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Microphytoplankton species assemblages, species-specific carbon stock and nutrient stoichiometry in the shallow continental shelf of the northern Bay of Bengal during winter

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Microphytoplankton species composition, diversity, abundance and biomass (chlorophyll-*a*) was studied for the first time in the shallow continental shelf (< 20 m bathymetry) of the northern Bay of Bengal during winter (December, 2011 to February, 2012). Species specific chlorophyll and carbon stock has been computed from biovolume calculation using standard formulae. Nutrient stoichiometry along with related biogeochemical variables has also been studied. Forty five phytoplankton species were recorded in total, out of which 38 were diatoms and the rest were dinoflagellates. *Thalassionema frauenfeldii* was the most abundant species, followed by *Thalassionema nitzschioides* and *Coscinodiscus radiatus.* Highest cell chlorophyll and carbon content was found in *Coscinodiscus gigas*. Dinoflagellate species were found to comprise 15.55% of the total taxa. Amongst the dinoflagellates, *Ceratium furca* had the highest abundance, whereas *Ceratium symmetricum* had the maximum species-specific chlorophyll and carbon stock. The nutrient stoichiometry was highly deviated from the standard Redfield ratio of Si: N: P (16:16:1).

[**Key words**: Phytoplankton, diatoms, dinoflagellates, nutrients, carbon stock, Bay of Bengal]

Introduction

The knowledge of phytoplankton species diversity is crucial for any ecological or eco-physiological work on marine as well as estuarine ecosystem. Phytoplankton are also highly sensitive to environmental changes. Their community composition, biomass and their shifts represent an excellent tool to interpret the dynamics of a pelagic ecosystem, transformation, cycling of key elements and impact on coastal water quality. The phytoplankton are a significant component of the natural carbon cycle as they are capable of fixing 35-50 Gt C yr^{-1} in the ocean[1]. Phytoplankton also help to detect variations induced by river discharge, eutrophication, pollution and even certain unusual climatic phenomena[2,3] and all these attributes significantly depicts the bio-physical environment of an estuary. An estuary is characterized by gradients of chemical, physical and biological components in the water column. One of the major characteristics of this transition zone is mixing of turbid, nutrient-rich and colored river discharge with relatively clear, nutrient-poor ocean water which in turn creates a continuum in salinity and the availability of nutrients and light[4]. The inflow of both freshwater and seawater provide high amount of nutrients both in water column and sediment which makes the estuaries one of the most productive natural habitats of the world[5]. Moreover, the mangrove forests acts as a prominent source of carbon and nutrient to the adjacent lagoonal and coastal systems[6,7,8,9]. Highly productive mangrove ecosystems (2500 mg C m^{-2} day^{-1}) in the estuarine phase of tropical rivers may be a source of nutrients to the coastal water on one hand and provide a sedimentary sink for nutrients on the other[10].

In this context, it is extremely essential to study the phytoplankton dynamics in the shallow continental shelf of the northern Bay of Bengal (nBoB). This continental shelf water mass lies in transition between the organic matter and nutrient rich mangrove dominated water of Sundarban and offshore zone of the nBoB. The northern most part of the BoB is bounded by the largest mangrove stretch of the world, i.e. Sundarban. River Hugli, a tributary of the River Ganga, provides a perennial supply of freshwater to this Sundarban mangrove ecosystem. Distributaries other than the River Hugli, in the Indian part of Sundarban that contributed to the formation of the Ganga Delta (from west to east: R. Muriganga, R. Saptamukhi, R. Thakuran, R. Matla, R. Gosaba and R. Bidya), have lost their original connections with the main flow of R. Ganga because of siltation, and thus their estuarine character is now maintained by the monsoonal runoff only[11].

Previous studies on phytoplankton dynamics in this area were concentrated either on the offshore region having the bathymetry of > 100 m[12,13,14,15] or inner estuarine zone of Sundarban within the confluence of the rivers[16,17,18,19]. There is no prior data on phytoplankton dynamics of this transition zone probably because of its inaccessibility with research vessel due to low bathymetry and/or unstable weather condition.

The foremost objectives of the present work may be enumerated as (i) documentation of phytoplankton species diversity, ii) species-specific chlorophyll and carbon stock assessment of these phytoplankton species, and (iii) study of biogeochemical factors along with nutrient status of this transition zone. We have conducted the work during the months December, January and February, because these are the phytoplankton bloom forming months[18] and can be accessed with ease for calm weather condition to survey the area with fishing trawler.

Materials and Methods

Bay of Bengal (BoB) forming the eastern flank of the northern Indian Ocean is a comparatively small basin of 2.2×10^6 km^2 area[20]. The BoB possess several distinguishing features like (i) lower surface salinity (22-33 psu)[14], (ii) weak and variable surface winds (0 to 10m s^{-1}) leading to strong stratification in the upper 50 m[21] (iii) massive supply of fresh water (1.5×10^{12} m^3)[22] and silt (16×10^8 t / y) from several peninsular rivers like Irrawady, Brahmaputra, Ganges and Godavari[23], (iv) on an average, the annual rainfall over the Bay is in excess of 2[24]m and (v) precipitation prevailing upon evaporation[25]. The southwest monsoon during June-September and northeast monsoon during November-February bring about large-scale precipitation far surpassing the evaporation in the BoB[26]. Ramage[27] stated that rainfall over BoB shows wide spatial variability and strong seasonality: the southeast coast of India has a winter rainfall maximum, whereas the rest of the BoB has a summer monsoon maximum. Large fresh water discharge from the north Indian rivers during summer monsoon not only lowers the salinity of the BoB, but also reduces the intensity of upwelling ~ 40km from the coast[20]. This enormous fresh water input causes strong vertical stratification (barrier layer) inhibiting the upliftment of nutrients[28,29,30].

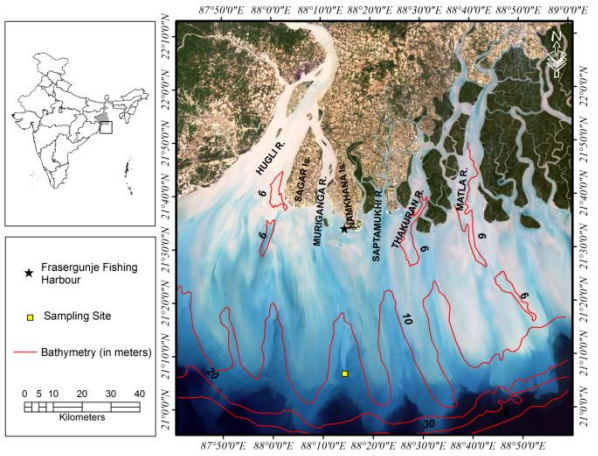

Fig. 1—Study sites and sampling locations in the shallow continental shelf of the northern Bay of Bengal

The present study was conducted in the shallow coastal waters (< 20 m bathymetry) of the northern Bay of Bengal. Ten field trips were conducted with mechanized fishing trawler having anchoring facility. Each journey was started from Frasergunje fishing harbor (21° 34′ 46.21″ N, 88° 15′ 03.12″ E) situated in West Bengal, India. The entire sampling was conducted within a 4 km^2 area situated 40 km off the coast (Fig. 1). During each survey, sampling was done at 10 spots (within the above mentioned 4 km^2 area) equidistant from each other. All the sampling was done between 0600 and 0800 hrs. Before each sampling, the engine of the boat was stopped for few minutes with an aim to allow the sea water to regain undisturbed state, and sampling was done under anchored condition. Water samples were collected from two to three centimeter below the water surface with the help of a BOD bottle (300 ml) and all the physicochemical parameters were analyzed on board (except chlorophyll-*a* and the nutrients).

Phytoplankton samples were collected with plankton nets made up of bolting silk with mesh size of 20 µm. In the study area, due to high suspended matter content, sedimentation method could not be implemented. Instead, 50 litre of surface water was passed through the phytoplankton net from each spot of the transect. Samples were collected and preserved with Lugol's iodine solution (1:100 v/v). Phytoplankton cell counts were performed using a Sedgwick rafter counting chamber. All the qualitative and quantitative phytoplankton studies were done within three months of the sample collection with the help of a compound microscope (Carl Zeiss, Germany) having image capture facility. Surface area and bio-volume of each phytoplankton species were estimated by measuring the different dimensions of the phytoplankton species in the microscopic imagery (using the software AxioVision LE Rel. 4.3). All the species were identified with the help of standard monograph[31].

Phytoplankton species' cell bio-volume was calculated according to the simple geometrical model of Sun and Liu[32]. Phytoplankton dimensions were measured for at least 20 randomly chosen individuals from each taxon. Chlorophyll-*a* and organic carbon content per cell was estimated from the cell volume according to the conversion formulae coined by Montagnes et al.[33] and Menden-Deuer & Lessard [34] respectively.

Sea surface salinity (SSS) was measured using a Multikit (WTW Multi 340 i Set, EMERCK, Germany) fitted with the probe WTW Tetracon 325. Dissolved oxygen (DO) was measured by Winkler's titrimetric method. In order to collect water samples for DO measurement, each BOD bottles were acid washed and dried previously. pH and water temperature was also measured instantaneously with a micro-pH meter (pH 620, Eutech Instrument, Singapore) having a precision of 0.001pHu. Glass electrode for pH measurements were calibrated daily in the NBS scale with technical buffers of pH 4.01 (Part no: 1.09475.0500, MERCK, Germany) and pH 7 (Part no: 1.09477.0500, MERCK, Germany) at controlled temperature of 25°C. The pH readings taken on-board at the respective temperatures were corrected for the standard temperature of 25°C. Secchi disc was used to measure the degree of transparency of the water column. Turbidity was measured with the help of a turbidity meter (Eutech TN-100, Singapore). The nutrient concentrations namely dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonia), dissolved inorganic phosphate (DIP) and silicate were measured using spectrophotometric methods[35]. Euphotic depth was calculated using the relationship: k (attenuation coefficient) = 1.7/D (D = Secchi depth in meters) and euphotic depth = 4.606/k[36]. Total suspended solids (TSS) were measured by gravimetric methods.

Chlorophyll-*a* was estimated following standard spectrophotometric methods[37]. The spectrophotometer was calibrated once during each day of measurement by a set of well preserved standard chlorophyll-*a* stock solution of strengths 2µM, 5 µM, 10 µM and 20 µM. The standard solutions were prepared from lyophilized chlorophyll-*a* (C6144-1MG, Sigma chemicals, USA).

The species diversity was calculated by the Shannon Weaver [38] formula:

$$H = -\sum_{i=1}^{s} Pi \ln Pi \quad (1)$$

where 'S' is total number of species and 'Pi' is the proportion of the numbers of individuals of species 'i' to the total number of individuals

$$Pi = ni / N \text{ [39]}. \quad (2)$$

Species Richness (SR) of the number of species recorded from a region was calculated by Margalef's formula[40].

$$SR = (S-1) / \ln N \quad (3)$$

where 'S' stands for total number of species and 'N' denotes total individuals present in the sample. Index of dominance[41] was calculated using the formula

$$C = \sum [ni / N]^2 \quad (4)$$

where, '*ni*' is number of individual per taxon, '*N*' is total number of individual.

Ten parameters (chlorophyll-*a*, SSS, SST, pH, DO, silicate, DIN, DIP, Euphotic depth and turbidity) were included in the statistical analysis[19,42,43,44]. Principal component analysis (PCA) was performed by the statistical software STATISTICA (version 8).

Results

The average concentration of the biogeochemical variables for the three months is tabulated in Table 1. Highest SST was recorded in December (26.0 ± 1.2°C) while in January (23.3 ± 0.8°C) it was lowest. The month of December marked the lowest mean SSS (21.3 ± 1.2 psu) and it increased in the following months (23.4 ± 0.9 psu in January and 25.5 ± 1.0 psu in February). A significant negative correlation ($r = -0.369$, $p < 0.005$, $n = 68$) between SST and SSS was noticed. Surface DO saturation varied from 47 % to 83 %. Surface water pH ranged between 8.029 and 8.621.

Table 1─The monthly mean ± S.D of the physico-chemical variables of surface water

Baseline parameters	December 2011	January 2012	February 2012
SSS (psu)	21.3 ± 1.2	23.4 ± 0.9	25.5 ± 1.0
SST (^oC)	26.0 ± 1.2	23.3 ± 0.8	24.4 ± 2.0
pH	8.163 ± 0.041	8.285 ± 0.142	8.188 ± 0.073
DO (mg l^{-1})	5.6 ± 0.4	5.5 ± 0.3	5.2 ± 0.3
Euphotic Depth (cm)	162 ± 64	204 ± 44	387 ± 273
Turbidity (NTU)	46.9 ± 25.8	40.2 ± 12.6	18.0 ± 10.1
TSS (mg l^{-1})	12.3 ± 7.67	44.3 ± 12.5	33.21 ± 11.12

Cruises undertaken in between the mid of January and the first week of February, recorded pH values of higher magnitude (Table 1). Euphotic depth varied between 29 and 1137 cm; the higher values were observed in February.

The depth of transparency negatively correlated with dissolved oxygen ($r = -0.369$, $p < 0.001$, $n = 68$).

In the present study, a total of 45 phytoplankton species (Table 2) were identified which includes 38 diatoms and 7 dinoflagellates (15.55% of the total number of species). Amongst the diatoms, 27 were found to be centric diatoms and 11 were pennate diatoms. On the other hand, among dinoflagellates, only *Protoperidinium* spp was heterotrophic regarding nutritional status. Overall average abundance and biomass of phytoplankton were 15.43 ± 12.23 ($\times 10^4$ m^{-3}) and 2.60 ± 0.37 µg l^{-1}, respectively. Among the total number of phytoplankton abundance, 4.13% was contributed by the dinoflagellate species.

Amongst the diatoms, *Thalassionema frauenfeldii* was found to be the most abundant (Relative abundance (RA): 30.52%) followed by *Thalassionema nitzschioides* (RA: 20.44%) and *Coscinodiscus radiatus* (RA: 9.88%). Among the dinoflagellates, *Ceratium furca* (RA: 0.94%) showed highest abundance followed by *Protoperidinium* spp (RA: 0.77%). Individual bio-volume of *Coscinodiscus gigas* was 6.4307 million µm^3 $cell^{-1}$, followed by *Odontella sinensis* (3.2255 million µm^3 $cell^{-1}$) and *Coscinodiscus granii* (1.7438 million µm^3 $cell^{-1}$). *Ceratium symmetricum* had highest bio-volume (0.3083 million µm^3 $cell^{-1}$) among the dinoflagellates.

The mean Shannon-Weaver diversity index, Simpson index of dominance and Margalef's index of species richness for the study area was calculated to be 3.68, 0.15 and 6.19 respectively.

Chlorophyll-*a* was observed to have a decreasing trend towards offshore and hence showed a negative correlation ($r = -0.646$, $p < 0.001$, $n = 68$) with SSS. It also had a significant negative correlation with euphotic depth ($r = -0.399$, $p < 0.001$, $n = 68$).

All the dissolved nutrients (DIN, DIP and silicate, Table 3) were found comparatively higher during the month of January. DIN and DIP varied from 0.10 to 27.79 µM (8.13 ± 5.62 µM) and 0.32 to 2.95 µM (1.03± 0.50) respectively (Fig. 2). The value of silicate ranged between 1.45 and 18.27 µM with a mean value of 12.44 ± 3.23 µM.

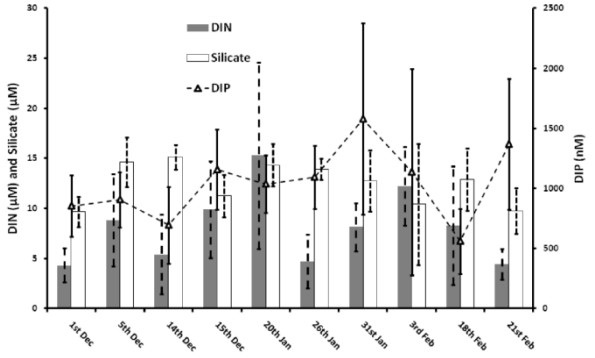

Fig.2─Mean and standard deviation of dissolved inorganic nitrogen (DIN in µM), silicate and dissolved inorganic phosphate (DIP in in µM) observed in each cruise date during the study

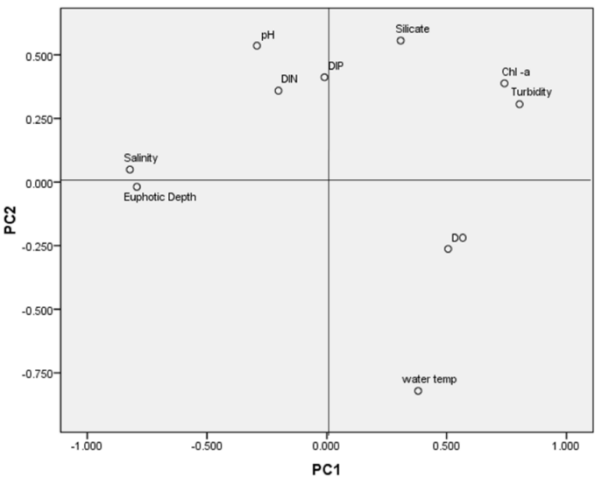

Fig.3─Scatter diagram based on the first two components derived from principal component analysis (PCA)

Results of PCA shows, among the 10 factors first 4 components were extracted with reference to eigen values more than 1 which only can explain 72.96% of total variation in the study (Fig. 3).

First component (PC 1) can alone explain 31.20% of the total variability. Here, chlorophyll-*a*, turbidity, DO are positively loaded in contrast to negatively loaded variables like SSS and euphotic depth. On the other hand, second component (PC 2) explains 18.85% of the total variability where pH and silicate are positively loaded in contrast to negatively loaded variable SST. However, the first two components were used to draw the scatter diagram of the variables under study.

Table 2—Species of phytoplankton with their relative abundance (mean ± SD), cell bio-volume, cell chlorophyll content (according to the conversion formula of Montagnes et al,1994) and cell carbon content (according to the conversion formula of Meden-Deuer and Lessard, 2000) of a particular species

Division	Phytoplankton Species	RA (mean ± SD)	Individual Bio-volume (million μm^3 $cell^{-1}$)	Chlorophyll Content per cell (pg)	Carbon Content per cell (pg)
Bacillariophyta	*Amphipleura* Kützing*	0.17 ± 0.02	0.0345	1380	62
	Asterionella japonica Cleve	1.63 ± 0.23	0.0260	907	39
	Bacillaria paxillifera (O.F.Müller) T.Marsson	0.43 ± 0.11	0.0033	207	7
	Bacteriastrum delicatulum Cleve	0.34 ± 0.03	0.0029	185	6
	Bacteriastrum hyalinum Lauder	0.17 ± 0.05	0.0029	185	6
	Bacteriastrum furcatum Shadbolt	1.03 ± 0.17	0.0089	463	18
	Cerataulina pelagica (Cleve) Hendey	0.68 ± 0.27	0.0623	2228	107
	Coscinodiscus radiatus Ehrenberg	9.88 ± 2.12	0.3046	8067	457
	Coscinodiscus excentricus Ehrenberg	8.42 ± 1.76	0.7082	15,991	990
	Coscinodiscus gigas Ehrenberg	1.54 ± 0.37	6.4307	95,695	7492
	Coscinodiscus granii Gough	5.58 ± 0.98	1.7438	33,209	2264
	Chaetoceros decipiens Cleve	1.46 ± 0.41	0.0084	439	17
	Chaetoceros lorenzianus Gruno	0.43 ± 0.15	0.1285	4008	207
	Chaetoceros didymus Ehrenberg	0.25 ± 0.04	0.0130	625	25
	Cyclotella (Kützing) Brébisson*	0.25 ± 0.09	0.0003	36	1
	Ditylum brightwellii (T.West) Grunow	0.25 ± 0.05	0.0426	1636	75
	Eucampia zodiacus Ehrenberg	0.77 ± 0.18	0.2352	6541	360
	Gyrosigma Hassall*	0.17 ± 0.02	0.2015	5770	313
	Hemiaulus sinensis Greville	0.17 ± 0.03	0.0091	469	18
	Hemiaulus indicus Karsten	0.08 ± 0.02	0.0079	419	16
	Lauderia annulata Cleve	0.25 ± 0.09	0.0294	1213	54
	Lepidocylindrus danicus Cleve	0.25 ± 0.06	0.0017	123	4
	Melosira moniliformis (O.F.Müller) C. Agardh	0.17 ± 0.06	0.0429	1648	76
	Navicula Bory de Saint-Vincent*	0.08 ± 0.02	0.0006	55	2
	Nitzschia longissima (Brébission) Ralfs	3.35 ± 0.78	0.0011	85	3
	Nitzschia seriata Cleve	0.17 ± 0.07	0.0028	182	6
	Odontella mobilensis (J.W.Bailey) Grunow	2.32 ± 0.31	0.2473	6813	378
	Odontella sinensis (Greville) Grunow	1.46 ± 0.14	3.2255	54,685	3979
	Planktoniella sol (C.G.Wallich) Schütt	0.08 ± 0.01	0.5379	12,795	770
	Pleurosigma W.Smith*	0.25 ± 0.05	0.0406	1576	72s
	Rhizosolenia hebetata Bailey	0.34 ± 0.02	0.0281	1169	51
	Rhizosolenia setigera Brightwell	0.68 ± 0.08	0.0054	310	11
	Schuettia annulata (Wallich) De Toni	0.08 ± 0.01	0.0641	2280	110
	Skeletonema costatum (Greville) Cleve	0.68 ± 0.17	0.0087	453	18
	Synedra Ehrenberg*	0.43 ± 0.09	0.0003	35	1
	Thalassionema frauenfeldii (Grunow) Tèmpere & Peragallo	30.54 ± 3.25	0.0077	410	16
	Thalassionema nitzschioides (Grunow) Mereschkowsky	20.44 ± 1.11	0.0003	30	1
	Thalassiosira subtilis (Ostenfeld) Gran	0.43 ± 0.09	0.0015	108	4
Dinophyta	*Ceratium furca* (Ehrenberg) Claparède & Lachmann	0.94 ± 0.33	0.0485	5237	85
	Ceratium fusus (Ehrenberg) Dujardin	0.60 ± 0.12	0.0044	739	9
	Ceratium tripos (O.F.Müller) Nitzsch	0.51 ± 0.09	0.0157	2086	30
	Ceratium trichoceros (Ehrenberg) Kofoid	0.34 ± 0.04	0.0131	1801	26
	Ceratium symmetricum Pavillard	0.08 ± 0.01	0.3083	23,785	462
	Dinophysis caudata Saville-Kent	0.86 ± 0.22	0.0403	4498	71
	Protoperidinium R.S.Bergh*	0.77 ± 0.21	0.1048	9831	172

*These species are identified only up to the genus level

Table 3—The monthly mean ± S.D of chlorophyll-*a* and nutrients

Baseline parameters	December 2011	January 2012	February 2012
Chlorophyll-*a* (μg l^{-1})	2.90 ± 0.56	2.60 ± 0.37	2.16 ± 0.52
Dissolved (NO_3^- + NO_2^-) (μM)	6.21 ± 4.20	9.50 ± 7.44	7.59 ± 5.12
Dissolved NH_4^+ (μM)	0.61 ± 0.30	0.48 ± 0.44	0.50 ± 0.29
Dissolved PO_4^{3-} (μM)	0.90 ± 0.29	1.23 ± 0.54	1.02 ± 0.66
Dissolved SiO_3^{2-} (μM)	12.46 ± 2.96	13.71 ± 2.25	11.06 ± 3.98
DIN/DIP ratio	7.5	8.1	7.9
Si/DIP	13.8	11.4	10.8
Si/DIN ratio	1.82	1.38	1.36

Discussion

In the present study area, *Thalassionema frauenfeldii* had the highest abundance, followed by *Thalassionema nitzschioides* and *Coscinodiscus radiatus*. On the contrary, *Asterionella japonica* followed by *Skeletonema costatum* was the most abundant species near the river confluence[18,19]. This shows that the species composition is markedly different in the two regions. In this context, it is worth mentioning that Shenoy et al.[45] while working in the open sea region of the BoB, observed a strong relationship between *T. frauenfeldii* and the dimethyl sulphide (DMS) concentrations in the Bay of Bengal. Hence the sheer abundance of *T. frauenfeldii* in this region may be related with DMS production and subsequent contribution to cloud condensation nuclei (CCN).

Among dinoflagellates, *Ceratium furca* was the most abundant species followed by *Ceratium fusus*. These species are known to be present in the stable stratified water column[46,47]. In a recent study, *C. furca* was reported to have an advantage over *C. fusus* as they have an efficient diel vertical migration capability[48]. On the other hand, the abundance of *Ceratium symmetricum* was much lower compared to the other species of *Ceratium*. Scarcity of this species was reported to be an indicative of warming in the Hugli-Matla estuary to offshore transition zone[49].

The Shannon-Weaver diversity index was much higher in the present study area, whereas Simpson's dominance index was comparatively lower than that observed by De et al.[18] in the river confluence during the study months (December, January and February). However, both the diversity and richness index found in this study was lower than the indices reported from western (H: 4.18; MI: 7.29) and central (H: 4.93; MI: 10.43) Bay of Bengal[14]. These observations makes us infer that the species diversity of the present study area was relatively lower than the open sea whereas much higher than that found in the river confluence. Moreover, the diversity index showed an inversely proportional relationship with dominance index. Floder & Sommer[50] reported that the value of H´ reduces to <2 when phytoplankton undergoes high frequency of disturbance through increased supply of nutrients. In our study area H´ was found to be much greater than 2 throughout the study period, which indicate the area was undisturbed with respect to the increased supply of nutrients.

According to De Jong[51] and Ilangovan[52] increase in species numbers along with environmental heterogeneity and incomplete mixing of waters leads to an increase in diversity. In addition to this, low levels of nutrients[53,54] are also known to promote species diversity[55]. Phytoplankton biomass (chlorophyll-*a*) has shown significant negative correlation with Shannon Weaver index. This observation is in parity with the statement of Irigoien et al.[56] that similar to terrestrial vegetation, marine phytoplankton diversity is a unimodal function of phytoplankton biomass, with maximum diversity at intermediate levels of biomass and minimum diversity during massive blooms.

In terms of bio-volume, according to the criteria (2 mm^3 L^{-1}) suggested by Badylak & Philips[57], no phytoplankton species reached bloom levels during the present study period. On the basis of individual cell volume, *Coscinodiscus gigas* had the highest cell chlorophyll (95,695 pg) and carbon (7,492 pg) content, followed by *Odontella sinensis* (54,685 pg and 3,979 pg respectively) and *Coscinodiscus excentricus* (33,209 pg and 2,264 pg respectively). Among dinoflagellates, *Ceratium symmetricum* had the highest chlorophyll-*a* and carbon content of 23,785 and 462 pg respectively.

In terms of the dynamics of diatoms, which are the dominant group of phytoplankton in this estuary, PCA analyses suggest that variations in silica concentrations are important as silica is one of the most important minerals for making the skeleton of diatom[58]. Besides that, the component of PC1 and PC2 further reflects that turbidity, pH

and SST were also crucial factors in this transition zone.

The mean DIN and silicate concentration in the present study area were much less than the value of 16.1 µM[59] and 147.8 µM[18] respectively which are the world average value of river water. However, the mean DIP value was found higher than the world average of 0.65 µM[59]. The nitrate concentration found in our study was less than the half saturation of eutrophic coastal water while for phosphate and silicate it was vice-versa (i.e., 2.0–10.0 µM for nitrate, 0.02–0.5 µM for phosphate, and 0.5–5.0 µM for silicate[60]). The stoichiometric proportions of dissolved nutrients in this study area highly deviated from the standard Redfield ratio (Si:N:P = 16:16:1), primarily because of the allochthonous nutrients derived from anthropogenic activities. The mean DIN: DIP ratio (~7.8) was found much lesser than 16 which indicate DIN is the limiting factor whereas, the mean Si:DIN ratio was found > 1 (~1.5). As per the conventional ecological theory, nitrogen is the limiting nutrient at the marine end and phosphorus is a limiting nutrient at the freshwater end[61,62]. Prasad[63] stated that Si:DIN ratios were >1 in all mangrove ecosystems, which indicates that high silica is supplied from the terrestrial weathering to the mangrove waters. As per Dortch[64], some phytoplankton species show preference towards ammonia over nitrate, but since no correlation was found between chlorophyll-*a* and NO_3^-/NH_4^+ ratio, it could be inferred that phytoplankton community in the present study area did not have specific preference for either NO_3^- or NH_4^+ as observed by Lie et al.[65].

On the whole it could be concluded that this estuary to offshore transition area is quite rich in terms of species diversity but not as rich as observed in the open ocean. Moreover, in terms of nutrient status the area is presently undisturbed i.e. far from attaining eutrophication during phytoplankton bloom forming months.

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