J. Indian Soc. Coastal Agric. Res. 39(2): 206-220 (2021) https://doi.org/10.54894/JISCAR.39.2.2021.110537

Quantification and Visualization of the Variability of Phytoplankton Assemblage in a Semi-lotic Seasonal Canal in Sundarbans, India

ARCHANA SINHA[1]*, PRANAB GOGOI[1], TASSO TAYUNG[2], SOMA DAS SARKAR[2], K. LOHIT KUMAR[2], ARUNAVA MITRA[1], V. R. SURESH[3] and BASANTA KUMAR DAS[2]

[1]Kolkata Centre of ICAR-Central Inland Fisheries Research Institute, Salt Lake City, Kolkata - 700 064, West Bengal, India
[2]ICAR-Central Inland Fisheries Research Institute, Barrackpore, Kolkata - 700 120, West Bengal, India
[3]ICAR-Central Marine Fisheries Research Institute, Kochi - 682 018, Kerala, India

Received: 17.02.2021 Accepted: 18.06.2021

Canals of Sundarbans in India are highly vulnerable to anthropogenic pressures which directly or indirectly impact the biological components of such ecosystems. Being at the base of the trophic pyramid, phytoplankton is exposed to environmental stressors and the impact will be reflected in the upper strata of the aquatic food chain. Hence, phytoplankton communities along with their interrelationship with environmental parameters were assessed in Bhetkimari canal, a semi-lotic system in Indian Sundarbans during June 2017 to September 2018. Seventy-seven species under 66 genera were recorded with Cyanophyceae (34%) as a major contributor, followed by Bacillariophyceae (31%) and Chlorophyceae (22%). Diatoms dominated round the year in terms of diversity (25 species) with maximum contribution from Pennales. ANOVA (post-hoc test) showed significant temporal heterogeneity ($p \leq 0.05$) in phytoplankton distribution in the canal. The Margalef richness index (d) and Shannon-Weiner diversity index (*H′*) were 2.59±0.43 and 2.26±0.59, respectively indicating that the environment is good and phytoplankton diversity in the system is moderate. Water temperature, dissolved oxygen, total alkalinity and nutrients (nitrate, silicate and phosphate) were the explanatory variables in shaping the phytoplankton assemblages in the canal, which was evident from Canonical correspondence analysis. The salient findings of this study can add to the existing knowledge on the abundance and distribution pattern of phytoplankton in semi-lotic canal environments, and help in planning better management of canal ecosystems for their sustainable utilization.

(***Key words:*** *Assemblages, Canal, Indian Sundarbans, Phytoplankton, Physicochemical)*

Phytoplankton communities are primary producers in aquatic ecosystems that play an important role in the trophic dynamics by becoming the key food source for primary consumers (Saravanakumar *et al*., 2008). These free-floating organisms are the photoautotrophic base of the primary production and global nutrient cycle (Wassie and Melese, 2017). Spatio-temporal dynamics of phytoplankton are regulated by the inorganic nutrients, which primarily includes nitrogen, phosphorus and silica (Daniel, 2001). Since these microforms are susceptible to environmental changes, their presence can be used as indicators for monitoring water quality and trophic status (Reynolds *et al*., 2002). Any alterations in the conducive environment have deleterious impacts in terms of growth, survival, and succession of phytoplankton in aquatic eco-niche (D'Costa *et al*., 2017).

The Sundarbans mangrove forests cover an area of about 10,000 km^2 in Bangladesh and in West Bengal, India. The area is characterized by low flat alluvial plain covered with mangrove swamps and marshes, and is traversed by many tidal rivers, and creeks (Bagchi, 1972). This is an extremely fragile ecosystem, rich in biodiversity which includes numerous species of phytoplankton, zooplankton, microbes, benthic invertebrates, fishes, molluscs, amphibians, and mammals (Gopal and Chauhan, 2006). The canal resources in Indian Sundarbans cover an area of 907.33 ha, the highest at Gosaba Block (427.34 ha) forming 50% of the total area (Mukharjee, 2016). These canals although supporting fisheries are still underutilized in terms of sustainable fish yield. Erection of barriers for catching fishes in these canals is a common practice, but this can lead to intensive fishing of innate fishes and hampering of natural recruitment of fish (Gogoi *et al*., 2020a). Studies have shown that channelization or creation of irrigation canals results in lowering

**Corresponding author:* E-mail: sinhaarchana@yahoo.com

fish species due to low temperature and low primary producer diversity when compared with nearby static water bodies (Tarplee *et al*., 1976). Understanding the spatio-temporal variations of species and how they are functionally related to environmental conditions is still a challenge in ecology (Cardoso *et al*., 2012). Notable studies carried out on phytoplankton community structure in Hooghly-Matlah estuarine system in Sundarbans Delta are Shetty *et al*. (1961), De *et al*. (1994), Sarkar and Naskar (2002), Biswas *et al*. (2004), Manna *et al*. (2010), Dey *et al*. (2012), Bhattacharjee *et al*. (2013) and Gogoi *et al*. (2019, 2020b). But the assessment on phytoplankton assemblage pattern in canal ecosystem from Indian Sundarbans is still poorly addressed. Therefore, it was found necessary to understand the ecological interactions in these canal ecosystems especially the dynamics of phytoplankton which form the base of food chain in aquatic trophic strata. Hence, the present study was attempted to evaluate the phytoplankton community assemblage in relation to water quality parameters in Bhetkimari. canal, Sundarbans Biosphere Reserve (SBR).

MATERIALS AND METHODS

Study area

The study area is located at Madanganj, a part of Sundarbans mangroves which is strongly influenced by riverine freshwater influx as well as tidal flow from the Bay of Bengal. Madanganj, the transition zone of the Indian part of the Sundarbans Biosphere Reserve has a dense human population. Bhetkimari (21° 36′ 08.9″ N 88° 15′ 14.8″ E to 21° 36′ 40.1″ N 88° 15′ 22.5″ E) is a tidal fed canal, connected to the river Hathenia-Dewania. The canal remains 2.4-3.6 m deep during peak monsoon and 1-1.2 m during winter. Human settlements are dense on both the banks of the canal. The 2.5 km long and ~25.0 m wide canal, is a source of fresh water supply for agriculture, livestock rearing, year-round fishing and household activities for the dense human population on both the banks. Three equidistant sampling stations along the canal *viz*., station S_1 near the sluice gate/ river, followed by S_2 and S_3 (Fig. 1) were selected for the study.

Sampling methodology

Bimonthly (once in two months) sampling was conducted from June 2017 to September 2018, representing three seasons following Chaudhuri *et al*. (2012) *viz*., monsoon (July-October), post-monsoon (November-February) and pre-monsoon (March-June). Sub-surface water was collected from the pre-defined sites using a standard water sampler designed after

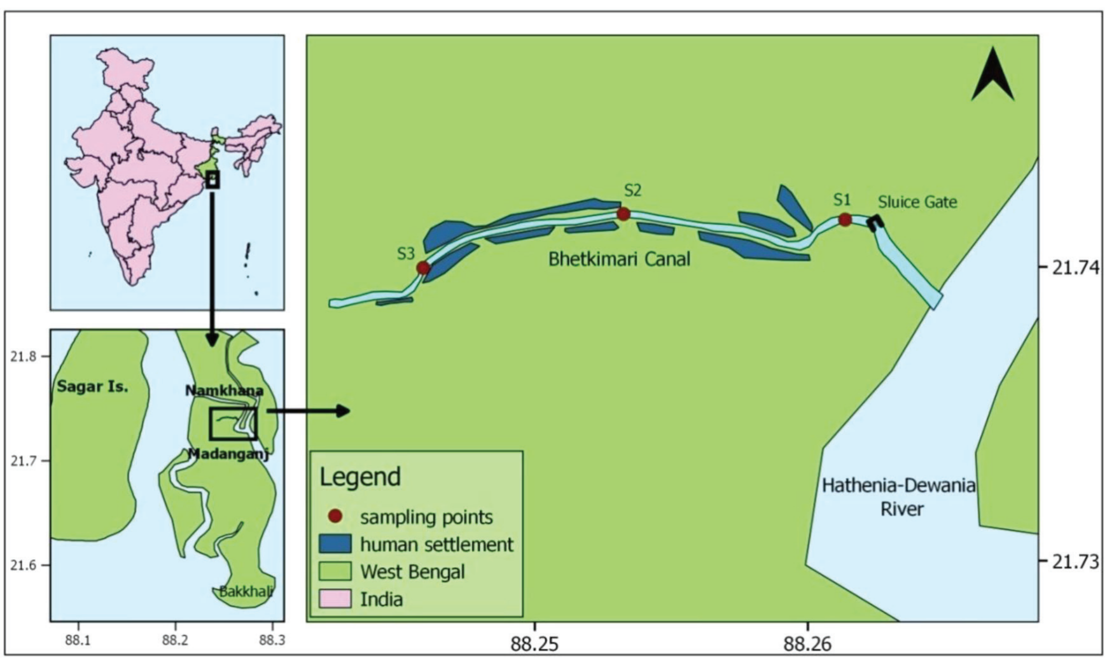

Fig. 1. Schematic diagram of Bhetkimari canal in Sundarbans, India showing sampling stations

'Ruttner Water Sampler (Das Sarkar *et al*., 2019), and immediately transferred to pre-rinsed polyethylene bottles (1 L). Water samples were transferred to the laboratory for analysis of nutrients such as nitrate, total nitrogen (TN), phosphate, total phosphorous (TP) and silicate. Water transparency (Trans.) was measured using Secchi disc (Strickland and Parsons, 1972). Water temperature (WT) was measured using a degree centigrade (-10 to 50°C) thermometer (P-601466); pH using a digital pH meter (HANA instruments), and specific conductivity (Sp. Con.) by handheld digital conductivity meter (Multiline P4-82362). Dissolved oxygen (DO), salinity, total alkalinity (TA) and nutrients were analyzed following recommendations and methods described by APHA (2012).

For phytoplankton, 50 L sub-surface water collected from the respective stations was filtered through (20 µm meshed bolting silk). The concentrated plankton samples were preserved in 4% buffered formalin for further analysis of plankton diversity and abundance. Plankton was identified by using a trinocular light microscope at 400x magnifications (Axioster plus - Carl Zeiss) and Sedgewick-Rafter counting cell (Wetzel and Likens, 2000) was used for enumeration. Phytoplankton species were identified up to genus or species level, wherever possible based on standard taxonomic identification keys (Prescott, 1962; Ward and Whipple, 1992; Cox, 1996; Bellinger and Sigee, 2010) and later, taxonomic names were confirmed at AlgaeBase (Guiry and Guiry, 2018). The density of phytoplankton species was expressed in cells per liter (cells L^{-1}).

Statistical analysis

Univariate and multivariate analyses were performed by using Plymouth Routines in Multivariate Ecological Research' (PRIMER), Version 6.1.6 (Clarke and Gorley, 2006) and 'Palaeontological Statistics' (PAST) version 3.06 (Hammer *et al*., 2001). The water quality parameters were subjected to one way ANOVA using post-hoc Duncan test and Pearson correlation matrix between water variables and algal groups was done using SPSS version 21.0. Similarity analysis (SIMPROF) was performed by treating the abundance data (square root transformed to remove the effect of high values) among the sampling stations. Based on Bray-Curtis similarity, an ordination plot was produced by non-metric dimensional scaling (nMDS). Further, analysis of similarity (ANOSIM) was performed to understand the significant differences between seasons/stations with respect to phytoplankton species composition. Canonical correspondence analysis (CCA) was performed by employing PAST to examine the empirical relationship between environmental factors and the phytoplankton groups. Shannon-Weiner Index (H') (Shannon-Weiner, 1949) was computed following the formula: $H' = -\sum [Pi \times \log (Pi)]$; Where, 'Pi' is the proportion of the individuals belonging to the 'i'th species, H' = Species diversity; Margalef richness index (d) (Margalef, 1958) was computed with the following formula: $d = (S-1)/\log N$; Where, N = total number of individuals; S = total number of species, and Pielou's evenness or equitability index (J') (Pielou, 1975) was calculated as: $J' = H'/ \text{Log} (S)$; Where H' = Shannon-Weiner diversity, and S = total number of species.

RESULTS AND DISCUSSION

Physico-chemical factors

Results of ANOVA revealed that, out of twelve water quality parameters, seven (WT, pH, Sp. Con., salinity, phosphate, silicate and transparency) showed significant heterogeneity ($p \leq 0.01$) across seasons (Table 1). Surface water temperature showed a clear seasonal cycle but displayed slight variations across stations. The canal water remained alkaline throughout the study period. No specific variations were recorded in the dissolved oxygen level. Lower concentration of dissolved oxygen during monsoon (5.8±0.1 mg L^{-1}) is due to increased temperature, salinity and biological activity. Similar findings were reported by Kadam and Tiwari (2011) where DO values varied from 4.76 to 5.92 mg L^{-1} in Dahanu creek, West Coast of India. Higher alkalinity during post-monsoon (125.7±14.7 mg L^{-1}) is due to run-off from the nearby agricultural fields and decomposition of plants and other organic wastes received during the monsoon (Chaurasia and Pandey, 2007). Salinity showed distinct temporal variations and remained high during pre-monsoon. Saravanakumar *et al*., (2008) stated that the low salinity level in brackish water habitats such as backwaters, estuaries and mangrove waters was due to influx of freshwater from land run-off caused by precipitations or by tidal variations. This is in conformity with our present findings. Pearson correlation matrix showed positive correlation of water temperature with pH ($r = 0.77$; $p \leq 0.05$), Sp. Con. ($r = 0.91$; $p \leq 0.01$) and salinity ($r = 0.76$; $p \leq 0.05$) and negative correlation with nutrients like phosphate

Table 1. *Seasonal variation in water quality parameters of Bhetkimari canal, Sundarbans*

Parameter/Season	Pre-monsoon	Monsoon	Post-monsoon	p-value
Water Temp (°C)	31.6±0.2[a]	30.5±0.4[b]	27.9±0.1[c]	0.001
pH	8.3±0.1[a]	7.4±0.1[b]	7.1±0.1[b]	0.001
DO (mg L^{-1})	6.1±0.1[a]	5.8±0.1[b]	6.3±0.1[a]	0.007
Sp. Con. (mS cm^{-1})	31.0±3.0[a]	13.9±1.8[b]	0.8±0.1[c]	0.001
TA (mg L^{-1})	110.4±2.3[a]	114.3±18.9[a]	125.7±14.7[a]	0.734
Salinity (ppt)	20.8±1.9[a]	0.2±0.03[b]	2.6±0.7[b]	0.001
Nitrate (mg L^{-1})	0.12±0.03[a]	0.15±0.01[a]	0.11±0.01[a]	0.567
Total N (mg L^{-1})	0.4±0.04[a]	0.4±0.06[a]	0.6±0.01[a]	0.123
Phosphate (mg L^{-1})	0.02±0.0[c]	0.04±0.0[b]	0.06±0.0[a]	0.001
TP (mg L^{-1})	0.07±0.01[a]	0.10±0.0[a]	0.4±0.3[a]	0.396
Silicate (mg L^{-1})	1.8±0.5[b]	2.0±0.4[b]	6.8+0.7[a]	0.001
Transparency (cm)	42.8±0.4[a]	26.8±0.2[c]	40.2±0.6[b]	0.001

Note: Values are means ± SE; means followed by the same letter are not significantly different at 5% probability level

(r = − 0.94; $p\leq0.01$) and silicate (r = − 0.88; $p\leq0.01$). Similarly, dissolved oxygen was positively correlated with silicate (r = 0.72; $p\leq0.05$) and transparency (r = 0.72; $p<0.05$) (Table 2).

Nutrients in the canal were primarily determined by the tidal flow and freshwater flows from the catchment areas (Gogoi *et al*., 2019). No major differences were observed in the concentrations of nitrate and total nitrogen during the study period. Maximum concentration of nitrate was recorded during monsoon due to the run-off received from catchment areas. The land-based nutrients received especially from the agricultural fields in proximity, contributed to a greater extent to the enrichment of nutrient concentrations during monsoon as previously reported by Sarkar and Bhattacharya (2010). Higher concentration of nitrate during monsoon season from Sundarbans creeks was also reported by Basu *et al*. (2021). The lower concentration of phosphate during pre-monsoon (0.02±0.01 mg L^{-1}) was due to its utilization by photoautotrophs (Rajasegar, 2003), and meagre rainfall received during the season. Higher values of silicate, as compared to other nutrients (nitrate, phosphate) are due to run-off from the residential areas or accelerated silicate concentration caused by wastes produced from adjacent households (Gogoi *et al*., 2019). Maximum concentrations of nutrients *viz*., total nitrogen, phosphate and silicate during post-monsoon as compared to pre-monsoon in Jharkhali waters (Sundarbans), as reported by Chaudhuri *et al*. (2012) is in conformity with the present study in Bhetkimaricanal. All the nutrients exhibited a negative correlation with salinity. The significant positive correlation between dissolved silicate and phosphate and total nitrogen indicates that the variables have a common source of origin primarily from the riverine influx. Results of a multidecadal comparative study on a set of physicochemical parameters (nutrients) conducted in the creeks of Sundarbans, (Basu *et al*., 2020) corroborate the present findings on factors that control the nutrients status.

Phytoplankton abundance and composition

Seventy-seven phytoplankton species belonging to 66 genera were recorded from Bhetkimari canal during the study period (Table 3). In community compositions, Cyanophyceae was the major microfloral component (34%) followed by Bacillariophyceae (31%) and Chlorophyceae (22%). The other eight groups of algal assemblages contributed less to the total phytoplankton community (Fig. 2). Synurophyceae and Dinophyceae were represented by only one genus each: Synura and Ceratium, respectively. Diatoms were the most diverse group (25 species) in the canal. Pennates constituted a major part of diatoms during winter in this study which corroborates the findings of Adesalu and Nwankwo (2005). On the contrary, Centric forms (21 genera) were the main diatom assemblage in the Chemaguri

Table 2. *Pearson correlation matrix between hydrographical parameters and phytoplankton groups*

	WT	pH	DO	Sp Con	TA	Sal	Nitr	TN	Phos	TP	Sili	Tran	Cya	Bac	Chl	Con	Cos	Med	Tre	Xan	Syn	Eug	Din
WT	1																						
pH	0.77*	1																					
DO	-0.53	-0.27	1																				
Sp con	0.91**	0.852**	-0.30	1																			
TA	-0.24	-0.44	0.30	-0.19	1																		
Sal	0.76*	0.83**	0.10	0.84**	-0.19	1																	
Nitr	0.09	-0.18	-0.30	0.21	0.14	-0.04	1																
TN	-0.63	-0.61	0.50	-0.53	0.25	-0.37	0.07	1															
Phos	-0.94**	-0.90**	0.40	-0.94**	0.36	-0.78*	-0.03	0.71*	1														
TP	-0.50	-0.43	0.20	-0.43	0.24	-0.20	-0.03	0.10	0.40	1													
Sili	-0.88**	-0.72*	0.72*	-0.72*	0.54	-0.38	-0.09	0.72*	0.85**	0.55	1												
Tran	-0.07	0.37	0.72*	0.21	0.02	.68*	-0.41	0.10	-0.20	0.07	0.28	1											
Cya	-0.44	-0.84**	-0.10	-0.56	0.53	-0.75*	0.42	0.50	0.65	0.42	0.47	-0.63	1										
Bac	0.69*	-0.64	0.40	-0.68*	-0.26	-0.47	0.04	0.50	0.64	0.51	0.51	-0.07	0.36	1									
Chl	-0.20	-0.70*	-0.30	-0.41	0.50	-0.65	0.28	0.10	0.40	0.49	0.24	-0.64	0.88**	0.20	1								
Con	-0.59	-0.59	0.30	-0.58	0.15	-0.35	-0.06	0.30	0.54	0.93**	0.62	0.02	0.50	0.69*	0.54	1							
Cos	-0.55	-0.57	-0.10	-0.67*	0.08	-0.70*	-0.07	0.60	0.66*	0.39	0.46	-0.40	0.64	0.40	0.45	0.53	1						
Med	0.18	-0.44	-0.40	-0.06	0.44	-0.44	0.36	0.10	0.08	-0.08	-0.10	-0.63	0.64	-0	0.79*	0.02	0.10	1					
Tre	-0.45	-0.75*	0.30	-0.60	0.13	-0.61	0.05	0.60	0.60	0.08	0.40	-0.24	0.53	0.60	0.50	0.40	0.40	0.60	1				
Xan	-0.25	-0.47	-0.10	-0.45	-0.42	-0.57	0.09	0.40	0.36	-0.10	0.10	-0.45	0.31	0.60	0.27	0.21	0.40	0.40	0.80**	1			
Syn	0.02	-0.29	-0.40	-0.15	0.25	-0.49	0.33	-0.40	0.11	-0.18	-0.19	-0.70*	0.37	-0	0.42	-0.30	-0.10	0.50	0.09	0	1		
Eug	-0.91**	-0.67*	0.50	-0.84**	0.06	-0.49	-0.17	0.40	0.80**	0.65	0.76*	0.12	0.30	0.81**	0.17	0.71*	0.40	-0.30	0.35	0.20	-0	1	
Din	-0.62	-0.34	0.30	-0.53	0.42	-0.39	-0.12	0.30	0.62	0.05	0.59	0.03	0.22	0.10	-0.10	-0	0.40	-0.30	-0.14	-0.30	0.22	0.42	1

Note: (i) **. Correlation is significant at 0.01 level, (ii) *. Correlation is significant at 0.05 level
(ii) Cya: Cyanophyceae; Bac: Bacillariophyceae; Chl: Chlorophyceae; Con: Conjugatophyceae; Cos: Coscinodiscophyceae; Med: Mediophyceae; Tre: Trebouxiophyceae; Xan: Xanthophyceae; Syn: Synuourophyceae; Eug: Euglenophyceae; Din: Dinophyceae

Table 3. *Phytoplankton profile in Bhetkimari canal; Abundance of species are rated as (+) = 1–50; (++) = 50 –100; (+++) = >100, and (–) = absent*

Algal group	Species	Pre-monsoon	Monsoon	Post-monsoon
Cyanophyceae	*Oscillatoria sp.*	+++	+++	+++
	Dolichospermum sp.	++	+++	+++
	Lyngbya sp.	+	+++	+++
	Chroococcus sp.	–	+++	++
	Merismopedia sp.	+	++	–
	Spirulina sp.	–	+	++
	Phormidium sp.	+	++	+
	Calothrix sp.	–	+	+
	Nostoc sp.	+	++	–
	Coelosphaerium sp.	-	+	–
Chlorophyceae	*Ulothrix sp.*	++	+	++
	Chlorella sp.	++	+++	+++
	Oedogonium sp.	+	++	+++
	Microspora sp.	+	–	+++
	Tetraedron sp.	+	++	+++
	Ankistrodesmus sp.	+	+	+
	Schroederia indica	–	+++	+++
	Monoraphidium sp.	–	+++	+
	Scenedesmus quadricauda	+	++	+
	Selenastrum sp.	+	+	+
	Chlamydomona ssp.	–	+	–
	Raphidiopsis sp.	–	++	–
	Planktosphaeria sp.	+	+	–
	Eudorina sp.	+	–	+
	Coelastrum sp.	–	+	–
Trebouxiophyceae	*Oocystis sp.*	–	–	+
	Actinastrum sp.	+	+	–
	Closteriopsis sp.	–	–	+
	Crucigenia sp.	+	++	++
Conjugatophyceae	*Closterium sp.*	–	+	–
(Zygnematophyceae)	*Spirogyra sp.*	+	+	–
Bacillariophyceae	*Fragilaria sp.*	++	++	+++
	Amphora sp.	+	–	+
	Amphipleura sp.	-	+	+
	Pinnularia sp.	+	+	+
	Mastogloia sp.	–	–	+
	Cymbella sp.	++	+	+
	Synedra ulna	++	+++	++

	S. acus	+	++	–
	Cylindrotheca closterium	+++	+	++
	Species	Pre-monsoon	Monsoon	Post-monsoon
Bacillariophyceae	*Epithemia sp.*	–	–	+
	Hantzschia sp.	+	+	+
	Navicula sp.	+	+++	+++
	N. rhyncocephala	–	+++	++
	N. gracilis	–	–	+
	N. angusta	–	–	++
	Gyrosigma sp.	++	–	–
	Nitzschia sp.	–	–	+++
	N. palea	+	–	+++
	N. reversa	+	++	++
	N. obtusa	–	–	+
	N. sigmoidea	+	+	++
	N. intermedia	–	++	–
	Tetracyclus sp.	+	–	+
	Tabellaria sp.	–	+	+
	Surirella sp.	+	+	–
	Asterionella sp.	–	+	–
	Gomphonema angustum	+	–	+
	G. truncatum	–	++	+
Mediophyceae	*Cyclotella sp.*	+	++	–
	Leptocylindrus sp.	+	–	–
Coscinodiscophyceae	*Melosira sp.*	+	+	+
	Trieris mobiliensis	+	–	+
	Planktioniella sol	+	+	–
	Lauderia sp.	–	++	+
	Skeletonema sp.	++	-	+
	Aulacoseira sp.	+	+++	+++
	Coscinodiscus sp.	+++	++	_
	Thalassiosira sp.	++	–	+
	Thalassionema nitzschioides	–	+	–
Xanthophyceae	*Centritractus sp.*	+	++	–
	Tribonema sp.	–	–	+
Synurophyceae	*Synura sp.*	–	+	–
Euglenophyceae	*Trachelomonas sp.*	+	–	++
	Euglena sp.	+	+	++
	Phacus sp.	–	+	–
Dinophyceae	*Tripos (Ceratium) sp.*	+	+	–

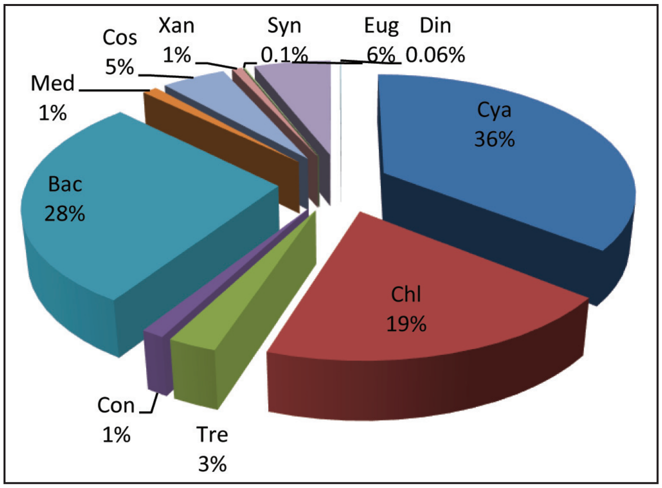

Fig. 2. Compositions of algal groups in Bhetkimari canal

Cya: Cyanophyceae; Bac: Bacillariophyceae; Chl: Chlorophyceae; Tre: Trebouxiophyceae; Med: Mediophyceae; Con: Conjugatophyceae; Cos: Coscinodiscophyceae: Xan: Xanthophyceae; Syn: Synurophyceae; Eug: Euglenophyceae; Din: Dinophyceae

creek, Sundarbans, as reported by Bhattacharjee *et al*. (2013). This contradiction is attributed to the different salinity regimes of Chemaguri creek that favors centric diatoms. Samanta and Bhaduri (2018) also reported a higher number of diatom species and cell abundance from the high saline areas with more Centric forms than the Pennales in Sundarbans. Several studies have been carried out on the diversity and assemblage patterns of phytoplankton in estuarine systems of Sundarbans. Bhattacharjee *et al*. (2013) reported 52 genera of phytoplankton (≥10 µm) from Chemaguri creek, Sundarbans, and 64 phytoplankton taxa belonging to six classes were recorded from Bara Herobhanga Khal, Sundarbans (Manna *et al*., 2010). A total of 84 species belonging to 62 genera with Bacillariophyceae as apex contributor in terms of species richness were reported by Gogoi *et al*. (2020) in their study from Sundarban mangrove waters. Cyanophyceae ($2.14 \times 10^3 \pm 0.81 \times 103$ cells L^{-1}) and Chlorophyceae ($1.51 \times 103 \pm 0.85 \times 10^3$ cells L^{-1}) emerged as the major groups during monsoon while Bacillariophyceae was maximum ($1.99 \times 10^3 \pm 1.42 \times 10^3$ cells L^{-1}) during post-monsoon. The overall seasonal abundance of phytoplankton population was maximum during post-monsoon ($6.36 \times 10^3 \pm 1.26 \times 10^3$ cells L^{-1}) and minimum during pre-monsoon season ($1.08 \times 10^3 \pm 1.08 \times 10^3$ cells L^{-1}) (Fig. 3). Bishnoi and Sharma (2016) recorded the highest phytoplankton density (4.5×105 cells L^{-1}) in summer and lowest (1.0×106 cells L^{-1}) in monsoon from Gang canal, Rajasthan. Maximum abundance of phytoplankton population during post-monsoon can be related to the stable hydrological conditions (Babu *et al*., 2013), and prolonged photoperiod (Wisharad and Mehrotra, 1988; Bohra and Kumar, 1999). Further, increased total nitrogen and phosphate during post-monsoon also have a role in augmenting phytoplankton standing crop. The bimodal pattern of abundance of Cyanophyceae during monsoon and post-monsoon is primarily driven by the enhanced nutrients in the Chemaguri creek, Sundarbans as proposed by Bhattacharjee *et al*. (2013). Bacillariophyceae was maximum during the post-monsoon due to stability of water column and bioavailability of silica in the canal. Kim *et al*. (2007) opined that over 0.5 µmol of nitrogenous nutrients and 0.2 µmol phosphate is sufficient for copious growth of phytoplankton. ANOVA (post-hoc test) showed no significant heterogeneity ($p>0.05$) in phytoplankton distribution among the stations but showed temporal variation in seasons. These findings agree with the report of Manna *et al*. (2010) and Bhattacharjee *et al*. (2013). The occurrence of Cyanobacteria, *viz*., *Anabaena, Lyngbya, Microcystis, Merismopedia, Oscillatoria* and *Nostoc* was quite common during the post-monsoon whereas genera *Coscinodiscus, Trieris (Odontella)* and *Aulacoseira* were predominant during the pre-monsoon season. Similarly, freshwater forms were higher in number during the monsoon. Roshith *et al*. (2018) stated that estuarine wetlands are mainly inhabited by Cyanobacteria which compares well with our results that Cyanophyceae dominated the total phytoplankton population. Naskar *et al*. (2013) reported dominance of epiphytic forms of Cyanophyceae and Chlorophyceae in their study from the Sundarbans irrespective of seasons. Phytoplankton diversity is influenced by differences in

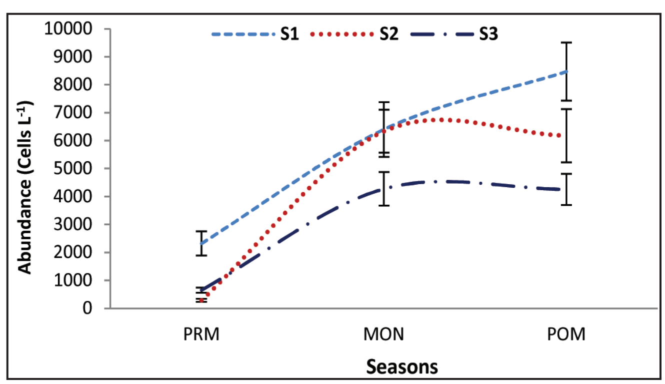

Fig. 3. Station-wise seasonal abundance of phytoplankton in Bhetkimari canal

ecological conditions, types of organisms and variability of climatic and geographical locations (Arumugum *et al*., 2016). The phytoplankton profile in different seasons is shown in Table 3.

Species similarity and diversity pattern

Similarity profile (SIMPROF) analysis (Figs. 4 and 5) falls way outside the 99% limits of the simulated profiles, which means relatively low similarity with multivariate structure of the community compositions (Clarke *et al*., 2008). Furthermore, the absolute deviation of true profile from means permuted profile (sample test statistic $\pi = 8.04$; $p<0.1\%$; Fig. 5) was larger than any value from the null distribution, thereby the null hypothesis, 'samples are homogenous' is rejected. Further, retreating of the data used in SIMPROF, reproduces the ordination pattern which showed the analogous pattern of grouping among samples/stations. It is clear from the nMDS that all stations (S_1, S_2, S_3) formed a distant group with 20% similarity during the pre-monsoon season. Similarly, stations during monsoon (S_1, S_2, S_3) and post-monsoon (S_1, S_2) formed a clear separate group and showed a closer affinity with 40% resemblance among stations. Thus, apparently two structurally different phytoplankton populations exist in the system highlighting the influence of increased salinity during pre-monsoon on the variation in phytoplankton assemblages. It reflects the fact that several assemblages found under various environmental conditions in the canal are distinct (Sommerfield and Clarke, 2013). The ANOSIM test further substantiated the significant differences between the seasons (Global R: 0.663; $p = 0.4\%$). However, no significant difference in phytoplankton species composition was seen between the stations due to the geographical proximity between the sampling stations that share similar habitat attributes. Gogoi *et al*. (2020b) reported similar results with significant variation of phytoplankton species composition between seasons and a subtle variation (Global R = 0.062; $p = 0.2\%$) between the stations from Sundarbans mangrove waters.

High values of diversity index generally indicate a healthy ecosystem while a low value implies a degraded state (Manna *et al*., 2011). The *d* and *H'* values were maximum during post-monsoon, and minimum during monsoon season (Fig. 6). Although, similar observations are apparent from the coastal wetland of Indian Sundarbans (Gogoi *et al*., 2019), *H'* index peaked in the month of August (monsoon) in a coastal lake of Bulgaria (Dimitrova *et al*., 2014). However, studies from the backwaters of China depict lower *H'* and *d* values in the months of February and September, respectively (Miao *et al*., 2019). In the present study, the minimum *H'* during monsoon in the canal is due to perturbed hydrological conditions. The prevalent turbid condition in the canal water during monsoon is one of the factors that can be related to low *H'*. Magurran (1988) opined that the

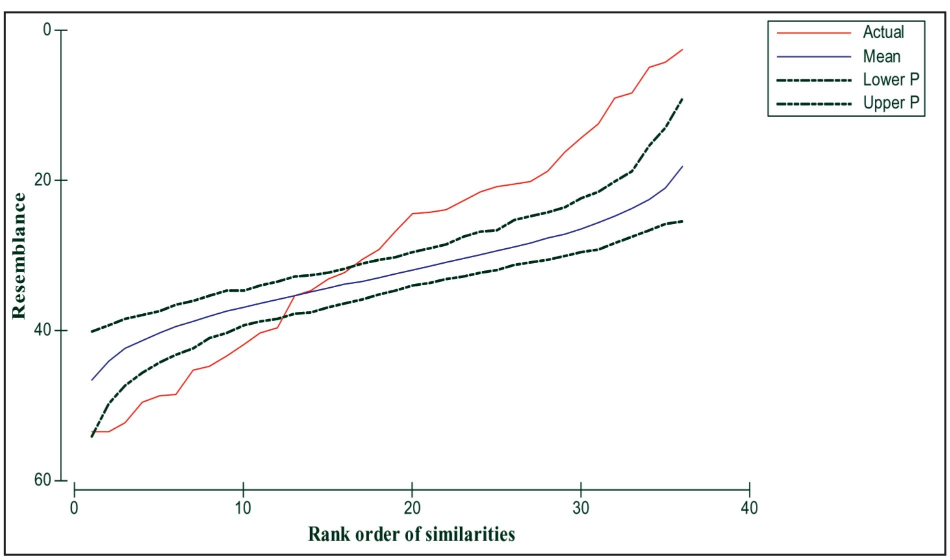

Fig. 4. *Phytoplankton similarity profile for all sampling sites; showing profiles for real data (actual), mean profile and simulated profile with 99% confidence limits (upper and lower P)*

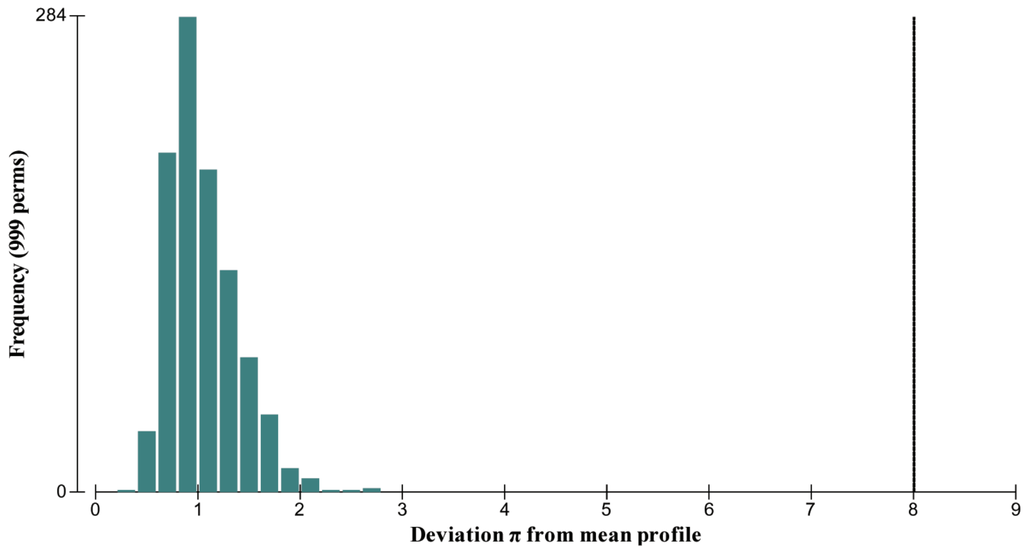

Fig. 5. *Histogram of absolute deviation of sample statistic π from the 999 permuted profiles (i. e. from the mean permuted profile are compared to π for the real profile)*

calculated value of *d* and *H′* exceeding 2.50 indicates 'healthy' environment of an aquatic ecosystem. The mean calculated values of 2.59±0.43 and 2.26±0.59 for *d* and *H′* respectively, indicate a moderate phytoplankton diversity in the system. The value of evenness index (*J′*) was low during monsoon (0.61±0.13), and it increased gradually towards the post-monsoon (0.88±0.04) to pre-monsoon (0.98±0.01) season. The evenness index indicated a uniform pattern of phytoplankton species distribution during post-monsoon and pre-monsoon seasons. Miao *et al*., (2019) reported that the evenness index varied from 0.42 to 0.74 with an elevating trend in June in the Backshore Wetland of Shanghai which agrees with the present investigation. The evenness index ranged from 0.65 to 0.92 in Hooghly estuarine system as previously reported by De *et al*. (1994). Manna *et al*. (2010) reported that the species diversity index (*H′*) declined with phytoplankton biomass during pre-monsoon and increased steadily during post-monsoon in Bara Herobhanga Khal, Sundarbans which also supported our results in Bhetkimari canal.

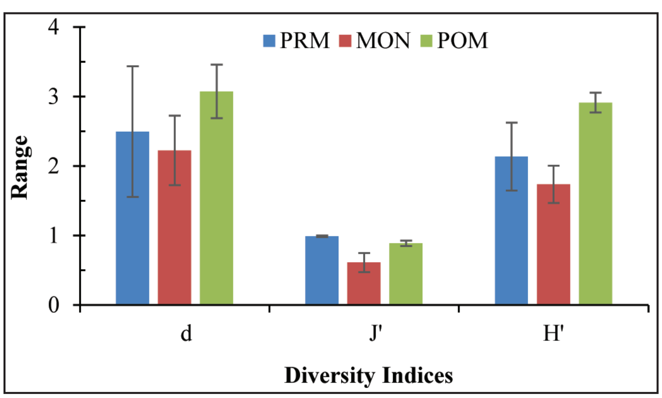

Fig. 6. *Univariate measures of phytoplankton diversity along the sampling stations in Bhetkimari canal. Error bars represent standard deviation*

Correlation between physico-chemical factors on phytoplankton community

Total alkalinity had a positive correlation with the abundance of Cyanophyceae and Chlorophyceae. Conversely, pH showed significant inverse correlation with Cyanophyceae ($r = -0.84$; $p \leq 0.01$), Chlorophyceae ($r = -0.70$; $p \leq 0.05$), Trebouxiophyceae ($r = -0.75$; $p \leq 0.05$) and Euglenophyceae ($r = -0.67$; $p \leq 0.05$). Algal groups Cyanophyceae, Bacillariophyceae, Chlorophyceae, Trebouxiophyceae, Euglenophyceae and Dinophyceae showed a positive correlation with nutrients *viz*., nitrate, TN, phosphate, TP and silicate (Table 2). Multivariate analyses are more useful for analyzing the interrelationship between abiotic and biotic variables at spatio-temporal scale (Kim *et al*., 2007). CCA plot was drawn between environmental variables and algal groups taking account of all the three stations (Fig. 7). Eigen value distribution explained 0.1288 and 50.16% of correlation in axis 1, and 0.0430 and 16.76% of correlation in axis 2. Algal group Bacillariophyceae, Xanthophyceae, Trebouxiophyceae, Conjugatophyceae and Euglenophyceae were positively correlated with salinity, DO, TN, phosphate, TP and silicate. At

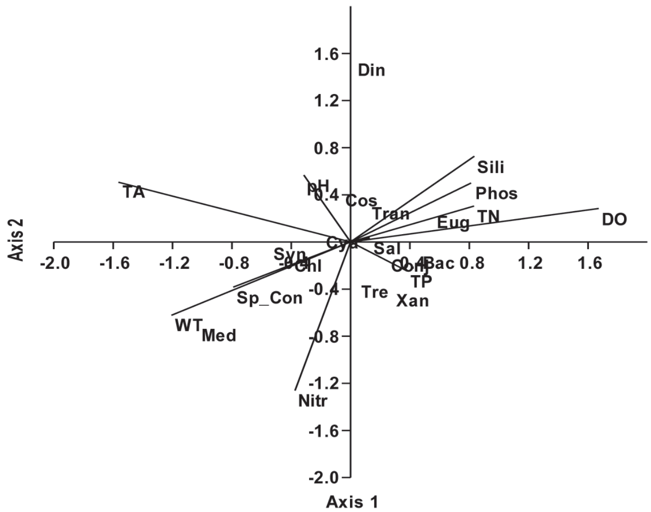

Fig. 7. *CCA plot showing the relationship between physico-chemical parameters and algal groups*

the same time, Chlorophyceae, Mediophyceae and Synurophyceae were negatively correlated with WT, Sp. Con., pH, TA and nitrate. From this observation, it can be inferred that DO, TA, WT, Sp. Con., nitrate, silicate and phosphate were the deterministic parameters influencing the variation of algal assemblage in the canal. Nassar *et al*. (2015) found a positive correlation between phytoplankton abundance with nitrate (r = 0.66), and with the dissolved oxygen (r = 0.51). Similarly, phytoplankton was negatively correlated with pH (r = −0.63). These results are in conformity with the present observations. Schabhüttal *et al*. (2013) found that Cyanophyceae fared well in an elevated temperature, but diatoms and green algae performed better in the low temperature regimes. The negative score loadings (in CCA) between the water temperature and algal groups- Bacillariophyceae and Chlorophyceae also supports the previous findings. Urrea-Clos *et al*. (2014) reported the influence of various environmental factors on algal biomass including a positive correlation between algal biomass and total alkalinity. Similarly, the positive impact of elevated water temperature on photosynthetic activity and phytoplankton biomass (diatoms and blue green algae) was reported by Sobrino and Neale (2007) from a low land aquatic ecosystem. Kozak *et al*. (2015) also reported a positive correlation between dissolved oxygen and micro phytoplankton, and an inverse relationship with the specific conductivity which compares well with the present observations. The positive correlation between nutrients (nitrate, TN, phosphate, TP and silicate) and phytoplankton groups in the present study also supports the general notion that nutrient concentration enhances the phytoplankton growth (Harris, 1986).

Seventy-seven species (66 genera) of phytoplankton were recorded with Cyanophyceae as the chief contributor in Bhetkimari canal. Pennate diatoms constituted a major part of diatom assemblages. The majority of the algal groups (Cyanophyceae, Bacillariophyceae, Chlorophyceae, Trebouxiophyceae, Euglenophyceae and Dinophyceae) showed positive correlations with the nutrient variables. Concurrently, Chlorophyceae, Mediophyceae and Synurophyceae were influenced negatively by WT, Sp. Con., and pH. Water variables such as WT, DO, Sp. Con., TA, nitrate, silicate, and phosphate influenced the phytoplankton assemblages in the canal as evident from CCA. The diversity indices (d, H') and the evenness index J' showed clear seasonal trends, and the calculated values indicate a moderate phytoplankton diversity in the system. The findings of this study are expected to enrich the existing knowledge on the abundance and distribution of phytoplankton communities and their interrelationships with various environmental parameters in semi-lotic canal environments. Further, it will inform the decision-making processes for the scientific management of canal systems.

CONFLICTS OF INTEREST

The authors declare they have no conflict of interest.

ACKNOWLEDGEMENT

Authors are grateful to the Director, ICAR-Central Inland Fisheries Research Institute, Barrackpore, Kolkata, India for extending financial support to carry out this research under the project entitled 'Exploration of canal resources in Punjab and Sundarbans (West Bengal) for fisheries development (REF/17-20/08). Assistance provided by the Technical Staff of the Project in analyses of physicochemical parameters is duly acknowledged.

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