosphaerium* sp., *Coscinodiscus* sp., *Gleotrichia natans*, *Microchaete* sp., *Netrium digitus*, *Rivularia* sp., *Spirogyra vandalurensis*, *Surirella* sp., *Zygea* sp., mostly benthic favored by shallow depth, good light, stagnant water, and moderately organic nutrient-rich conditions followed by higher temperature (Palmer 1980; Sin and Lee 2020). In the closed wetland, only filamentous algae appeared as the dominant indicator species *Ulothrix* sp. influenced by higher temperature and favorable nutrients in water. Chen et al. (2011) assessed the gut content of *Daphnia* sp. from February to May (summer) and found most dominant one was *Ulothrix* sp. However, the author has not confirmed the dominance of *Ulothrix* sp. in the gut content of *Daphnia* either due to its abundance in water or selectively fed upon. Riverine connectivity and their change in hydrological regimes during monsoon season are one of the driving factors (Marshall et al. 2005) for influencing the abundance of these species (*Mastogloia* sp., *Microspora* sp., *Rhodomonas* sp., *Schroederia* sp., *Volvox* sp., *Tetraedron regulare*, *Synedra ulna*) in open wetland and species (*Coelastrum reticulatum*, *Gomphosphaeria* sp.) dominance IndVal ($\geq 50\%$) in closed wetland. Thus, it revealed that taxa respond differently in varying monsoon water influx regimes. Belinger and Sigeo (2010) found that *Volvox* sp., *Synedra ulna*, *Microspora* sp., and *Rhodomonas* sp., were more abundant during the wet season, which was consistent with our results. The result suggested that the highest number of indicator species (IndVal $\geq 30\%$) was recorded during post-monsoon in open wetland. This change was possible due to riverine connectivity becoming more stagnant and favoring nutrient utilization at suitable temperatures leading to an increase in the abundance of certain groups of algae. In shallow lakes, an abundance of nutrients is primarily phosphate as one of the limiting factors controlling the phytoplankton growth especially Chlorophyceae (Prusty et al. 2010). Increasing the algal biomass and abundance during the post-monsoon seasons in freshwater wetland ecosystems has suggested that

environmental parameters and dissolving nutrients are driving factors of those changes (Sin and Lee 2020; Ray et al. 2023). The phytoplankton indicator species response in terms of *IndVal* was low in both wetlands during the winter season due to a reduction in nutrient concentration and grazing by zooplankton (Kumari et al. 2023). The present finding suggests that algal taxonomic structure shifts are likely due to monsoon flux in combination with nutrient and water temperature. Therefore, increasing temperature in freshwater wetland ecosystems may affect the eco-trophic structure and dominant harmful algal bloom.

Conclusion

In conclusion, our study highlights the crucial role of wetland connectivity with parent rivers in preserving ecological health and boosting plankton productivity. Open wetlands demonstrate greater variability in water quality parameters compared to closed ones, underscoring the importance of water mixing through link channels for sustaining plankton ecology. Re-excavation or dredging of blocked channels and reconnection to natural water sources can reestablish the water flow in the closed wetland. Controlled water management practices, like regulating sluice gates, can further maintain hydrological balance and improve water quality. The plankton community and biomass are essential for supporting sustainable fish production through ecosystem-based fisheries management, with phytoplankton functional groups (FGs) playing key roles in nutrient cycling, oxygen production, and maintaining ecological balance. Monitoring these groups is vital for safeguarding aquatic ecosystems. Canonical Correspondence Analysis (CCA) revealed significant relationships between water variables and phytoplankton FGs, highlighting their ecological interactions in both wetland types. Our study confirmed the value of identifying indicative phytoplankton species and FGs for assessing seasonal and spatial diversity. Using FGs as bioindicators can serve as early warnings of environmental changes, and the FG methodology effectively characterizes the spatiotemporal dynamics of aquatic environments. Continuous efforts to promote FG diversity and restore link channels are necessary to enhance the resilience and ecological health of aquatic ecosystems.

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