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Study on mangrove associated estuarine waters of Northeastern Bay of Bengal reveals potential diatom indicators of dissolved inorganic compounds

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Abstract. An extensive study (2011 and 2012) was performed to narrow down certain diatom species with bioindicator potentials of highly dynamic and well mixed tropical estuary. The Hooghly Estuary in the Northeastern coast of Bay of Bengal was chosen as the study sites. The comparison between mangrove impoverished and mangrove dominated estuarine rivers revealed intriguing variation in the phytoplankton species composition in response to the dissolved nitrate, phosphate and silicate concentrations, thus forming the kernel of the study by focusing on certain species with greater abundances pointing to their better adaptability and responsiveness to biotic/abiotic parameters in a well mixed estuary. *Coscinodiscus hyalinus*, *Coscinodiscus radiatus*, *Lioloma elongata*, *Skeletonema costatum*, *Synedra crystallinum*, *Thalassionema frauenfeldtii* and *Thalassionema nitzschioides* have expressed better as bioindicators.

Keywords: Bioindicator, *Coscinodiscus*, *Skeletonema*, *Synedra*, *Thalassionema*, Hooghly Estuary.

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Introduction

Diatoms are microscopic, unicellular, eukaryotic algae that are always in full contact with their immediate ambient environment (Smol and Stromer, 2010) and react to the changes in their environment in the most sensitive way. The diatoms owing to their siliceous frustules are entombed in sediments for many years, a trait which has rendered them useful for studying and interpreting ecological conditions of bygone eras. The ubiquitous distribution of the diatoms, their high specific diversity and their siliceous frustules, all enable diatoms to function as sound environmental indicators (Stevenson and Pan, 1990). “It is estimated that diatoms account for 40% of the total marine production of carbon (Nelson et al., 1995). The chief inorganic compounds which govern the growth and proliferation of the diatoms are nitrate, phosphate and silicate apart from carbon.

Nitrogen is considered to be one the most significant growth constraints for phytoplanktons. Around 70% of nitrogen assimilation is governed by the phytoplankton on a global scale and nitrate has been most widely studied as the chief nitrogen source of the phytoplankton. Its concentration ranges from undetectable to 50 µmol.L^{-1} in oceans and increase manifolds in the coastal waters as a result of riverine run-off and upwelling. Nitrate, in coastal waters, normally ranges within 500 µmol.L^{-1}. Orthophosphate is the only form of phosphorus that autotrophs are able to assimilate. In contrary to the freshwater environment, in estuarine and marine environments phosphate plays the most important role of a growth limiting nutrient. More conclusive evidence for the effect of phosphorous on growth rate has been reported using culture of certain algal species (Fuhs, 1971). The diatom cell walls are silicified and known as frustules. They generally consist of hydrated amorphous silica with empirical formula ($Si_nO_{2n-(nx/2)}OH_{nx}$), with x ≤ 4. According to Tréguer et al. (1995), the use of silicon by diatoms dominates the biogeochemical cycling of Si in the sea, with each atom of Si weathered from land passing through a diatom on average 39 times before burial in the sea. Cell wall silicification and silicic acid transport are tightly coupled to the cell cycle, which results in a dependency in the extent of silicificationn on growth rate. According to Martin-Jézéquel et al. (2000) silica dissolution is an important part of diatom cellular silicon metabolism, because dissolution must be prevented in the living cell, and because much of the raw material for mineralization in natural assemblages is supplied by dissolution of dead cells.

Diatom indicators have been documented from time to time in aquatic environments such as lakes and lagoon but, hardly any substantial data exist on the use of particular diatom species as bioindicators of eutrophic conditions in well mixed tropical estuarine ecosystems. Both mangrove associated water bodies and rivers without apparent mangrove vegetation on their flanks harbor unique microalgal communities, dominated mostly by diatoms in estuarine ecosystems. Comparative accounts from their natural set ups and their responses towards various physiochemical conditions may be useful in revealing probable species with affinity towards a certain condition. The primary objective of the study was to delineate the response of phytoplanktons to changes in the inorganic nutrients so that few species can be demarcated with potential of being used as bioindicators to nutrient enriched environments in well mixed tropical estuaries.

Materials and methods

Study area

The sampling stations were Kachuberia (21° 51’ 39” N, 88° 08’ 37” E), Chemaguri (21° 40’ 43” N, 88°07' 28"E) and Gangasagar (21° 38’ 00” N, 88° 05’ 00” E) located in the Hooghly Estuary (Figure 1). The selection of these locales were mainly based on their clearly discernible salinity differences and mangrove vegetation covers, ranging from region with high riverine influence (Kachuberia) as mangrove impoverished zone, to brackish water regions and mangrove vegetation (Chemaguri) and marine dominated region (Gangasagar) with sparse mangrove cover. Three stations at Chemaguri were chosen to be sites with mangrove vegetation dominance (21° 40’ 43” N and 88° 07’ 28” E, 21° 40’ 48” N and 88° 09’ 04”E, and 21° 40’57.54” N and 88° 09’ 09.49” E]. Results from mangrove dominated regions and mangrove impoverished regions have been grouped under the two headings and average data from the stations under respective groups has been used for the present manuscript. The Hooghly Estuary is the first deltaic offshoot of the River Ganges. It is a coastal plain estuary and lies approximately between 21° 32’ N-22° 40’ N and 88° 05’ E-89° 00’ E and the lower 80 km of the estuary flows through the western part of the marshy coastal areas covered with thick mangrove vegetation and is known worldwide as the Sundarbans.

Three primary sampling stations were selected due to their variation in salinity, ranging from river dominated (Kachuberia), brackish water (Chemaguri) and up to marine influenced (Ganga Sagar). The entire Hooghly Estuary was devastated by a severe tropical super cyclone and the study performed on it should help to find valuable information about the effect of such a catastrophe on microphytoplanktons population of a well mixed estuary (Hooghly Estuary is one of the most important part of the largest deltaic system in the World).

The northeast coast of the Bay of Bengal is highly irregular near the land-ocean boundary and is dissected by a large number of strewing rivulets, creeks and tributaries. The River Hooghly is the main artery of the River Ganges and is morphed into swampy marshy lands near its estuarine gateway to the Bay of Bengal, with severe fluvial deposits. The Hooghly Estuary exchanges flow with the Bay of Bengal near the Sagar Island and its tidal

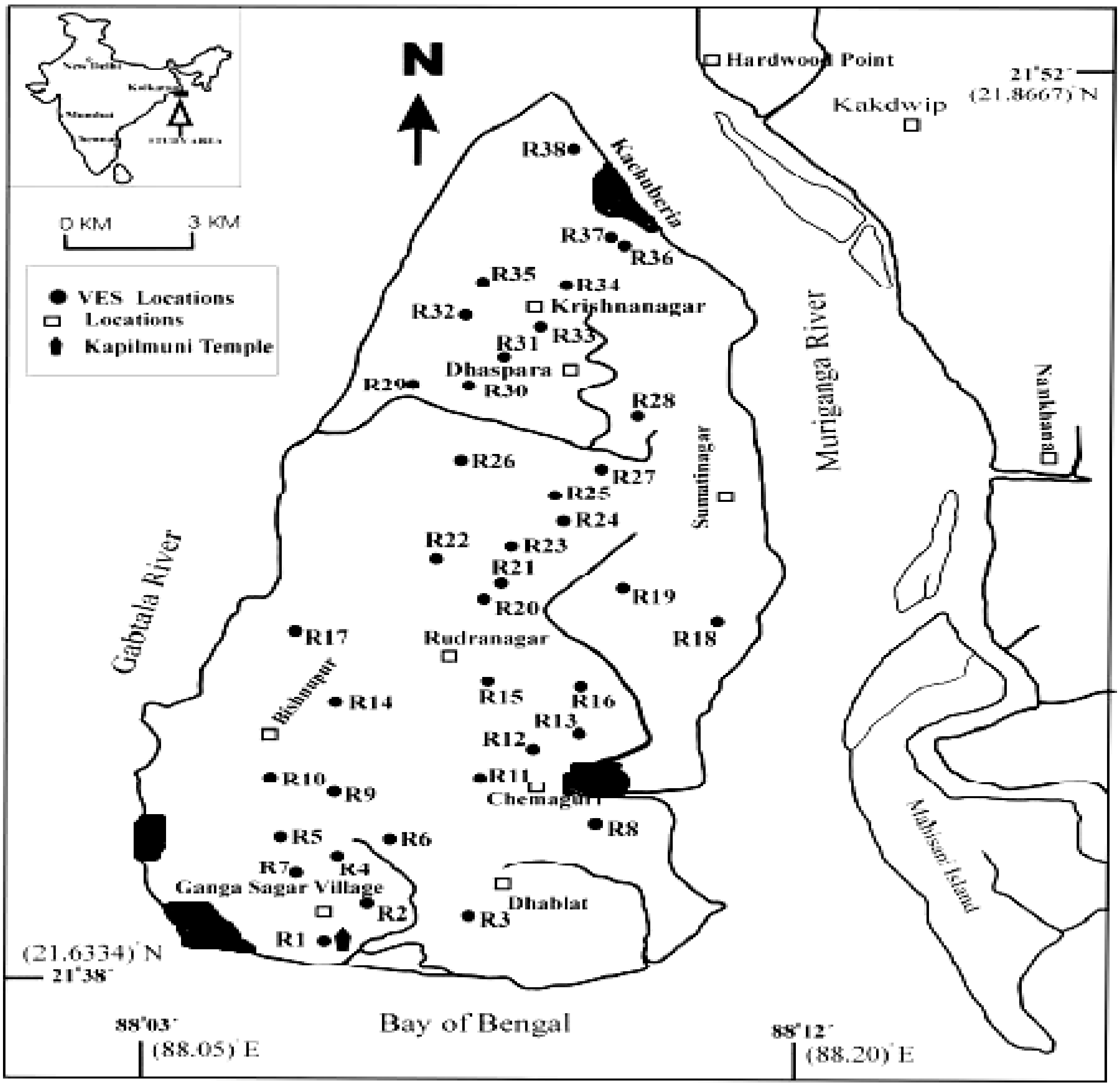

Figure 1. Map of the study sites with sampling stations (black blotches).

domain for nearly 250 km. the mouth of the estuary has a funnel shape and the predominant tidal regime is semidiurnal in nature. The vertical tide range at the mouth varies from 5.2 m during the spring tide to 1.8 m during the neap period. This is a well mixed estuary due to the intense tidal and wave actions with a meso-macrotidal setting (2.5-7 m amplitude). Mean current velocities are between 108 $cm.s^{-1}$ and 117 $cm.s^{-1}$ during high and low tides respectively. The climate of this region is characterized by the southwestern monsoon (July-October), northeast monsoon or post monsoon (November-February) and premonsoon (March-June); at least 70-80% of the rainfall occurs during the summer monsoon (SW monsoon), resulting in the high river discharge (2,952-11,897 $m^3.s^{-1}$), which gradually diminishes to 900-1500 m^3s^{-1} during non-monsoonal months (Biswas et al., 2004; Mukhopadhyay et al., 2006).

Data collection and sample analysis

Monthly data of surface water salinity, air temperature, water temperature, wind speed, dissolved oxygen, primary productivity and essential nutrients (nitrate, phosphate and silicate) were recorded and monthly phytoplanktonic sampling was performed from study sites for a total period of two years, 2011 and 2012. The essential meteorological back ground data of the days of the collections were procured from the usage of Shimadzu Weather Station. Salinity of the water was first

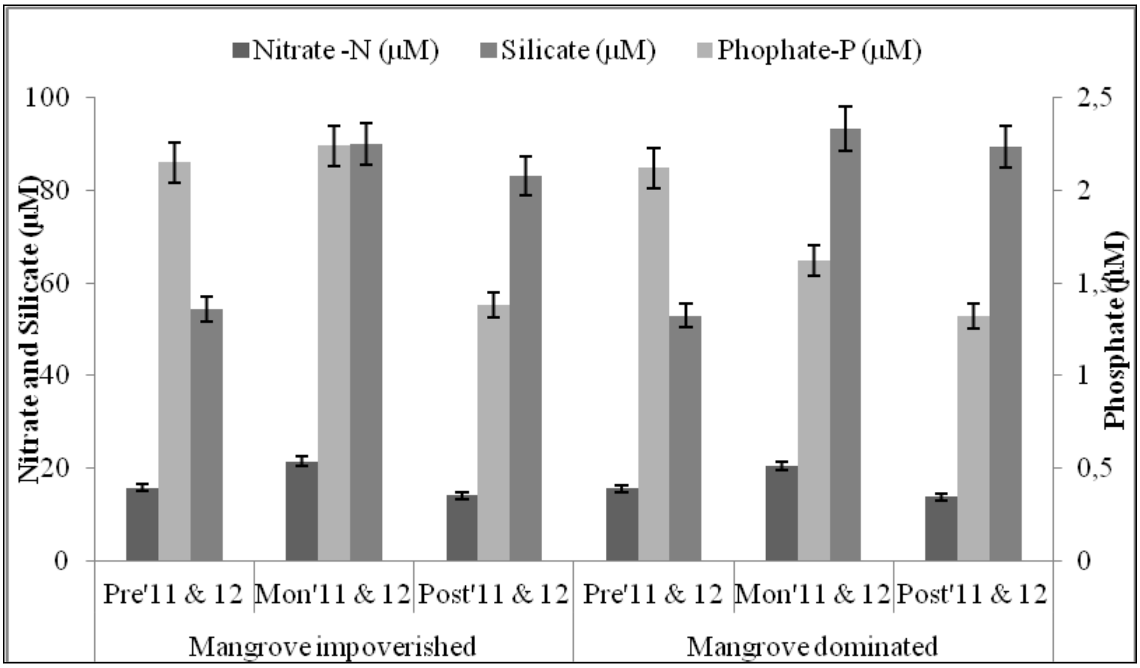

Figure 2. Seasonal fluctuations in the three chief nutrient parameters viz. nitrate-nitrogen, phosphate-phosphorus and silicate in mangrove impoverished and mangrove dominated waters of the Hooghly Estuary (error bars of the selected macronutrients with 5% value).

measured with the aid of refractometer and then estimated using argentometric method and the factor corrected values were put in.

Water sample for the estimation purposes was collected using the Niskin water sampler. For the estimation of phosphate, nitrate and silicate, the standard methods were followed (Grasshoff et al., 1983). Gross primary production and community respiration were measured *in situ* using the light and dark bottle method (Strickland and Parsons, 1972). The phytoplankton (diatom) sampling was performed using a handheld net [phytoplankton net (bolting silk no. 30, mesh size 20 µm) equipped with flow meter] from different stations in the Hooghly Estuary. The mesh size was fixed for the microphytoplanktons and not the nanoplanktons to maintain a certain degree of separation during the study and also due to the reason that increased turbidity rendered the usage of smaller mesh size impossible due to large quantities of silt clogging. The chief gear used in this purpose was country boats to ensure the least disturbance of the prevalent population of phytoplanktons. After the collection, the phytoplankton concentrates were transferred into 25 mL Tarson polythene containers and 4% formalin along with lugol's iodine were used as preservatives depending on the need of clarification and specific preferences. The formalin is a very good agent for clearing cells off organic debris but it doesn't stain cells hence it is hard to discriminate between living, viable cells from dead, resuspended ones. The samples were then analyzed under light microscopes, bright field microscopes and phase contrast microscopes for their accurate and proper identification, using proper literature (effective and valid) (Desikachary, 1986-1989; Hasle and Syvertsen, 1997; Al-Kandari et al., 2009).

Another method for the quantification of phytoplanktons was used where 1 L water samples in triplicates were collected; each preserved with lugol's iodine solution and buffered formalin. After 72 h of sedimentation, the supernatant was filtered off (20 µm) and the phytoplanktons (diatoms, flagellates and dinoflagellates) were enumerated in a Sedgwick Rafter counting chamber. The data generated from both the methods were tallied and the deviation was negligible ensuring accurate enumeration.

Data compilation and statistical analyses

All data tabulation and compilation were accomplished using the MS-Excel software but for statistical analyses, the ‘add-in’ of Excel, the Xlstat software was used and the principal component analysis tool of the data analysis package of the Xlstat 12 was employed to deduce the Pearson Correlation Matrix.

Result

The study was performed with the objective of finding diatom species with bioindicator potentials in well mixed estuarine waters of Hooghly Estuary (Figure 1). Water samplings near mangrove mudflat (mangrove dominated) and water bodies with no apparent mangroves in sight (mangrove impoverished) were chosen due to their differences in physico-chemical parameters and may provide a wider platform for the diatom species to respond to, in terms of indicating a particular condition. The Figure 2 and the Table 1 summarize the comparative variations in water quality parameters such as nutrients (nitrate-nitrogen, phosphate-phosphorus and silicate), salinity, dissolved oxygen, primary, air and water temperatures, wind speed etc.

From Table 1, it is quite obvious that water quality parameters which mainly govern any phytoplankton (diatom) population assemblages in any aquatic environment are comparatively different on average in mangrove dominated and mangrove impoverished. Figure 2 depicts the variation in nutrients where it can be observed that among the three chief nutrients taken into consideration, dissolved phosphate actually followed a somewhat different pattern of seasonal fluctuation.

Tables 2, 3 and 4 comprehensively describes the seasonal comparative variations (in the relative abundances as well as the composition of the phytoplanktons) in the phytoplankton population (mainly diatoms) sampled from both mangrove dominated and mangrove impoverished water bodies of the Hooghly Estuary. The number of phytoplankton species in general was higher in mangrove dominated regions as compared to mangrove impoverished sampling stations in all the three seasons. Again the relative abundances of phytoplankton species observed in the mangrove dominated region were found to be comparatively on the higher side as well.

The Table 5 depicts the species which had appeared in both the years of the study (2011 and 2012) in at least one of the three seasons, with few appearing in all the three. These phytoplanktons (diatoms) can best serve as indicators to the changes in their ambient environments. Species such as *Coscinodiscus radiatus*, *Coscinodiscus marginatus*, *Coscinodiscus lineatus*, *Ditylum brightwellii*, *Skeletonema costatum*, *Thalassionema frauenfeldtii*, *Thalassionema nitzschioides*, *Synedra crystallinum* etc are of more significance since they have been observed in both the years as well as all the three seasons, hence shall be able to reflect the effects of the seasonal changes in the selected physicochemical parameters on their composition and abundances and thus can be of greater use as bioindicators of well mixed tropical estuaries such as the one being dealt with presently. A very curious feature that can be observed from Table 5 is, almost all the species exhibited higher relative abundances in mangrove dominated waters than their abundances recorded from mangrove impoverished waters. Few species of *Coscinodiscus*, *Thalassionema* etc. however showed much higher abundances in mangrove impoverished waters.

A correlation was performed among relative abundance values of those species of phytoplanktons (diatoms) which were documented in both the years of the study, on all three seasons along with the chief nutrient parameters which is clearly exhibited in Table 6. From the table it is quite apparent that the correlation values were largely significant and a more common trend was that a species exhibited highly negative and positive correlations for a particular parameter in mangrove dominated and mangrove impoverished and vice versa. This suggests that although the parameter is similar, its exploitation might differ in mangrove dominated and mangrove impoverished conditions since the species composition differed leading to

Table 1. Average annual values of the background parameters with standard deviations (the data from mangrove dominated and impoverished waters were recorded seasonally and made average to capture the variations annually).

Parameters (2011 and 2012)	**Mangrove dominated**	**Mangrove impoverished**
PP (mgC m^{-3} h^{-1})	30.20±5.45	29.77±5.49
Salinity (psu)	15.79±5.71	14.52±5.80
Air Temp. (aT°C)	26.50±3.05	26.52±3.67
Water Temp (wT°C)	27.45±3.87	27.51±3.34
Wind Speed (km.h^{-1})	6.66±1.52	6.25±1.82
D.O. (mgL^{-1})	5.82±1.49	5.93±1.40

Table 2. Comparative account of the premonsoonal (2011 and 2012) phytoplankton composition in mangrove impoverished and mangrove dominated waters of Hooghly Estuary in terms of relative abundance.

Mangrove Impoverished PRE'11 and 12		**Mangrove dominated PRE'11 and 12**	
Species	**R.A. (%)**	**Species**	**R.A. (%)**
Asterionella japonicus	0.9102	*Actinocyclus octonarius*	0.2249
Aulacodiscus kittonii	1.2136	*Asterionella japonicas*	2.142
Bacteriastrum varians	0.3034	*Bacillaria paxillifera*	0.5335
Biddulphia (*Odontella*) *longicruris*	2.8322	*Bacteriastrum varians*	1.4726
Biddulphia (*Odontella*)*mobiliensis*	1.2136	*Campylodiscus impressus*	0.3681
Biddulphia (*Odontella*) *regia*	1.011	*Ceratium cylindrus*	1.0389
Biddulphia (*Odontella*) *sinensis*	2.4272	*Ceratium furca*	1.6641
Campylodiscus impressus	0.6068	*Ceratium fusus*	1.8073
Ceratium cylindrus	0.9102	*Ceratium indicum*	0.7363
Ceratium inflatum	1.011	*Ceratium lineatum*	1.0014
Chaetoceros balticum	0.3034	*Ceratium trichoceros*	1.071
Chaetoceros decipiens	1.517	*Ceratium tripos*	3.0525
Chaetoceros lorenzianus	1.8204	*Chaetoceros compressus*	4.9923
Chaetoceros quarctatus	0.6068	*Chaetoceros constrictum*	1.0308
Climacosphaenia moniligera	1.2136	*Chaetoceros curvisetus*	4.1194
Cocconeis scutellum	0.405	*Chaetoceros danicus*	4.0297
Coscinodiscus asteromphalus	1.2136	*Chaetoceros decipiens*	4.0605
Coscinodiscus centralis	3.7417	*Chaetoceros externum*	1.6641
Coscinodiscus concinnus	4.6527	*Chaetoceros lorenzianus*	4.6817
Coscinodiscus eccentricus	0.6068	*Chaetoceros pseudocurvisetus*	0.7363
Coscinodiscus gigas	0.9102	*Chaetoceros peruvianus*	2.7498
Coscinodiscus hyalinus	4.551	*Chaetoceros quarctatus*	0.7363
Coscinodiscus lineatus	2.6297	*Corethron criophilum*	0.7363
Coscinodiscus marginatus	3.5399	*Coscinodiscus concinnus*	2.9493
Coscinodiscus oculus-iridis	1.2136	*Coscinodiscus eccentricus*	0.7363
Coscinodiscus radiatus	10.6191	*Coscinodiscus gigas*	0.2249
Coscinodiscus tumidus	0.3034	*Coscinodiscus hyalinus*	1.9184
Cyclotella caspia	2.3263	*Coscinodiscus marginatus*	0.3681
Cyclotella striata	1.2136	*Coscinodiscus radiates*	5.2132
Cyclotella stylorum	1.4161	*Cyclotella striata*	0.2249
Ditylum brightwellii	0.7076	*Ditylum brightwellii*	2.7766
Gyrosigma angulatum	0.6068	*Ditylum buchananii*	1.6065
Haslea warwickea	2.7306	*Hemidiscus kanayanus*	1.5543
Hemidiscus cuneiformis	1.011	*Lauderia annulata*	2.9748
Hemidiscus kanayanus	0.7084	*Leptocylindrus minimus*	2.1875
Lioloma elongata	1.4161	*Lioloma elongate*	0.3681
Navicula transitans	1.2136	*Okedenia inflexa*	0.7363

Table 2. Continued.

Mangrove impoverished PRE'11 and 12		Mangrove dominated PRE'11 and 12	
Species	**R.A. (%)**	**Species**	**R.A. (%)**
Navicula spp.	0.9102	*Noctiluca scintillans*	2.3388
Nitzschia elongata	1.2136	*Pleurosigma aestuarii*	1.1045
Nitzschia sigma	0.6068	*Proboscia alata var. indica*	0.5335
Nitzschia sigmoidea	2.7306	*Prorocentrum micans*	0.7363
Nitzschia spp.	0.3034	*Protoperidinium breviceps*	1.6493
Noctiluca scintillans	0.3034	*Protoperidinium depressum*	0.589
Pinnularia viridis	0.6068	*Protoperidinium divergens*	1.2959
Pleurosigma aestuarii	0.3034	*Protoperidinium pallidum*	1.2959
Pleurosigma formosa	0.3792	*Pseudonitzschia concatenatum*	1.071
Pleurosigma sp.	0.6068	*Pseudonitzschia delicatissima*	2.4781
Pleurosigma spp.	0.6068	*Pseudonitzschia seriata*	1.1567
Proboscia alata var. indica	0.7084	*Rhizosolenia hebetate*	1.8073
Protoperidinium depressum	0.6068	*Rhizosolenia setigera*	2.6253
Protoperidinium divergens	0.6068	*Trichodesmium erythraeum*	2.4245
Protoperidinium pallidum	0.6068	*Thalassionema frauenfeldtii*	5.2333
Roperia tessellata	0.6068	*Thalassionema nitzschioides*	5.3658
Thalassionema frauenfeldtii	9.608	*Skeletonema costatum*	6.6749
Thalassionema nitzschioides	6.6749	*Synedra crystallinum*	0.9102
Thalassiosira condensata	1.2136	*Synedra ulna*	0.3681
Thalassiothrix longissima	1.011		
Skeletonema costatum	0.405		
Synedra crystallinum	0.9102		
Synedra ulna var. oxyrhyncus	2.8315		

Table 3. Comparative account of the monsoonal (2011 and 2012) phytoplankton composition in mangrove impoverished and mangrove dominated waters of Hooghly Estuary in terms of relative abundance.

Mangrove impoverished MON'11 and 12		Mangrove dominated MON’11 and 12	
Species	**R.A. (%)**	**Species**	**R.A. (%)**
Actinocyclus octonarius	3.5014	*Amphora ostrearia*	0.3368
Amphora ostrearia	1.4005	*Amphora ovate*	0.3062
Asterionella japonicus	2.8011	*Aulacodiscus kittonii*	0.6329
Aulacodiscus kittonii	1.1204	*Bellerochea malleus*	0.689
Bacteriastrum varians	1.4005	*Biddulphia (Odontella) longicruris*	0.7758
Biddulphia (Odontella) mobiliensis	1.8674	*Biddulphia (Odontella) mobiliensis*	0.6125
Biddulphia (Odontella) regia	1.4005	*Biddulphia (Odontella) regia*	0.8452
Biddulphia (Odontella) sinensis	1.5406	*Biddulphia (Odontella) sinensis*	2.1029
Ceratium inflatum	1.2605	*Campylodiscus impressus*	0.6125
Climacosphaenia sp.	1.4005	*Ceratium furca*	1.4677
Cocconeis pediculus	1.4005	*Ceratium inflatum*	0.8575
Chaetoceros curvisetum	1.4005	*Ceratium tripos*	1.4677
Chaetoceros lorenzianus	0.7002	*Chaetoceros curvisetum*	1.4677
Chaetoceros peruvianus	0.7002	*Chaetoceros compressum*	1.4677
Chaetoceros subtilis	1.4005	*Chaetoceros decipiens*	1.4677
Coscinodiscus asteromphalus	2.661	*Chaetoceros pseudocurvisetus*	0.9187
Coscinodiscus centralis	1.2605	*Chaetoceros quarctatus*	0.6125
Coscinodiscus concinnus	1.3071	*Coscinodiscus centralis*	1.4904
Coscinodiscus eccentricus	1.1671	*Coscinodiscus concinnus*	0.8268
Coscinodiscus granii	1.6339	*Coscinodiscus granii*	1.8375
Coscinodiscus hyalinus	2.2408	*Coscinodiscus hyalinus*	1.6966

Table 3. Continued.

Mangrove impoverished MON'11 and 12		Mangrove dominated MON’11 and 12	
Species	**R.A. (%)**	**Species**	**R.A. (%)**
Coscinodiscus lineatus	1.6806	*Coscinodiscus lineatus*	1.4547
Coscinodiscus marginatus	2.8011	*Coscinodiscus marginatus*	1.2403
Coscinodiscus radiatus	2.1008	*Coscinodiscus radiatus*	2.2908
Cyclotella striata	1.4005	*Cyclotella caspia*	3.6751
Diatoma anceps	1.4005	*Cyclotella striata*	0.6125
Ditylum brightwelllii	3.3613	*Diploneis sp.*	0.4593
Ditylum buchananii	1.4005	*Ditylum brightwellii*	0.2848
Hemidiscus kanayanus	1.1204	*Gyrosigma angulatum*	0.3675
Lioloma elongata	10.6442	*Gyrosigma scalproides*	0.6125
Leptocylindrus danicus	1.4005	*Haslea warwickea*	0.245
Navicula pupalis	1.1204	*Lioloma elongata*	0.8575
Navicula sp.	1.1204	*Melosira nummuloidea*	1.6384
Navicula pediculus	1.4005	*Microcystis robusta*	4.5938
Navicula transitans	1.4005	*Navicula balticum*	0.6125
Nitzschia sigma	0.7002	*Navicula transitans*	0.4593
Nitzschia sigmoidea	1.1204	*Navicula sp.*	0.3062
Pleurosigma elongatum	2.1008	*Navicula pupalis*	0.9187
Proboscia alata var. indica	1.4005	*Nitzschia bilobata*	0.6125
Pseudonitzschia seriata	1.8674	*Nitzschia elongata*	0.7758
Rhizosolenia setigera	2.1008	*Nitzschia sigma*	0.5512
Skeletonema costatum	5.042	*Nitzschia sigmoidea*	0.8039
Skeletonema grevillei	4.4817	*Noctiluca scintillans*	0.8268
Surirella ovata	1.4005	*Pinnularia viridis*	0.98
Synedra crystallinum	2.1708	*Pleurosigma sp.*	0.6125
Synedra ulna	1.2605	*Pleurosigma elongatum*	1.8375
Synedra ulna var. oxyrhyncus	2.1008	*Prorocentrum micans*	0.6125
Thalassionema nitzschioides	2.4509	*Rhizosolenia setigera*	0.6125
Thalassionema frauenfeldtii	1.4007	*Skeletonema costatum*	15.6804
Thalassiosira condensata	1.6806	*Skeletonema grevillei*	7.5952
Thalassiothrix longissima	1.4007	*Surirella ovata*	0.3062
Trichodesmium erythraeum	1.4007	*Synedra crystallinum*	3.2157
		Thalassiosira condensata	5.2926
		Thalassionema nitzschioides	8.7057
		Thalassionema frauenfeldtii	0.9968
		Triceratium favus	0.58
		Trichodesmium erythraeum	14.2055

Table 4. Comparative account of the post monsoonal (2011 and 2012) phytoplankton composition in mangrove impoverished and mangrove dominated waters of Hooghly estuary in terms of relative abundance.

Mangrove impoverished POST'11 and 12		Mangrove dominated POST’11 and 12	
Species	**R.A. (%)**	**Species**	**R.A. (%)**
Actinocyclus senarius	1.1985	*Amphora ovate*	0.2921
Bellerochea malleus	1.1985	*Aulacodiscus kittonii*	0.4381
Biddulphia (*Odontella*) *regia*	2.0599	*Bellerochea malleus*	1.0954
Biddulphia (*Odontella*) *mobiliensis*	0.5617	*Biddulphia* (*Odontella*) *longicruris*	0.5969
Biddulphia (*Odontella*) *sinensis*	2.2097	*Biddulphia* (*Odontella*) *mobiliensis*	0.5477
Cerataulina pelagica	2.0224	*Biddulphia* (*Odontella*) *regia*	0.7795
Ceratium cylindrus	1.1235	*Biddulphia* (*Odontella*) *sinensis*	1.7066

Table 4. Continued.

Mangrove impoverished	**POST'11 and 12**	**Mangrove dominated**	**POST’11 and 12**
Species	**R.A. (%)**	**Species**	**R.A. (%)**
Ceratium indicum	1.1235	*Ceratium cylindrus*	1.3144
Chaetoceros compressus	2.0599	*Ceratium furca*	0.8069
Chaetoceros decipiens	1.6853	*Ceratium indicum*	1.0954
Chaetoceros lorenzianus	2.7715	*Ceratium inflatum*	0.5887
Chaetoceros peruvianus	2.9213	*Ceratium tripos*	1.0954
Chaetoceros quarctatus	1.2359	*Chaetoceros compressus*	0.8215
Coscinodiscus asteromphalus	1.7977	*Chaetoceros curvisetus*	1.6431
Coscinodiscus centralis	5.131	*Chaetoceros danicus*	0.3833
Coscinodiscus gigas	1.7602	*Chaetoceros decipiens*	0.3067
Coscinodiscus granii	1.6479	*Chaetoceros lorenzianus*	0.6627
Coscinodiscus hyalinus	4.4569	*Chaetoceros pseudocurvisetus*	1.0954
Coscinodiscus lineatus	2.322	*Chaetoceros quarctatus*	0.3505
Coscinodiscus marginatus	3.7453	*Coscinodiscus asteromphalus*	1.2323
Coscinodiscus radiatus	5.0936	*Coscinodiscus centralis*	0.6755
Cyclotella caspia	1.7977	*Coscinodiscus concinnus*	1.7855
Cyclotella striata	0.5617	*Coscinodiscus granii*	1.2432
Cyclotella stylorum	1.1235	*Coscinodiscus hyalinus*	1.089
Diploneis sp.	0.5617	*Coscinodiscus lineatus*	1.2323
Ditylum buchananii	2.0599	*Coscinodiscus marginatus*	0.931
Ditylum brightwellii	8.4269	*Coscinodiscus radiatus*	6.7915
Haslea warwickea	2.9213	*Diploneis sp.*	0.5477
Hemidiscus kanayanus	0.8239	*Ditylum brightwellii*	1.4459
Lauderia annulata	0.8239	*Ditylum buchananii*	0.3067
Lioloma elongata	0.8239	*Gyrosigma angulatum*	0.4929
Navicula transitans	2.397	*Guinardia sp.*	0.23
Navicula angulatum	1.7977	*Haslea warwickea*	0.3286
Nitzschia bilobata	3.7078	*Lauderia sp.*	0.23
Nitzschia sigma	1.6853	*Lioloma elongata*	0.8259
Nitzschia sigmoidea	0.8239	*Melosira nummuloidea*	5.9152
Noctiluca scintillans	1.9475	*Microcystis robusta*	8.2155
Okedenia inflexa	1.1235	*Navicula sp.*	1.0954
Pinnularia rectangulata	2.4719	*Navicula balticum*	0.5477
Porosira sp.	1.1985	*Navicula pupalis*	0.2738
Pseudonitzschia seriata	1.1985	*Navicula transitans*	0.4107
Rhizosolenia styliformis	0.8239	*Nitzschia bilobata*	0.5477
Rhizosolenia setigera	1.6853	*Nitzschia sigmoidea*	0.6586
Skeletonema costatum	1.6853	*Noctiluca scintillans*	0.7394
Skeletonema grevillei	1.1235	*Pinnularia rectangulata*	1.0954
Synedra crystallinum	2.9213	*Pinnularia viridis*	0.6846
Thalassionema frauenfeldtii	1.2359	*Pleurosigma sp.*	1.6431
Thalassiosira condensata	1.7977	*Pleurosigma aestuarii*	1.1227
Thalassionema nitzschioides	1.1985	*Pleurosigma elongata*	1.0954
Trichodesmium erythraeum	1.1985	*Pleurosigma rectangulata*	0.23
		Prorocentrum micans	0.5477
		Rhizosolenia styliformis	0.3833
		Skeletonema costatum	17.9647
		Skeletonema grevillei	6.0247
		Synedra ulna	0.3286
		Synedra crystallinum	2.8754
		Thalassionema frauenfeldtii	0.9968
		Thalassionema nitzschioides	3.1931
		Thalassiosira condensata	4.0676
		Triceratium favus	0.2738
		Trichodesmium erythraeum	0.7302

Table 5. Spices of diatoms which occurred in both the years of the study tenure, in mangrove impoverished and mangrove dominated estuarine waters, serving as tools to understand the effect of the two different ambiences on the existing phytoplankton populations. The bolder names are of those which have appeared in more than one season.

Pre'11 and 12	**M.I. R.A. (%)**	**M.D. R.A. (%)**	**Mon'11 and 12**	**M.I. R.A. (%)**	**M.D. R.A. (%)**	**Post '11 and 12**	**M.I. R.A. (%)**	**M.D. R.A. (%)**
Asterionella japonicus	0.9102	2.142	*Amphora ostrearia*	1.4005	0.3368	*Bellerochea malleus*	1.1985	1.0954
Bacteriastrum varians	0.3034	1.4726	*Aulacodiscus kittonii*	1.1204	0.6329	***Biddulphia (Odontella) regia***	**2.0599**	**0.5477**
Campylodiscus impressus	0.6068	0.3681	***Biddulphia (Odontella) mobiliensis***	**1.8674**	**0.6125**	***Biddulphia (Odontella) mobiliensis***	**0.5617**	**0.7795**
Ceratium cylindrus	**0.9102**	**1.0389**	***Biddulphia (Odontella) regia***	**1.4005**	**0.8452**	***Biddulphia (Odontella) sinensis***	**2.2097**	**1.7066**
Chaetoceros decipiens	**1.517**	**4.0605**	***Biddulphia (Odontella) sinensis***	**1.5406**	**2.1029**	***Ceratium cylindrus***	**1.1235**	**1.3144**
Chaetoceros lorenzianus	**1.8204**	**4.6817**	*Ceratium inflatum*	1.2605	0.8575	*Ceratium indicum*	1.1235	1.0954
Chaetoceros quarctatus	**0.6068**	**0.7363**	*Chaetoceros curvisetum*	1.4005	1.4677	*Chaetoceros compressus*	2.0599	0.8215
Coscinodiscus concinnus	**4.6527**	**2.9493**	***Coscinodiscus centralis***	**1.2605**	**1.4904**	***Chaetoceros decipiens***	**1.6853**	**0.3067**
Coscinodiscus eccentricus	0.6068	0.7363	***Coscinodiscus concinnus***	**1.3071**	**0.8268**	***Chaetoceros lorenzianus***	**2.7715**	**0.6627**
Coscinodiscus gigas	0.9102	0.2249	***Coscinodiscus granii***	**1.6339**	**1.8375**	***Chaetoceros quarctatus***	**1.2359**	**0.3505**
Coscinodiscus hyalinus	**4.551**	**1.9184**	***Coscinodiscus hyalinus***	**2.2408**	**1.6966**	*Coscinodiscus asteromphalus*	1.7977	1.2323
Coscinodiscus marginatus	**3.5399**	**0.3681**	***Coscinodiscus lineatus***	**1.6806**	**1.4547**	***Coscinodiscus centralis***	**5.131**	**0.6755**
Coscinodiscus radiatus	**10.6191**	**5.2132**	***Coscinodiscus marginatus***	**2.8011**	**1.2403**	***Coscinodiscus granii***	**1.6479**	**1.2432**
Cyclotella striata	**1.2136**	**0.2249**	***Coscinodiscus radiatus***	**2.1008**	**2.2908**	***Coscinodiscus hyalinus***	**4.4569**	**1.089**
Ditylum brightwellii	**0.7076**	**2.7766**	***Cyclotella striata***	**1.4005**	**0.6125**	***Coscinodiscus lineatus***	**2.322**	**1.2323**
Hemidiscus kanayanus	0.7084	1.5543	***Ditylum brightwellii***	**3.3613**	**0.2848**	***Coscinodiscus marginatus***	**3.7453**	**0.931**
Lioloma elongata	**1.4161**	**0.3681**	***Lioloma elongata***	**10.6442**	**0.8575**	***Coscinodiscus radiatus***	**5.0936**	**6.7915**
Noctiluca scintillans	**0.3034**	**2.3388**	***Navicula transitans***	**1.4005**	**0.4593**	*Diploneis* sp.	0.5617	0.5477
Pleurosigma aestuarii	0.3034	1.1045	*Nitzschia sigma*	0.7002	0.5512	*Ditylum buchananii*	2.0599	1.4459
Proboscia alata var. indica	0.7084	0.5335	***Nitzschia sigmoidea***	**1.1204**	**0.8039**	***Ditylum brightwelli***	**8.4269**	**0.3067**
Protoperidinium depressum	0.6068	0.589	*Pleurosigma elongatum*	2.1008	1.8375	*Haslea warwickea*	2.9213	0.3286
Protoperidinium divergens	0.6068	1.2959	*Rhizosolenia setigera*	2.1008	0.6125	*Lauderia annulata*	0.8239	0.23
Protoperidinium pallidum	0.6068	1.2959	***Skeletonema costatum***	**5.042**	**15.6804**	***Lioloma elongate***	**0.8239**	**0.8259**
Thalassionema frauenfeldtii	**9.608**	**5.2333**	***Skeletonema grevillei***	4.4817	7.5952	***Navicula transitans***	**2.397**	**0.4107**
Thalassionema nitzschioides	**6.6749**	**5.3658**	***Surirella ovata***	**1.4005**	**0.3062**	***Nitzschia sigmoidea***	**0.8239**	**0.6586**
Skeletonema costatum	**0.405**	**6.6749**	***Synedra crystallinum***	**2.1708**	**3.2157**	***Noctiluca scintillans***	**1.9475**	**0.7394**
Synedra crystallinum	**0.9102**	**0.9102**	***Thalassionema nitzschioides***	**2.4509**	**5.2926**	*Pinnularia rectangulata*	2.4719	1.0954
Synedra ulna var. oxyrhyncus	2.8315	0.3681	***Thalassionema frauenfeldtii***	**1.4007**	**8.7057**	*Rhizosolenia styliformis*	0.8239	0.3833
			Thalassiosira condensata	**1.6806**	**0.9968**	***Skeletonema costatum***	**1.6853**	**17.9647**
			Trichodesmium erythraeum	**1.4007**	**14.2055**	***Skeletonema grevillei***	**1.1235**	**6.0247**

Table 5. Continued.

Pre'11 and 12	**M.I. R.A. (%)**	**M.D. R.A. (%)**	**Mon'11 and 12**	**M.I. R.A. (%)**	**M.D. R.A. (%)**	**Post '11 and 12**	**M.I. R.A. (%)**	**M.D. R.A. (%)**
						Synedra crystallinum	**2.9213**	**2.8754**
						Thalassionema frauenfeldtii	**1.2359**	**0.9968**
						Thalassiosira condensata	**1.7977**	**3.1931**
						Thalassionema nitzschioides	**1.1985**	**4.0676**
						Trichodesmium erythraeum	**1.1985**	**0.7302**

M.I. = Mangrove impoverished; M.D. = Mangrove dominated.

Table 6. The following table is depicting the major diatoms species and their responses to various nutrient fluctuations in mangrove dominated and impoverished waters of Hooghly Estuary, through the correlation with the nutrients contents and relative abundances.

	M.I.	**M.D.**	**M.I.**	**M.D.**	**M.I.**	**M.D.**
Species	Nitrate-N	Nitrate-N	Phosphate-P	Phosphate-P	Silicate	Silicate
Coscinodiscus hyalinus	**-0.9681**	**+0.5115**	**-0.5504**	**+0.9188**	**-0.6737**	**-0.6408**
Coscinodiscus marginatus	**-0.9999**	**+0.8266**	**+0.7419**	-0.4505	+0.4672	**+0.8057**
Coscinodiscus radiatus	**-0.6132**	**-0.9969**	+0.0745	-0.2079	**-0.9849**	-0.2571
Ditylum brightwellii	-0.3852	-0.2538	**-0.9045**	**+0.9257**	+0.6358	**-0.9966**
Lioloma elongata	**+0.9866**	+0.3019	**+0.6230**	**-0.9056**	**+0.6048**	**+0.9995**
Synedra crystallinum	-0.0715	+0.3766	**-0.7218**	**-0.8691**	**+0.8483**	**+0.9988**
Skeletonema costatum	**+0.8834**	+0.0564	+0.3413	**-0.9824**	**+0.8270**	**+0.9605**
Thalassionema frauenfeldtii	-0.2853	**+0.9534**	+0.4308	+0.4259	**-0.9806**	+0.0321
Thalassionema nitzschioides	-0.0864	**+0.6801**	**+0.6037**	**+0.8157**	**-0.9211**	-0.4657

M.I. = Mangrove impoverished; M.D. = Mangrove dominated.

different interspecific competition stress. All the diatom species have expressed significantly high correlation values with nutrients but very few have actually reflected a constant trend to be utilized as indicators to a certain conditions. But the ones that have expressed such affinities can truly serve as potential bioindicators of well mixed estuarine aquatic ecosystems.

Discussion

The water bodies adjacent to mangrove mudflats and those that are devoid of any mangrove mudflats were chosen due to their variations in the selected background physicochemical parameters which are clearly depicted in Figure 2 and Table 1. Although fluctuation in seasonal dissolved nitrate-nitrogen and dissolved silicate contents in mangrove impoverished and mangrove dominated well mixed estuarine waters were found to be more or less similar, the difference in phosphate concentration was quite obvious during the tenure of the study. The reason behind dissolved phosphate contents in mangrove dominated regions to be high is due to the fact that mangrove mudflats harbor large number of phosphate solubilizing bacteria (De et al., 2012) or PSB and they through the formation of low molecular weight organic acid, bind and release the inorganic phosphate into solution phase. Hence, higher number of PSB means greater solubilization of phosphate.

Primary productivity in the mangrove dominated waters appeared to be comparatively higher than the mangrove impoverished waters (Table 1), a fact that can be vindicated from the Tables 2, 3 and 4 which depict comparatively higher number of phytoplankton species (diatoms mainly) in mangrove dominated waters. Greater dissolved phosphate might lead to conditions conducive enough to support a higher population density.

Dissolved oxygen however exhibited a more or less similar fluctuation in both the specific study sites with slightly lower values recorded from mangrove dominated estuaries.

Salinity was also found to be higher in mangrove dominated waters since the mangrove dominated sampling stations were situated closer to the estuary mouth, compared to the mangrove impoverished stations that included stations with riverine dominance along with marine influence, eventually decreasing the average salinity of the surface water. Another fact that can contribute to the surface water salinity is the prevailing wind speed, which was recorded to be relatively high over mangrove dominated sampling sites than their mangrove impoverished counterparts. This could have triggered higher rates of evaporation resulting in higher salinity of the surface water.

From the Table 2, 3 and 4, the fact that phytoplankton population density in mangrove dominated waters were much higher compared to the mangrove impoverished waters. The above mentioned governing physicochemical parameters can explain phytoplankton proliferation in mangrove dominated water. The three tables are depicting seasonal variations in the phytoplankton (diatom mainly) relative abundances. Table 5 describes the phytoplankton species which have been observed in mangrove dominated and mangrove impoverished waters in a given season. From this table, it can be observed that in general the species appearing in mangrove dominated waters had higher relative abundances than when they appeared in mangrove impoverished waters with exceptions like *Coscinodiscus* spp, *Odontella* spp, *Thalassionema frauenfeldtii* and *Thalassionema nitzschioides* etc. These species showed very high relative abundances in mangrove impoverished waters. It has to be borne in mind that the species were not collected at different stations on different days, but on the same days of collection, hence emphasizing more on the growth conducive factors of the mangrove dominated waters, viz. dissolved phosphate.

Among the species mentioned in Table 5, only a handful of phytoplankton species were observed to occur in all the three seasons, both the years of study as well as both in mangrove dominated and in mangrove impoverished estuarine waters.

A correlation study was performed among these species in terms of their relative abundances in both mangrove dominated and mangrove impoverished waters and the chief governing nutrients (Table 6). From the table it is quite obvious that almost all the species which have appeared in mangrove dominated and impoverished waters throughout the year have generated significant correlation values, both positive and negative. Mostly a particular parameter has shown positive and negative values for the same parameter considered in mangrove dominated and impoverished waters. This could be due to the fact that both the different study zones might have had different constraints and various species composition in a given zone rendered the exploitation of a particular parameter specific to that zone only, depending on background parameters, interspecific competition stress of a zone as well as due to factors unaccounted for.

Only those with a consistent correlation value have been chosen to serve as potential indicators to nutrient contents in well mixed estuarine waters. From table 6, the following species viz., *Coscinodiscus hyalinus* [M.I. silicate: -0.6737 and M.D. silicate: -0.6408], *Coscinodiscus radiatus* [M.I. nitrate: -0.6132 and M.D. nitrate: -0.9939; M.I. silicate: -0.9849 and M.D. silicate: -0.2571], *Lioloma elongata* [M.I. nitrate: +0.9866 and M.D. nitrate: +0.3019; M.I. silicate: +0.6048 and M.D. silicate: +0.9995], *Skeletonema costatum* [M.I. silicate: +0.8270 and M.D. silicate: +0.9605], *Synedra crystallinum* [M.I. phosphate: -0.7218 and M.D. phosphate: -0.8691; M.I. silicate: +0.8483 and M.D. silicate: +0.9988], *Thalassionema frauenfeldtii* [M.I. phosphate: +0.4308 and M.D. phosphate: +0.4259; M.I. silicate: -0.9806 and M.D. silicate: +0.0321] and *Thalassionema nitzschioides* [M.I. phosphate: +0.6037 and M.D. phosphate: +0.8157; M.I. silicate: -0.9277 and M.D.

silicate: -0.4657], where M.I. = Mangrove Impoverished, M.D. = Mangrove Dominated.

From the above stated data set it is quite obvious that these few diatom species do possess the potential of being established as probable bioindicators of various nutrients in well mixed tropical estuaries such as the Hooghly Estuary. The positive correlation implies that the relative abundance of a particular species increased with increase of a specific nutrient content and inversely negative correlation means the relative abundance is lowest when the nutrient concentration is highest, which could be due to over proliferation of a competitive species exploiting the increased nutrient or it could be because the species in question has utilized the nutrient to increase in number, rendering the dissolved nutrient low in concentration. Both the scenarios are highly probable in any well mixed estuarine ecosystem.

Conclusion

Although the study encompassed a tenure of two years (2011 and 2012), but the results generated from it is of immense significance since it was aimed at establishing probable bioindicator phytoplankton species (mainly diatoms due to their preponderance) in a well mixed estuary. An estuarine river system might be influenced by the presence and absence of mangrove forests along its bank, a fact prominently shown in the present study. Any changes in the ambient water quality parameters governing phytoplankton species composition and their relative abundances in a population gets reflected through the absence, presence or proliferation of certain species. The diatoms are the most dominant phytoplanktons in a well mixed estuarine aquatic ecosystem and those species which expressed a very strong degree of affinity towards a certain trophic condition have been documented through rigorous analyses of samples from natural set ups, thereby ensuring the highest possible authenticity regarding the applicability and implication of the study results. Establishment of phytoplanktons with potential as bioindicators in well mixed estuarine waters will ensure better monitoring of the ever changing and highly dynamic ecosystem in a holistic way, along with the existing abiotic estimation and survey methods.

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Conflict of interest statement

Authors declare that they have no conflict of interests.

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