Oceanologia (2018) 60, 114—127

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.journals.elsevier.com/oceanologia/

ORIGINAL RESEARCH ARTICLE

Seasonal influence of physico-chemical parameters on phytoplankton diversity, community structure and abundance at Parangipettai coastal waters, Bay of Bengal, South East Coast of India

Manigandan Vajravelu[a], **Yosuva Martin**[a], **Saravanakumar Ayyappan**[b,*], **Machendiranathan Mayakrishnan**[a]

[a] *Centre of Advanced Study in Marine Biology, Annamalai University, Parangipettai, India*
[b] *Faculty of Marine Science, Centre of Advanced Study in Marine Biology, Annamalai University, Parangipettai, India*

Received 3 May 2017; accepted 25 August 2017
Available online 19 September 2017

KEYWORDS
Phytoplankton;
Nutrient;
CCA analysis;
Diversity;
Richness;
Productivity

Summary The present investigation studied the seasonal variation between physico-chemical parameters and phytoplankton diversity, community structure and abundance; quantitative samples were collected on a monthly basis from April 2015 to March 2016 at Parangipettai coast, the Bay of Bengal (BOB). Statistical analyses were performed on physico-chemical parameters such as salinity, dissolved oxygen (DO), pH, temperature, nitrate, nitrite, silicate, and inorganic phosphate (IP). The significant ($P < 0.0005$) variation among seasons as well as a high influence of these parameters was observed on phytoplankton productivity. Totally, 117 species were identified, belonging to five different classes, Coscinodiscophyceae (62%), Bacillariophyceae (17%), Fragilariophyceae (8%), Dinophyceae (8%) and Cyanophyceae (5%). Throughout the study period, the occurrence of most dominant species was observed from class Coscinodiscophyceae and Bacillariophyceae. The phytoplankton species also showed significant changes according to seasonal variations as well as the nutrient availability. Phytoplankton attained their maximum population density during premonsoon; whereas minimum population was observed during monsoon. The performed statistical analysis on phytoplankton species, the Shannon & Wiener diversity index was found to be higher during postmonsoon and lower during monsoon season. The

---

[*] Corresponding author at: Faculty of Marine Sciences, Centre of Advanced Study in Marine Biology, Annamalai University, Parangipettai 608502, Tamil Nadu, India. Tel.: +91 9443610371.
E-mail address: asarvaan@gmail.com (S. Ayyappan).
Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.oceano.2017.08.003

Canonical Correspondence Analysis (CCA) was used, to find out the seasonal relationship between phytoplankton and physicochemical parameters. Hence, the executed CCA results revealed that temperature, salinity, silicate, DO and IP have a higher influence on phytoplankton abundance.

---

1. Introduction

Phytoplankton are the primary source of a food chain, which contributes to the major fishery resource around the world. They are responsible for the formulation of a biological community and regulate the food web (Falkowski et al., 2008; Field et al., 1998). Phytoplankton act as an important component of the marine ecosystem, as they liberate oxygen during photosynthesis and aid in energy exchange process (Khan, 2003). They play a crucial role in mitigating the climate change and global warming, thereby recede the global CO_2 levels (Santhosh Kumar and Perumal, 2012). Phytoplankton community structure, composition and species diversity in aquatic ecosystem are determined by several physico-chemical parameters (Sin et al., 1999). Spatial and temporal variations in phytoplankton distribution are widely affected by the hydrochemical and physical factors such as temperature, salinity, pH, nitrate, nitrite, ammonia, silicate and IP. The influence of these factors on phytoplankton community alters species composition and their diversity in the marine ecosystem (Durate et al., 2006; Madhu et al., 2007). Generally, shallow water and estuaries show seasonal fluctuations among variables depending on the regional rainfall, tidal inflow and various abiotic and biotic processes, which play substantial role in nutrient cycle (Choudhury and Panigrahy, 1991).

The relationship between phytoplankton and nutrients is highly dynamic and has always been the major focus among researchers to explicate experimental ecology (Chattopadhyay et al., 2003). Recently, various anthropogenic activities have increased, which in turn enhance the nutrient concentration thus, leads to high productivity in coastal environment (Rakhesh et al., 2013). Availability of nutrient plays an important role in phytoplankton diversity that reflects the environmental condition of the ecosystem (Dugdale, 1967; Rhyther and Dunstan, 1971; Smayda, 1980). Phytoplankton species shows wide variation in distribution due to changes in factor like hydro-chemical and physical parameters. These dramatic changes in physico-chemical parameters, exhibit differential effect in distribution and abundance of many phytoplankton species, ultimately indicating the quality of water (Shashi Shekhar et al., 2008). Phytoplankton species can be very sensitive to slight modification in its environment and hence, it provides good insight about water quality before it reaches to extreme visible condition like eutrophication (Brettum and Andersen, 2005). Eutrophication is caused by several factors such as substrate remineralization, upwelling, increase river inflow and resuspension of particulate matter (Guinder et al., 2015; Su et al., 2015). It might have both positive and negative impact on phytoplankton diversity depending on the state of an ecosystem (Crossetti et al., 2008; Marasović and Pucher-Petković, 1985; Skejić et al., 2014; Su et al., 2015). Species diversity and community composition are subjective to substantial changes by environmental parameters and eutrophication. Phytoplankton biomass increases due to eutrophication and causes uniform distribution in species composition. Simultaneously, opportunistic species start proliferating by dominating other (McQuatters-Gollop et al., 2009). The factors such as eutrophication, changes in nutrients concentration and competition between species reduce the phytoplankton species diversity (Spatharis et al., 2007). The phytoplankton biomass (chlorophyll-*a*) is used as a good indicator of water quality and eutrophication because it provides good insights of that particular area (McQuatters-Gollop et al., 2009; Ninčević-Gladan et al., 2015). Monitoring the seasonal changes in phytoplankton diversity and its community structure provides the better understanding about the state of coastal waters and they are one of the most important biological elements that provide the ecological status of the sea (Barić et al., 1992; Legović et al., 1994). A marine phytoplankton community is mostly dependent on nutrients and physical parameters in a coastal environment. The nutrient availability is frequently considered as a key factor regulating the phytoplankton abundance, growth and metabolism. Significant work has been done in relation to seasonal variation in phytoplankton species composition in the different coastal ecosystem of India (Menon et al., 2000; Sahu et al., 2012; Siva Sankar and Padmavathi, 2012; Sridhar et al., 2006). The present study area is highly influenced by seasonal changes in freshwater. In addition, aquaculture and anthropogenic activities also significantly contribute to changes in the coastal ecosystem of Parangipettai. Therefore, comprehending the dynamic environmental parameters and their influence on phytoplankton productivity is extremely important as it plays a vital role in the food web and coastal productivity. This will also aid in assessing the water quality in future. Hence, the present study aims to find out the seasonal variation in phytoplankton diversity, composition and their abundance in response to various environmental parameters.

2. Material and methods

2.1. Description of study area

The present investigation was carried out from April 2015 to March 2016 in Parangipettai coast of Tamil Nadu, Southeast Coast of India. The freshwater influence is high due to fluctuations in tide and incursion of freshwater during monsoon because of Vellar estuary debouching in the Bay of

Bengal. Sampling sites are shown in Fig. 1. Totally five sampling sites were fixed and monthly sampling was carried out.

2.2. Sampling

Monthly samples were collected at different depths using Niskin water sampler. Seawater was collected for 1 L in polypropylene bottles to analyze chlorophyll *a*nd physico-chemical parameters, which were then filtered through Whatman GF/F filters for further analysis as described by (Strickland and Parsons, 1972). Physical parameters such as temperature, pH, salinity were measured on the site itself by using standard instruments (a multistem digital thermometer (accuracy ± 0.1), a hand-held refractometer (ATAGO S/Mill-E), pH pen).

Nutrients such as nitrite (NO_2), nitrate (NO_3), ammonia (NH_4), inorganic phosphate (PO_4), reactive silicate (SiO_4) were analyzed following the standard methodology described by Strickland and Parsons (1972). Chlorophyll-*a* concentration was estimated by pigment extraction method using 90% acetone. Extracted samples were kept for incubation in refrigerator under dark condition and the pigment concentration was obtained through UV—VIS spectrophotometer (Shimadzu-UV) using 5 cm cells at 630 nm, 645 nm, and 665 nm (Strickland and Parsons, 1972).

To estimate the total suspended solids (TSS) in seawater, glass filter paper (Whatmann GF/C, 0.45 μm) was weighed before filtration, the filtered paper was kept in an oven for 24 h at 75°C and weighed again to find out the TSS.

Phytoplankton were collected at monthly intervals on surface water by towing plankton net (mouth diameter — 1.5 m) made up of bolting silk cloth (mesh size 54 μm). The flow meter (Hydro-bios, Germany) was attached at the center of the net to calculate the volume of seawater passed through the net. Collected phytoplankton samples were preserved in 4% buffered formalin for further analysis. Qualitative and quantitative analysis of phytoplankton were executed using an inverted microscope. Quantification of phytoplankton was carried out using Sedgwick rafter counting chamber and phytoplankton species were identified by following standard manuals of Subramanyan (1946), Al-Kandari et al. (2009), Venkataraman (1939), Perumal et al. (1998), Santhanam et al. (1987) and Smith (1977).

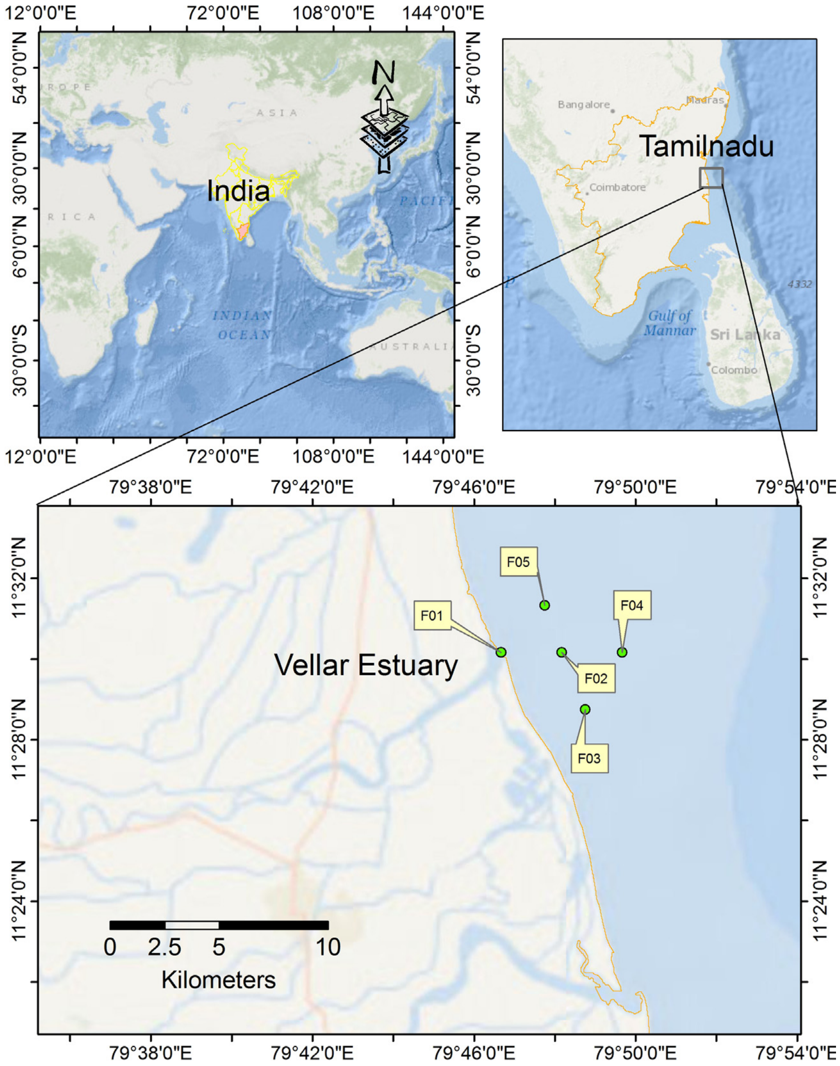

Figure 1 The GPS location of sampling sites.

2.3. Statistical analysis

Canonical Correspondence Analysis was used to determine the relationship between phytoplankton and environmental parameters. Biological diversity (H′) and richness (S) were calculated by following the equation of Shannon and Wiener (1949), and Pielou (1966). One way ANOVA was performed using Tukey's HSD test to observe the seasonal variation in nutrients. Variations in physico-chemical parameters were depicted using box plot. All of these analyses were run in R software (R Version 3.4.0, 2016), vegan: community ecology package. R (Oksanen et al., 2016) was used to run the CCA and Shannon diversity index analysis. Box plot and line diagrams were plotted using ggplot2 package (Wickham, 2009).

3. Results and discussion

3.1. Physico-chemical characteristics of water

Variation in phytoplankton distribution and abundance were mostly influenced by the seasonal changes in environmental parameters (DO, salinity, temperature, nitrate, IP, silicate). It is of paramount importance to study the hydro-chemical parameters to distinguish the difference in phytoplankton diversity on a seasonal scale in marine ecosystem (Chang, 2008). The environmental parameters which drive the succession of plankton diversity were depicted seasonally in Figs. 2 and 3. Physico-chemical parameters showed significant difference among seasons.

Temperature is an important factor for marine environment as it influences the life of organisms and physico-chemical parameters (Sukumaran et al., 2013). Temperature showed significant variations between seasons ($F = 191.9$; $P < 0.0005$) and varied from 27.15°C (November 2015; monsoon) to 32.4°C (May 2015; summer) with the mean of 29.53°C (± 1.23). Seasonal variations in temperature may attribute with wind force, influx of freshwater and atmospheric temperature. The low temperature could be attributed to the heavy rainfall received during monsoon season. Earlier reports also stated that temperature reduction in water depends mainly on the intensity of rainfall received on monsoon and less air temperature.

Salinity reached a maximum of 34.33 ppt (May 2015) during summer and minimum was recorded as 27.11 ppt (November 2015) with the mean value of 31.80 (±1.83). Salinity showed significant difference among seasons ($F = 143$; $P < 0.0005$). Salinity plays a major role as a limiting factor since it controls the faunal and floral diversity of coastal ecosystems (Govindasamy et al., 2000; Sridhar et al., 2006; Subramanian and Mahadevan, 1999). Generally, salinity shows seasonal variation in Parangipettai coastal waters due to Vellar estuary as it brings continuous freshwater during monsoon (Soundarapandian et al., 2009). The intrusion of neritic water and high intensity of solar radiation during summer could be the reason for high salinity, and the reduced salinity during monsoon might be due to the freshwater influence and fluctuation in tides (Jyothibabu et al., 2008; Sukumaran et al., 2013). Thus the present investigation evidenced earlier reports on variation in salinity.

Hydrogen ion concentration varied from 7.5 to 8.2 with the mean of 7.97 (±0.22). Maximum pH was observed during March 2015 and minimum was recorded in November 2015. pH was alkaline during summer and showed downward pattern up to monsoon and remained alkaline during post-monsoon, significant difference was observed in between seasons ($F = 52.47$; $P < 0.0005$). Changes in pH will depend on the factor like the removal of CO_2 by photosynthesis through bicarbonate degradation, fresh water influx, reduction in salinity and temperature and decomposition of organic matter (Rajasegar et al., 2002). Higher pH in post-monsoon could be attributed to the high photosynthetic activity by phytoplankton whereas the lowered pH value in monsoon was due to freshwater influx by Vellar estuary.

Dissolved oxygen is a major component in an aquatic ecosystem which determines the quality of water and support aquatic life. Dissolved oxygen in water ranged between 4.23 mg L^{-1} and 5.5 mg L^{-1} (4.77 ± 0.34) registering the maximum value during monsoon (November 2015) and minimum in summer (April 2015). Analysis of variance showed significance difference between seasons ($F = 40.9$; $P < 0.0005$). Dissolved oxygen showed marked seasonal variation throughout the study period. During summer and premonsoon less dissolved oxygen content was recorded, this could be due to the high temperature, salinity and biological activity (Davis, 1975; Levinton, 2001). High concentration of dissolved oxygen during monsoon and postmonsoon is attributed to high fresh water input and evidenced by the maximum occurrence of phytoplankton species (Morgan et al., 2006).

Chlorophyll-*a* concentration varied from 0.35 μg L^{-1} (April 2015) to 3.72 μg L^{-1} (February, 2016) (mean = 1.28 ± 0.88) and significant variation was observed between different seasons ($F = 158.7$; $P < 0.0005$). Chlorophyll-*a*, the most principle pigment is responsible for primary production in marine water. The elevated concentration of chlorophyll-*a* in postmonsoon might be due to the availability of sufficient amount of UV radiation, pristine water condition, consumption of silicate and phosphate by primary producers, which were brought up by river runoff during monsoon (Prabhahar et al., 2011; Sardessai et al., 2007).

Total suspended solids (TSS) varied from 18.04 mg L^{-1} (February 2016) to 44.60 mg L^{-1} (November 2015) (mean = 31.28 mg L^{-1}; ±5.17) and the observed TSS values showed significant variations in between seasons ($F = 43.3$; $P < 0.0005$). High terrestrial runoff, along with heavy suspended solid loads, was brought to coast during monsoon season could be responsible for the increased suspended solid concentration (Vinayachandran et al., 2002).

3.2. Nutrient dynamics

Nutrients such as nitrate, nitrite, IP, and silicate in the coastal environment would exhibit substantial seasonal variations depending on the rainfall, freshwater input, tidal ingress and consumption of nutrients by autotrophs. Nitrate concentration ranged from 1.24 μmol (August 2015) to 6.89 μmol (April 2015) and the significant difference was observed between seasons in statistical analysis (mean = 3.158 ± 1.45; $F = 42.62$; $P < 0.0005$). Nitrite concentration varied from 0.12 μmol (February 2016) to 0.88 μmol (February 2016) and varied significantly throughout the season (mean = 0.41 ± 0.17; $F = 4.08$; $P < 0.0005$). The higher concentration of nitrate during summer and

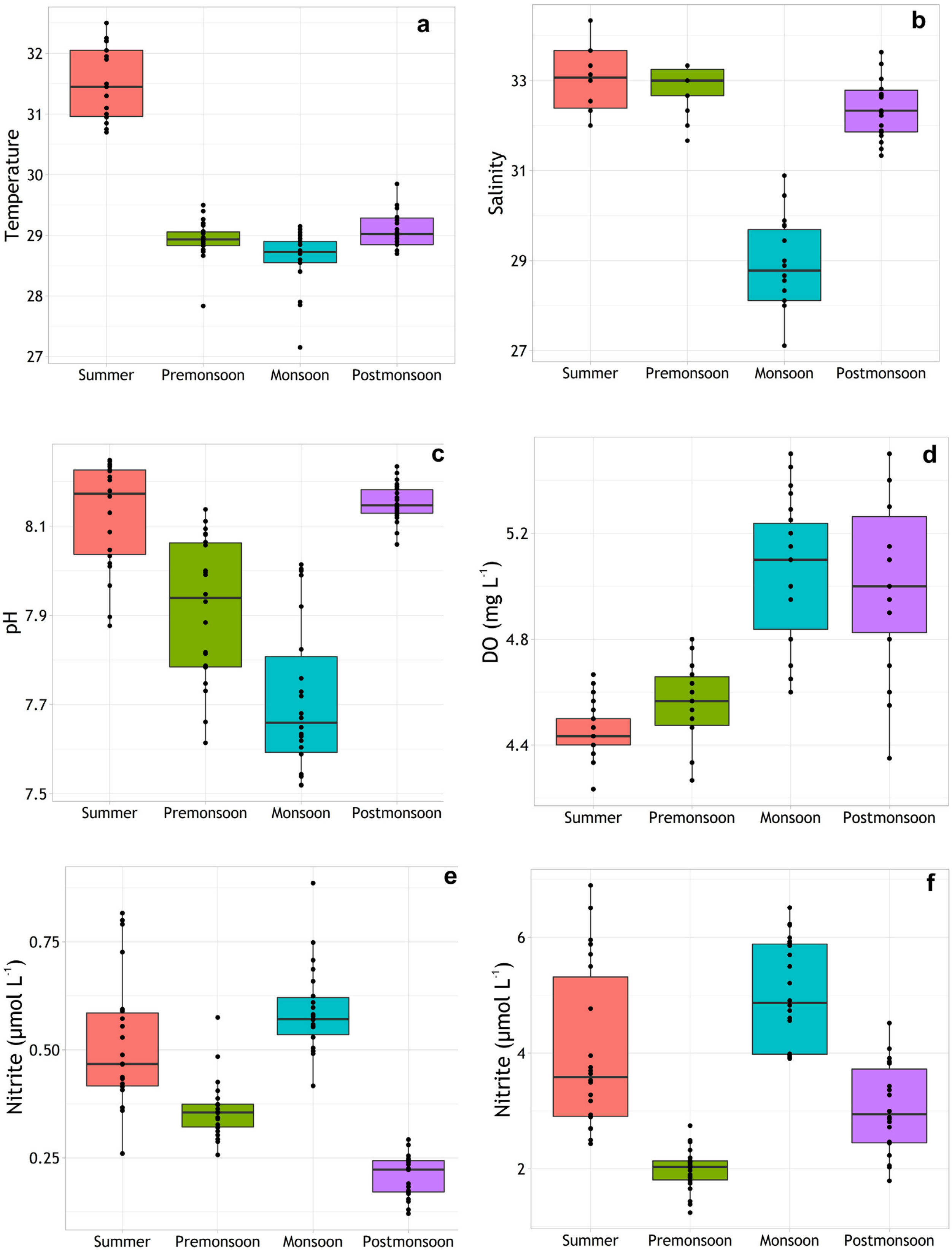

Figure 2 Seasonal variation of physico-chemical parameters during the study period. Temperature (a), salinity (b), pH (c), DO — dissolved oxygen (d), nitrite (e), nitrate (f).

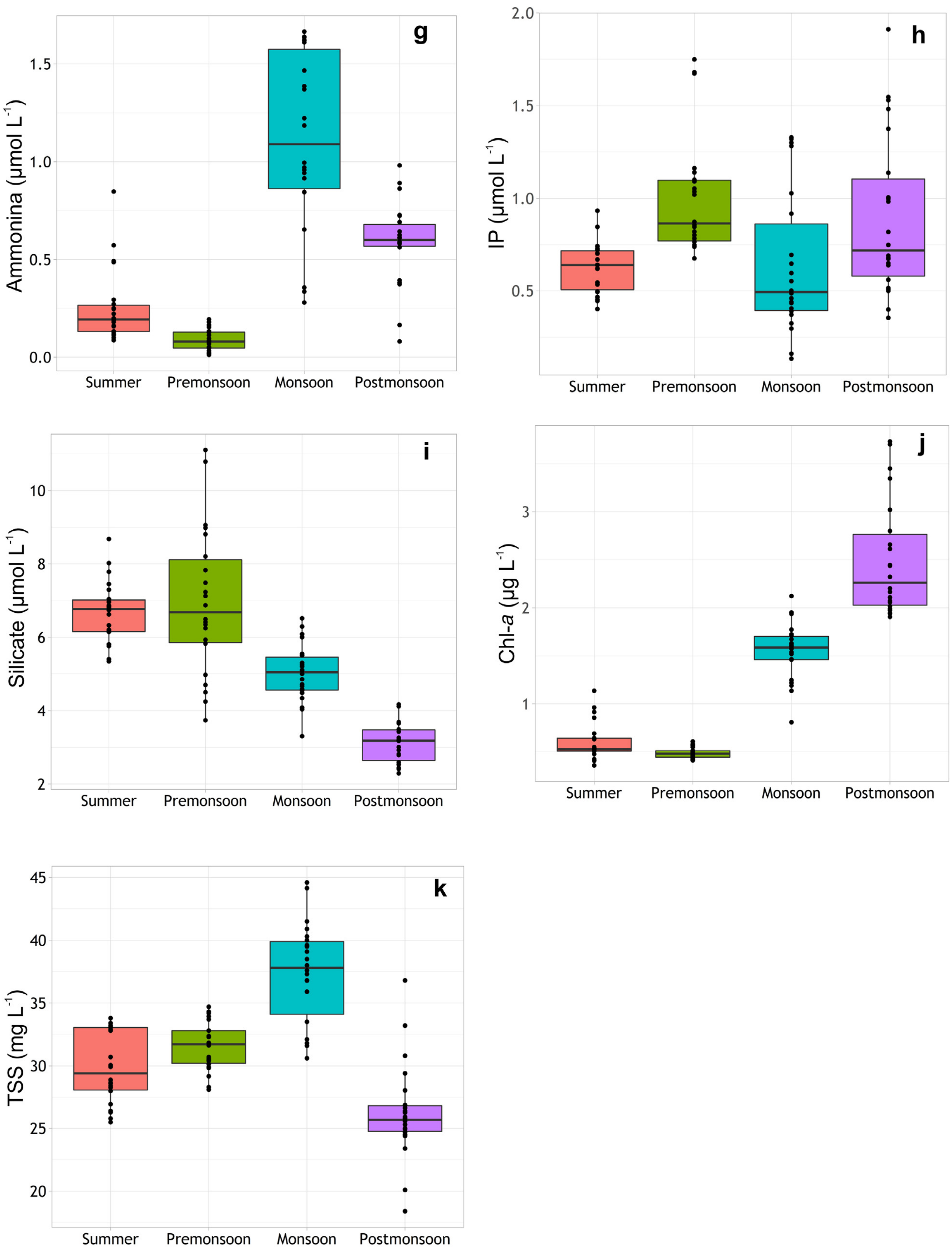

Figure 3 Seasonal variation of physico-chemical parameters during the study period. Ammonia (g), IP — inorganic phosphate (h), silicate (i), Chl-*a* — Chlorophyll-*a* (j), TSS — total suspended solids (k).

monsoon could be due to fresh water inflow, terrestrial runoff, and high rate of biological production, oxidation of ammonia, reduction of nitrate by recycling of nitrogen and also by biodegradation of planktonic detritus present in the environment (Govindasamy et al., 2000; Hutchinson, 1957; Santhanam and Perumal, 2003). The registered lower concentration of nitrate during non-monsoon period might be due to high consumption of nitrate by photosynthetic organisms and the incursion of neritic water which constitute only the smaller amount of nitrate (Das et al., 1997; Gouda and Panigrahy, 1995; Govindasamy et al., 2000).

Ammonia concentration ranged between 0.0116 μmol (August 2016) and 1.66 μmol (November 2016) with significant variation (mean = 0.509 ± 0.47; $F = 63.28$; $P < 0.0005$). Increased concentration of ammonia during monsoon season was due to the incursion of terrestrial runoff and decomposition of phytoplankton (Segar and Hariharan, 1989; Senthilkumar et al., 2008; Thangaradjou et al., 2013). Decreased ammonia concentration during summer and premonsoon, may be attributed to quick utilization of specific phytoplankton community as they prefer ammonia more than nitrate at certain environment (Dugdale et al., 2007; Lipschultz, 1995).

Phosphate plays a major role in primary productivity in an aquatic ecosystem as it promotes growth for organisms and limits the phytoplankton production (Cole and Sanford, 1989). The recorded phosphate values ranged between 0.13 μmol (June 2015) and 1.91 μmol (mean = 0.79 ± 0.36). Statistical analysis also evidenced that the dissolved inorganic phosphate concentration has a significant difference within seasons ($F = 6.899$; $P < 0.0005$). Higher concentration of inorganic phosphate might be attributed to the monsoonal intrusion due to rainfall along with terrestrial runoff (Satpathy et al., 2009) and the low value in summer might be due to utilization of phosphate by photoautotrophs and buffering process of sediment under varying environmental conditions (Perumal et al., 2009).

Variation in silicate concentration is driven by physical mixing of seawater with a freshwater addition, adsorption and sediment particles, interaction between chemicals and minerals, co- precipitation with humic components, and biological removal by phytoplankton, particularly diatoms and silicoflagellates (Satpathy et al., 2009). The minimum concentration of 2.29 μmol (February 2016) was observed during postmonsoon whereas the maximum concentration of 11.10 μmol (October 2015) was recorded during premonsoon season. The high significant difference was found with the mean value of 5.43 ($\pm$1.92) ($F = 48.55$; $P < 0.0005$). Increased concentration of silicate in premonsoon was due to the intermittent rainfall which might have brought up the terrestrial runoff to the coast. High consumption of silicate by silicoflagellates and diatoms might have contributed to the less availability of silicate concentration during postmonsoon (Satpathy et al., 2009).

3.3. Phytoplankton composition, population density, and diversity

Phytoplankton species composition, development, proliferation and quantification are majorly influenced by physicochemical parameters of that particular environment. The abundant and common species recorded during the study period are presented in Table 1. Totally 117 species of phytoplankton were identified in the present study belonging

Table 1 Checklist of dominant phytoplankton species surveyed during the study period.

No.	Species name	Summer	Premonsoon	Monsoon	Postmonsoon
	Diatoms				
	Coscinodiscophyceae (Centric diatoms)				
1	*Bacteriastrum delicatulum*	+	+	+	+
2	*B. hyalinum*	+	+	+	+
3	*B. varians*	+	+	+	
4	*Bellerochea malleus*	+	+		+
5	*Chaetoceros affinis*	+	+	+	+
6	*C. atlanticus*	+	+	+	+
7	*C. compressus*	+	+	+	+
8	*C. costatus*	+	+		+
9	*C. curvisetum*	+	+	+	+
10	*C. curvisetus*		+	+	+
11	*C. decipiens*		+	+	+
12	*C. didymus*	+	+	+	+
13	*C. diversus*	+	+	+	
14	*C. laciniosus*	+	+		+
15	*C. lorenzianus*	+	+	+	+
16	*C. messanensis*	+		+	+
17	*Coscinodiscus centralis*	+	+	+	+
18	*C. asteromphalus*		+	+	+
19	*C. concinnus*	+	+	+	+
20	*C. gigas*	+		+	+
21	*C. granii*	+	+	+	+
22	*C. marginatus*	+	+	+	+

Table 1 (*Continued*)

No.	Species name	Summer	Premonsoon	Monsoon	Postmonsoon
23	*C. oculus-iridis*	+		+	+
24	*C. wailesii*	+	+	+	+
25	*Ditylum brightwelli*	+	+	+	+
26	*Guinardia flaccida*	+	+	+	+
27	*G. striata*	+	+		+
28	*Hemiaulus membranaceus*	+		+	+
29	*Hemiaulus sinensis*	+	+	+	+
30	*Lampriscus shadboltianum*	+	+		+
31	*Lauderia annulata*	+	+		+
32	*Leptocylindrus danicus*	+		+	+
33	*Odontella mobiliensis*	+	+		+
34	*Palmeria hardmaniana*	+	+		+
35	*Proboscia alata*	+	+		+
36	*Pseudosolenia calcar-avis*	+		+	+
37	*Rhizosolenia imbricata*	+	+	+	+
38	*R. setigera*	+	+		+
39	*R. shrubsolei*		+	+	+
40	*Skeletonema costatum*	+	+	+	+
41	*Stephanopyxis palmeriana*		+	+	+
42	*Streptotheca thamensis*	+		+	+
43	*Triceratium cf. broecuii*	+	+		+
	Fragilariophyceae (Pennate diatoms)				
44	*Asterionella japonica*	+	+	+	
45	*Asterionellopsis glacialis*	+	+	+	+
46	*Thalassionema nitzschioides*	+	+	+	+
	Bacillariophycea (Pennate diatoms)				
47	*Bacillaria socialis*	+	+	+	+
48	*Nitzschia longissima*	+	+		+
49	*N. seriata (Pseudo-nitzschia seriata)*	+	+	+	
50	*N. sigma*	+	+		
51	*Pleurosigma cuspidatum*	+		+	+
	Dinoflagellates				
	Dinophyceae				
52	*Alexandrium leei*	+		+	+
53	*Ceratium breve*	+	+		+
54	*C. furca*	+	+	+	+
55	*C. fusus*		+	+	+
56	*C. massiliense*	+	+		+
57	*C. trichoceros*	+	+		+
58	*C. tripos*	+	+	+	+
59	*Dinophysis caudata*	+	+		+

to five different classes, Coscinodiscophyceae (62%), Bacillariophyceae (17%), Fragilariophyceae (8%), Dinophyceae (8%), Cyanophyceae (5%). *Chaetoceros atlanticus*, *Chaetoceros curvisetum*, *Coscinodiscus granii*, *Coscinodiscus wailesii*, *Coscinodiscus marginatus* and *Guinardia flaccida* of Coscinodiscophyceae, *Nitzschia longissima*, *Nitzschia seriata* (*peudo nitzschia seriata group*) of Bacillariophyceae, *Asterionellopsis glacialis* of Fragellariophycea and *Ceratium tripos*, *Ceratium furca* of Dinophyceae were most common group observed throughout the study period. Species composition of phytoplankton was more diverse during postmonsoon period, especially diatoms found to be more dominant group than the others. This could be due to the terrestrial runoff during monsoon season might have brought up the sufficient amount of silicate which in turn enhanced the species composition. It has been reported that the suitable environmental condition, late monsoonal effects such as land runoff and upwelling which favors the growth and proliferation of diatoms (Dehradrai and Bhargava, 1972; Dupuis and Hann, 2009).

Noticeable seasonal and spatial differences in population density were observed among phytoplankton communities and the density of phytoplankton ranged between 8771 cells L^{-1} (November 2015) and 1,303,142 cells L^{-1} (September 2015). In the present study, the phytoplankton population density was observed in the order of premonsoon > summer > postmonsoon > monsoon. Phytoplankton population density attained its maximum

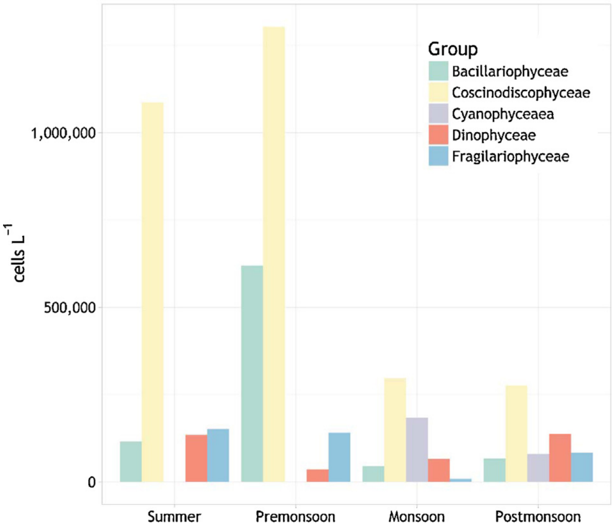

Figure 4 Seasonal variation in phytoplankton population density.

(1.303×10^6 cells L^{-1}, and 1.086×10^6 cells L^{-1}) during premonsoon (September 2015) and summer (April 2015) are shown in Fig. 4. The investigated high population density during premonsoon was due to the prevalence of *N. seriata* (*pseudo-nitzschia seriata group*) and *Skeletonema costatum*. The same phenomenon has been reported earlier with other few different species during premonsoon season (Senthilkumar et al., 2002; Thillai Rajsekar et al., 2005). The observed high density during summer might have attributed to more stable hydrographical parameters (Babu et al., 2013). However, species composition was comparatively higher in postmonsoon and summer than premonsoon. Phytoplankton abundance was low during monsoon season and this could be due to heavy rainfall, decreased salinity, temperature, pH and high turbidity (Babu et al., 2013; Rajasekar et al., 2010).

Seasonal variations in phytoplankton species diversity index and species richness is illustrated in Fig. 5. The phytoplankton diversity index and species richness ranged from 1.39 to 3.60 and 1.68 to 1.96 respectively. The highest values were found during postmonsoon and the lowest values were observed during monsoon season. The observed highest value in postmonsoon was due to high species composition observed during the study. Dupuis and Hann (2009) also reported desirable environmental condition promotes the growth of diatoms during postmonsoon season. Low species richness and diversity indices on monsoon might have associated with lower salinity and temperature as reported by Rajasegar et al. (2000) and Mani (1992).

3.4. Canonical Correspondence Analysis of phytoplankton and environmental parameters

Canonical Correspondence Analysis was intended to find out the relationship between environmental variables and phytoplankton distribution (Ariyadej et al., 2004). Important environmental variables responsible for the phytoplankton community changes were identified with CCA are represented in Fig. 6.

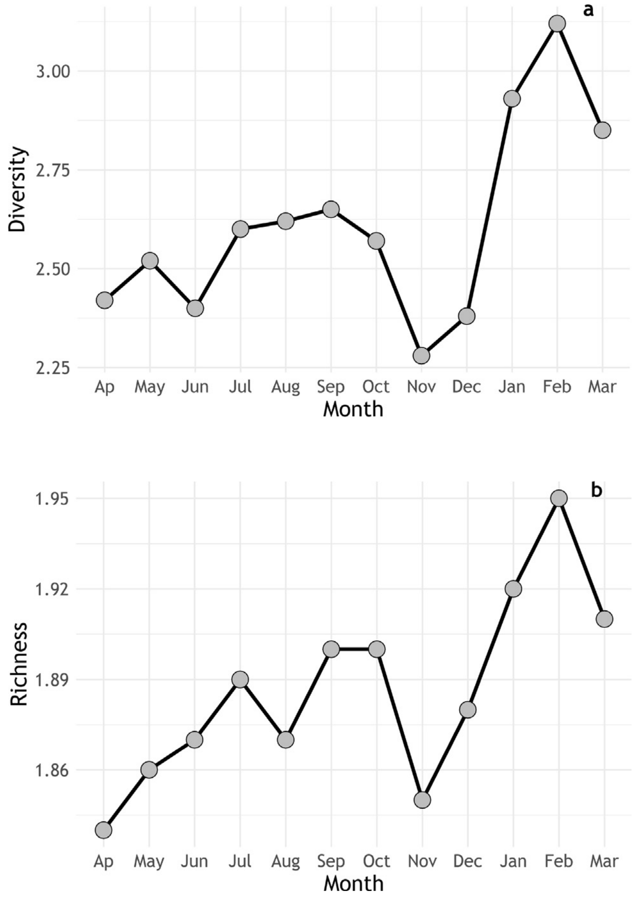

Figure 5 Shows seasonal variation in phytoplankton species diversity and richness. Phytoplankton species diversity (a), phytoplankton species richness (b).

During summer axis 1 and 2 explained 71% of the variability in the species environment biplot (Fig. 6). Temperature, DO, silicate, pH, chlorophyll-*a*, IP, and nitrite had positive correlation in axis 1 and highly associated with *A. glacialis*, *Bacteriastrum delicatalum*, *Bacteriastrum hyalinum*, *Leptocylindrus minimus*, *Chaetoceros curvisteum*, *Chaetoceros decipiens*, *Chaetoceros lorenzianus*, *S. costatum*, *Lauderia annualta*, *C. tripos* among these *A. glacialis*, *Chaetoceros curviesteum*, *C. decipiens*, *S. costatum*, *Ditylum brightwelli*, *Lauderia annualata* and *C. tripos* exhibited maximum canonical values (1.246, 0.656, 1.025, 0.913, 0.938, 0.541 and 0.920). In previous studies, it has been proven that stable environmental parameters like increased salinity, pH, high temperature, high nutrients and high intensity of light penetration during summer favor these species proliferation especially *S. costatum*, *Dityum* spp., *Chaetoceros* spp., *Odontella* spp. (Gouda and Panigrahy, 1996; Rajasegar et al., 2000; Saravanakumar et al., 2008; Vengadesh et al., 2009). In axis 2 *C. furca*, *Chaetoceros tortissimum*, *Chaetoceros diversus*, and *C. granii*, had a strong positive correlation with salinity. CCA biplot explained that temperature, pH and salinity had a close relation with phytoplankton species than other variables which indicated the increased temperature in summer is responsible for its positive relationship. Concurrently DO, IP, silicate, and chlorophyll-*a* also expressed strong positive relation in both axis 1 and 2, which

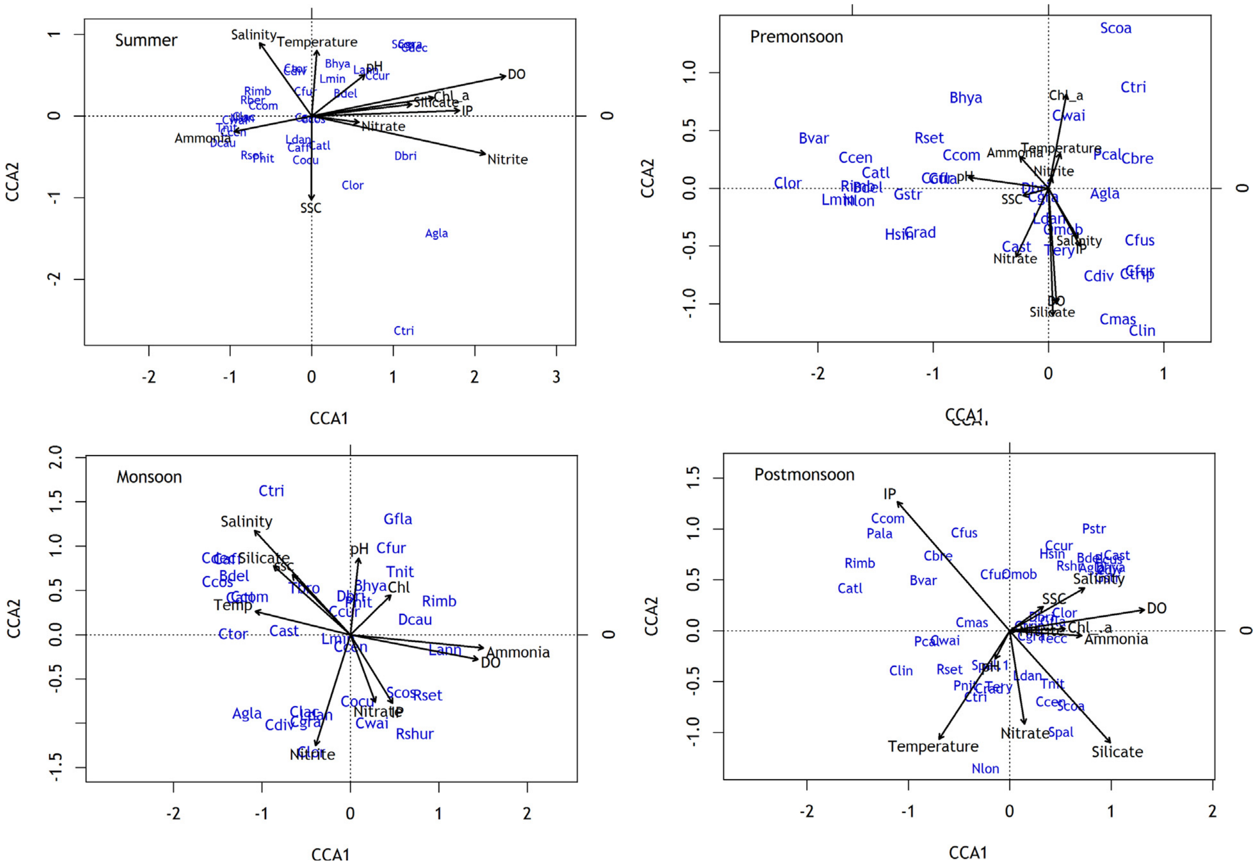

Figure 6 CCA biplot showing the seasonal variation between phytoplankton species and environmental parameters. Environmental variables are depicted by long arrows and species are given in code words. The correlation between species and environmental variables are explained by the length of the arrows. (DO — dissolved oxygen, Chl-*a* — chlorophyll-*a*, IP — inorganic phosphate: Agla — *Asterionellopsis glacialis*, Bdel — *Bacteriastrum delicatulum*,Bhya — *Bacteriastrum hyalinum*, Bvar — *Bacteriastrum varians*, Caff — *Chaetoceros affinis*, Cast — *Coscinodiscus cf. asteromphalus*, Catl — *Chaetoceros atlanticus*, Cbre — *Ceratium breve*, Ccen — *Coscinodiscus centralis*, Ccom — *Chaetoceros compressus*, Ccos — *Chaetoceros costatus*, Ccur — *Chaetoceros curvisetum*, Cdec — *Chaetoceros decipiens*, Cdiv — *Chaetoceros diversus*, Cfur — *Ceratium furca*, Cfus — *Ceratium fusus*, Cgra — *Coscinodiscus granii*, Clac — *Chaetoceros laciniosus*, Clor — *Chaetoceros lorenzianus*, Cma — *Ceratium massiliense*, Cocu — *Coscinodiscus oculus-iridis*, Crad — *Coscinodiscus radiatus*, Ctor — *Chaetoceros tortissimum*, Ctri — *Ceratium trichoceros*, Ctrip — *Ceratium tripos*, Cwai — *Coscinodiscus wailesii*, Dbri — *Ditylum brightwelli*, Gfla — *Guinardia flaccida*, Gstr — *Guinardia striata*, Hsin — *Hemiaulus sinensis*, Lann — *Lauderia annulata*, Ldan — *Leptocylindrus danicus*, Lmin — *Leptocylindrus minimus*, Nlon — *Nitzschia longissima*, Omob — *Odontella mobiliensis*).

implies the stable and favorable condition of water parameters for phytoplankton. However, temperature, pH and salinity exhibited the maximum relationship with phytoplankton species indicating that light and salinity are the major source for supporting the phytoplankton species positively during summer (Cetin and Sen, 2004; Litchman, 2000; Richardson et al., 2000).

In premonsoon the variation explained by CCA analysis was 64% (Fig. 6). The variable that positively correlated in axis 2 were nitrite, pH, ammonia and salinity, DO, silicate had a negative correlation in the same axis. Chlorophyll-*a* and temperature were in a positive relationship in both axis 1 and 2, they explained the closer association with *C. wailesii*, *C. tripos*, *Ceratium breve*, *B. hyalinum*, *S. costatum*. However, some species were negatively correlated in axis 2 with salinity and inorganic phosphate (*A. glacialis*, *C. diversus*, *Odontella mobilensis*, *C. tripos)*. In axis 1 diatoms and dinoflagellates exhibited both positive and negative correlation, especially species of dinoflagellates (*Ceratium massilensis*, *C. breve*, *C. furca*, *Ceratium fusus*, *C. tripos*, *Ceratium trichoceros*) explained very strong positive association by having high canonical values of 0.500, 0.643, 0.659, 0.677, 0.615, and 0.640 respectively. This must be due to the favorable intermediate salinity values and moderate nutrient concentrations that might have favorably increased their abundance during premonsoon (Kannan, 1980; Mani et al., 1986; Mani, 1992; Perumal et al., 1999).

As for postmonsoon, the variation explained by CCA ordination was 57% (Fig. 6), the main environmental parameters which had a positive correlation with axis 1 and 2 were salinity, DO, chlorophyll-*a*, ammonia, SSC and inorganic phosphate. Silicate showed a positive and a negative correlation in axis 1 and 2, genera like *Leptocylindrus danicus*, *Thalassionema nitzschioides*, *Coscinodiscus centralis*, *S. costatum*, *Stephanopyxis palmeriana* were in the negative relation with silicate. Species like *Guinardia striata*, *A. glacialis*, *Rhizosolenia shurbsolei*, *Bacteriastrum delicatulum*, *B. hyalinum*, *C. diversus* found to have the positive correlation with salinity in axis 1 whereas in axis 2 species such as *Ceratium massiliense*, *C. breve*, *C. fusus*, *C. furca*, *Chaetoceros compressus*, *Bacteriastrum variance* were having a close association with IP. This result confirms with Rajkumar et al. (2012) observation with presence of similar species in abundance during postmonsoon and he also reported that high nutrient input caused by northeast monsoon rainfall might have contributed in their abundance. The same observation also reported during postmonsoon season by several authors (Kannan, 1980; Mani et al., 1986). Both diatom and dinoflagellates showed a positive and negative relationship with different environmental variable but most of the species showed a significant positive relationship in axis 2 with IP, and salinity. This confirms that IP and salinity plays a vital role in phytoplankton abundance and composition (Thangaradjou et al., 2012). On the contrary the dinoflagellate species (*C. breve*, *C. furca*, *C. fusus*, *C. tripos*, *C. trichoceros*) which had a high positive relationship in premonsoon showed a significant negative correlation in axis 2. This implies that the shift in physico-chemical parameters can dramatically change the species composition and abundance.

During monsoon the variation explained by CCA in first two axes was 53% (Fig. 6) ammonia, DO, nitrate, IP in axis 1 and temperature, salinity, silicate in axis 2 had positive and negative correlations in CCA biplot, implying the influence of freshwater on contributing hydrochemical parameters. Species such as *Coscinodiscus cf. asteromphalus, C. diversus, C. lorenzianus, C. centralis, C. granii, L. minimus* were positively correlated with temperature, silicate, nitrite in axis 1, and few species of phytoplankton (*T. nitzschioides, D. brightwelli, Triceratium cf. broecii*) were negatively correlated with salinity in the same axis. In axis 1 most of the species were in negative correlation with high canonical values especially genera like *A. glacialis* (−0.921), *B. delicatulum* (−1.038), *C. tripos* (−0.703), *Chaetoceros affinis* (−1.091), *C. atlanticus* (−0.986), *C. compressus* (−0.898), *C. decipiens* (−1.174), *C. diversus* (−0.627), *Chaetoceros tortissum* (−1.047), and *Coscinodiscus asteromphaus* (−0.588). This pattern clearly shows that less temperature and salinity results in scarce phytoplankton diversity and abundance. The revealed results coincide with the earlier investigation as monsoon season causes dramatic changes in environmental parameters due to heavy freshwater discharges and high turbidity thereby reduces the phytoplankton diversity and abundance (Rajkumar et al., 2009; Vengadesh et al., 2009). Similarly, high positive association with DO and ammonia indicates the freshwater influence and high organic matters.

The CCA executed on the phytoplankton data in the preset study revealed that the abundance of phytoplankton was dynamic and was controlled mainly by temperature, DO, salinity, inorganic phosphate and silicate. In CCA analysis, several phytoplankton species showed a significant positive relationship with environmental parameters irrespective to season specifically centric diatoms such as *A. glacialis*, *B. delicatulum*, *B. hyalinum*, *C. decipiens*, *C. diversus*, and *S. costatum* implying their persistent nature and high tolerance to wide variation in environmental parameters. Similarly, earlier investigations also reported the occurrence of these diatom species in all the season (Kobayashi and Takahashi, 2002; Paul et al., 2008). In the present investigation phytoplankton showed a positive correlation with salinity during summer and had a negative correlation in premonsoon and monsoon, implying that the estuarine regions are subjected to considerable fluctuations in environmental parameters, which enable phytoplankton to adapt such dynamic environment (Lionard et al., 2005). Phosphate and nitrogen are crucial chemical elements for phytoplankton survival (Dawes, 1981). In CCA, inorganic phosphate showed a high positive correlation in all the seasons except, premonsoon. This could be due to less concentration of IP or rapid recycling. Similar results have been stated by Steinhart et al. (2002), Hergenrader (1980). However, certain species restricted their abundance to a particular season. For example *pseudo nitzschia seriata* species proliferated abundantly during premonsoon season which implies that suitable nutrient availability for their growth on premonsoon. Similarly, CCA result for dinoflagellate species showed a positive and negative correlation in premonsoon and postmonsoon season implying the seasonal shift of physico-chemical parameters influence their occurrence and abundance. A similar scenario was observed in the Bay of Bengal with particular species as it appeared to be seasonally dominant (Paul et al., 2008). In addition, it had a high tolerance to large variation in environmental parameters (Bonilla et al., 2005). It is evidenced from CCA results that the environmental parameters played a vital role in phytoplankton abundance and species composition and influence the occurrence of phytoplankton species with respect to seasonal changes in physico-chemical parameters.

4. Conclusion

The present investigation summarizes the seasonal fluctuations in physico-chemical parameters and phytoplankton diversity at Parangipettai coastal waters seasonally. Parangipettai waters are highly subjective to riverine freshwater influence as the Vellar estuary debouches in the Bay of Bengal. The addition of nutrients such as nitrate and silicate to the coastal waters are mainly during monsoon season. Introduction of the high organic load during monsoon season containing phosphate, silicate, and nitrate plays the substantial role in phytoplankton growth in the forthcoming seasons, which helps the phytoplankton to avail the nutrients and proliferate. It is clearly evidenced from ANOVA that the nutrients have significant variation between seasons and substantially influenced the phytoplankton diversity and abundance. Phytoplankton diversity is highly dynamic depending on the nutrient availability which is clearly explained by Canonical Correspondence Analysis in the present study. From CCA biplot, it is clear that temperature, salinity, silicate, DO and IP played a tremendous role in phytoplankton growth and abundance. Thus, the overall study gives a good outline of the seasonal dynamic relationship between phytoplankton and environmental parameters.

Funding

This study was funded by Indian National Centre for Ocean Information Service (grant number: INCOIS:F&A: XII:A1:028).

Acknowledgments

The authors would like to thank Dean and Director of CAS in Marine Biology and authorities of Annamalai University for providing facilities. We would like to express deep gratitude to Indian National Centre for Ocean Information Service for providing us financial support.

References

Al-Kandari, M., Al- Yamani, F.Y., Al-Rifaie, K., 2009. Marine Phytoplankton Atlas of Kuwait's Waters. Kuwait Inst. Sci. Res., Safar, 351 pp.

Ariyadej, C., Tansakul, R., Tansakul, P., Angsupanich, S., 2004. Phytoplankton diversity and its relationships to the physicochemical environment in the Banglang reservoir, Yala province. Songklahnakarin J. Sci. Technol. 26 (5), 595—607.

Babu, A., Varadharajan, D., Vengadesh, P.N., Thilagavathi, B., Manikandarajan, T., Sampathkumar, P., Balasubramanian, T., 2013. Diversity of phytoplankton in different stations from Muthupettai, South east coast of India. J. Mar. Sci.: Res. Dev. 3 (3), http://dx.doi.org/10.4172/2155-9910.1000128 128 pp.

Barić, A., Marasović, I., Gačić, M., 1992. Eutrophication phenomenon with special reference to the Kaštela Bay. Chem. Ecol. 6 (1—4), 51—68, http://dx.doi.org/10.1080/02757549208035262.

Bonilla, S., Conde, D., Aubriot, L., Perez, M.D.C., 2005. Influence of hydrology on phytoplankton species composition and life strategies in a subtropical costal lagoon periodically connected with the Atlantic Ocean. Estuaries 28 (6), 884—895, http://dx.doi.org/10.1007/BF02696017.

Brettum, P., Andersen, T., 2005. The Use of Phytoplankton as Indicators of Water Quality. NIVA Rep. SNO 4818-2004, 33 pp.

Cetin, A.K., Sen, B., 2004. Seasonal distribution of phytoplankton in Orduzu Dam Lake (Malatya, Turkey). Turk. J. Bot. 28 (3), 279—285.

Chang, H., 2008. Spatial analysis of water quality trends in the Han River basin, South Korea. Water Res. 42 (13), 3285—3304, http://dx.doi.org/10.1016/j.watres.2008.04.006.

Chattopadhyay, J., Sarkar, R.R., Pal, S., 2003. Dynamics of nutrient—phytoplankton interaction in the presence of viral infection. Biosystems 68 (1), 5—17.

Choudhury, S.B., Panigrahy, R.C., 1991. Seasonal distribution and behavior of nutrients in the Greek and coastal waters of Gopalpur, East coast of India. Mahasagar — Bull. Natl. Inst. Oeanogr. 24 (2), 88—91.

Cole, C.V., Sanford, R.L., 1989. Biological aspects of the Phosphorus cycle. In: Proceedings of a Symposium "Phosphorous requirements for sustainable agriculture in Asia and Oceania March 6—10 1989". SCOPE/UNEP, 1989, Int. Rice Res. Inst. 497 pp.

Crossetti, L.O., Bicudo, D.C., Bicudo, C.E.M., Bini, L.M., 2008. Phytoplankton biodiversity changes in a shallow tropical reservoir during the hypertrophication process. Braz. J. Biol. 68 (4), 1061—1067, http://dx.doi.org/10.1590/S1519-69842008000500013.

Das, J., Das, S.N., Sahoo, R.K., 1997. Semidiurnal variation of some physicochemical parameters in the Mahanadi estuary, east coast of India. Indian J. Mar. Sci. 26 (3), 323—326.

Davis, J.C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species. Rev. J. Fish. Res. Board Canada 32 (12), 2295—2332.

Dawes, C.J., 1981. Marine Botany. Wiley & Sons, New York, 496 pp.

Dehradrai, P.V., Bhargava, R.M.S., 1972. Distribution of chlorophyll, carotenoids and phytoplankton in relation to certain environmental factors along the central west coast of India. Mar. Biol. 17 (1), 30—37.

Dugdale, R.C., 1967. Nutrient limitation in the sea: dynamics, identification, and significance. Limnol. Oceanogr. 12 (4), 685—695, http://dx.doi.org/10.4319/lo.1967.12.4.0685.

Dugdale, R.C., Wilkerson, Hogue, V.E., Marchi, A., 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Est. Coast. Shelf. Sci. 73 (1—2), 17—29, http://dx.doi.org/10.1016/j.ecss.2006.12.008.

Dupuis, A., Hann, B.J., 2009. Warm spring and summer water temperatures in small eutrophic lakes of the Canadian prairies: potential implications for phytoplankton and zooplankton. J. Plankton. Res. 31 (5), 489—502, http://dx.doi.org/10.1093/plankt/fbp001.

Durate, P., Macedo, M.F., Da Fonseca, L.C., 2006. The relationship between phytoplankton diversity and community function in a coastal lagoon. Hydrobiologia 183, 3—18, http://dx.doi.org/10.1007/1-4020-4697-9_1.

Falkowski, P.G., Fenchel, T., Delong, E.F., 2008. The microbial engines that drive Earth's biogeochemical cycles. Science 320 (5879), 1034—1039, http://dx.doi.org/10.1126/science.1153213.

Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. Science 281 (5374), 237—240, http://dx.doi.org/10.1126/science.281.5374.237.

Gouda, R., Panigrahy, R.C., 1995. Seasonal distribution and behavior of nitrate and phosphate in Rushikulya estuary, East coast of India. Indian J. Mar. Sci. 24 (4), 233—235.http://nopr.niscair.res.in/handle/123456789/37362.

Gouda, R., Panigrahy, R.C., 1996. Ecology of phytoplankton in coastal waters off Gopalpur, east coast of India. Indian J. Mar. Sci. 25 (2), 81—84.http://nopr.niscair.res.in/handle/123456789/37094.

Govindasamy, C., Kannan, L., Jayapaul, A., 2000. Seasonal variation in physico-chemical properties and primary production in the coastal water biotopes of Coramandal coast, India. J. Environ. Biol. 21 (1), 17.

Guinder, V.A., López-Abbate, M.C., Berasategui, A.A., Negrin, V.L., Zapperia, G., Pratolongo, P.D., Fernández Severini, M.D., Popovich, C.A., 2015. Influence of the winter phytoplankton bloom on the settled material in a temperate shallow estuary. Oceanologia 57 (1), 50—60, http://dx.doi.org/10.1016/j.oceano.2014.10.002.

Hergenrader, G.L., 1980. Eutrophication of the salt valley reservoirs, 1968—1973 II. Changes in physical and chemical parameters of eutrophication. Hydrobiologia 74 (3), 225—240, http://dx.doi.org/10.1007/BF00008756.

Hutchinson, G.E., 1957. Concluding remarks. CSH Sympos. 22, 415—457, http://dx.doi.org/10.1101/SQB.1957.022.01.039.

Jyothibabu, R., Madhu, N.V., Maheswaran, P.A., Jayalakshmy, K.V., Nair, K.K.C., Achuthankutty, C.T., 2008. Seasonal variation of microzooplankton (20200 μm) and its possible implications on the vertical carbon flux in the western Bay of Bengal. Cont. Shelf. Res. 28 (6), 737—755.

Kannan, L., 1980. Hydrobiological studies in nearshore and estuarine waters of Portonovo (India) with special reference to diatoms. (Ph.D. thesis). Annamalai Univ., India, 120 pp.

Khan, T.A., 2003. Limnology of four saline lakes in western Victoria, Australia. Limnologica 33 (4), 327—339, http://dx.doi.org/10.1016/S0075-9511(03)80027-0.

Kobayashi, F., Takahashi, K., 2002. Distribution of diatoms along equatorial transect in the western and central Pacific during La Niña conditions. Deep-Sea Res. Pt. II 49 (13—14), 2801—2821, http://dx.doi.org/10.1016/S0967-0645(02)00059-0.

Legović, T., Žutić, V., Gržetić, Z., Cauwet, G., Precali, R., Viličić, D., 1994. Eutrophication in the Krka estuary. Mar. Chem. 46 (1—2), 203—215, http://dx.doi.org/10.1016/0304-4203(94)90056-6.

Levinton, J.S., 2001. Marine Biology. Chapter 4 — The Chemical and Physical Environment. Oxford Univ. Press, New York, 560 pp.

Lionard, M., Muylaert, K., Gansbeke, V., Vyverman, W., 2005. Influence of changes in salinity and light intensity on growth of phytoplankton communities from the Scheldt River and estuary (Belgium/The Netherlands). Hydrobiologia 540 (1—3), 105—115, http://dx.doi.org/10.1007/s10750-004-7123-x.

Lipschultz, F., 1995. Nitrogen- specific uptake rates of marine phytoplankton isolated from natural populations of particles by flow cytometry. Mar. Ecol.-Prog. Ser. 123, 245—258, http://dx.doi.org/10.3354/meps123245.

Litchman, E., 2000. Growth rates of phytoplankton under fluctuating light. Freshw. Biol. 44 (2), 223—235, http://dx.doi.org/10.1046/j.1365-2427.2000.00559.x.

Madhu, N.V., Jyothibabu, R., Balachandran, K.K., Honey, U.K., Martin, G.D., Vijay, J.G., Shiyas, C.A., Gupta, G.V.M., Achuthankutty, C.T., 2007. Monsoonal impact on planktonic standing stock and abundance in a tropical estuary (Cochin Backwaters—India). Estuar. Coast. Shelf Sci. 73 (1—2), 54—64.

Mani, P., 1992. Natural phytoplankton communities in Pichavaram mangroves. Indian J. Mar. Sci. 21 (4), 278—280.http://nopr.niscair.res.in/handle/123456789/38123.

Mani, P., Krishnamurthy, K., Palaniappan, R., 1986. Ecology of phytoplankton blooms in the Vellar estuary, east coast of India. Indian J. Mar. Sci. 15 (1), 24—28.http://nopr.niscair.res.in/handle/123456789/38590.

Marasović, I., Pucher-Petković, T., 1985. Effect of eutrofication on the structure of the coastal phytoplankton community. Rapp. Comm. Int. Mer. Medit. 29 (9), 137—139.

McQuatters-Gollop, A., Gilbert, A.J., Mee, L.D., Vermaat, J.E., Artioli, Y., Humborg, C., Wulff, F., 2009. How well do ecosystem indicators communicate the effects of anthropogenic eutrophication? Estuar. Coast. Shelf Sci. 82 (4), 583—596, http://dx.doi.org/10.1016/j.ecss.2009.02.017.

Menon, N.N., Balchand, A.N., Menon, N.R., 2000. Hydrobiology of the Cochin backwater system — a review. Hydrobiologia 430 (1—3), 149—183, http://dx.doi.org/10.1023/A:10040334.

Morgan, A.M., Royer, T.V., David, M.B., Gentry, L.E., 2006. Relationships among nutrients, chlorophyll-*a*, and dissolved oxygen in agricultural streams in Illinois. J. Environ. Qual. 35, 1110—1117, http://dx.doi.org/10.2134/jeq2005.0433.

Ninčević-Gladan, Ž., Bužančić, M., Kušpilić, G., Grbec, B., Matijević, S., Skejić, S., Marasović, I., Morović, M., 2015. The response of phytoplankton community to anthropogenic pressure gradient in the coastal waters of the eastern Adriatic Sea. Ecol. Indic. 56, 106—115, http://dx.doi.org/10.1016/j.ecolind.2015.03.018.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2016. R Package Version 2.4-0. Vegan: Community Ecology Package, https://cran.r-project.org.

Paul, J.T., Ramaiah, N., Sardessai, S., 2008. Nutrient regimes and their effect on distribution of phytoplankton in the Bay of Bengal. Mar. Environ. Res. 66 (3), 337—344, http://dx.doi.org/10.1016/j.marenvres.2008.05.007.

Perumal, P., Sampathkumar, P., Santhanam, P., 1998. Zoopalnkton of Parangipettai Coastal Waters. Monogr. Ser., Vol. 1: UGC-SAP, CAS in Marine Biology. Annamali Univ., Parangipettai, 31 pp.

Perumal, P., Sampathkumar, P., Karuppasamy, P.K., 1999. Studies on the bloom forming species of phytoplankton in the Vellar estuary, southeast coast of India. Indian J. Mar. Sci. 28 (4), 400—403.

Perumal, N.V., Rajkumar, M., Perumal, P., Rajasekar, K.T., 2009. Seasonal variations of plankton diversity in the Kaduviyar estuary, Nagapattinam, southeast coast of India. J. Environ. Biol. 30 (6), 1035—1046.

Pielou, E.C., 1966. Species-diversity and pattern-diversity in the study of ecological succession. J. Theor. Biol. 10 (2), 370—383.

Prabhahar, C., Saleshrani, K., Dhanasekaran, D., Tharmaraj, K., Baskaran, K., 2011. Seasonal variations in physico-chemical parameters of Nagapattinam Coastal area, Tamil nadu, India. Int. J. Curr. Life Sci. 1 (6), 29—32.

Rajasegar, M., Srinivasan, M., Rajaram, R., 2000. Phytoplankton diversity associated with the shrimp farm development in Vellar estuary, south India. Seaweed Res. Utiln. 22 (1—2), 125—213.

Rajasegar, M., Sirnivasan, M., Ajmal Khan, S., 2002. Distribution of sediment nutrients of Vellar estuary in relation to shrimp farming. Indian J. Mar. Sci. 31 (2), 153—156.

Rajasekar, K., Thillai, R.M., Jun, S., Ashok Prabu, V., Perumal, P., 2010. Seasonal variations of phytoplankton diversity in the Coleroon coastal waters, southeast coast of India. Acta Oceanol. Sin. 29 (5), 97—108.

Rajkumar, M., Perumal, P., Ashok, P.V., Vengadesh, Perumal, N., Thillai Rajasekar, K., 2009. Phytoplankton diversity in pichavaram mangrove waters from south east coast of india. J. Environ. Biol. 30 (4), 489—498.

Rajkumar, M., Jankinson, I.R., Sun, J., Pachiappan, P., 2012. Phytoplankton diversity in the Parangipettai coastal waters, southeast coast of India. J. Environ. Biol. 33 (6), 1115—1125.

Rakhesh, M., Raman, A.V., Ganesh, T., Chandramohan, P., 2013. Small copepods structuring mesozooplankton community dynamics in a tropical estuary-coastal system. Estuar. Coast. Shelf Sci. 126 (7), 7—22, http://dx.doi.org/10.1016/j.ecss.2013.03.025.

Rhyther, J.H., Dunstan, W.M., 1971. Nitrogen, phosphorous and eutrophication in the coastal marine environment. Science 171 (3975), 1008—1013.

Richardson, T.L., Gibson, C.E., Heaney, S.I., 2000. Temperature, growth and seasonal succession of Phytoplankton in Lake Baikal, Siberi. Freshw. Biol. 44 (3), 431—440, http://dx.doi.org/10.1046/j.1365-2427.2000.00581.x.

Sahu, G., Satpathy, K.K., Mohanty, A.K., Sarkar, S.K., 2012. Variations in community structure of phytoplankton in relation to physicochemical properties of coastal waters, southeast coast of India. Indian J. Geo-Mar. Sci. 41 (3), 223—241.

Santhanam, P., Perumal, P., 2003. Diversity of zooplankton in Parangipettai coastal waters, Southeast coast of India. J. Mar. Biol. Assoc. India 45 (2), 144—151.

Santhanam, R., Ramanathan, N., Venkataramanuja, K.V., Jegatheesan, G., 1987. Phytoplankton of the Indian Seas: An Aspect of Marine Botany. Daya Publ., House, Delhi, 127 pp.

Santhosh Kumar, C., Perumal, P., 2012. Studies on phytoplankton characteristics in Ayyampattinam coast. Indian J. Environ. Biol. 33 (3), 585—589.

Saravanakumar, A., Rajkumar, M., Serebiah, J.S., Thivakaran, G.A., 2008. Seasonal variations in physico-chemical characteristics of water, sediment and soil texture in arid zone mangroves of Kachchh-Gujarat. J. Environ. Biol. 29 (5), 725—732.

Sardessai, S., Ramaiah, N., Prasanna Kumar, S., De Souza, S.N., 2007. Influence of environmental forcings on the seasonality of dissolved oxygen and nutrients in the Bay of Bengal. J. Mar. Res. 65 (2), 301—316. http://drs.nio.org/drs/handle/2264/623.

Satpathy, K.K., Sahu, G., Mohanty, A.K., Prasad, M.V.R., Panigrahy, R. C., 2009. Phytoplankton community structure and its variability during southwest to northeast monsoon transition in the coastal waters of Kalpakkam, east coast of India. Int. J. Oceans Oceanogr. 3 (1), 43—74.

Segar, K., Hariharan, V., 1989. Seasonal distribution nitrate, nitrite, ammonia and plankton in effluent discharge area of Mangalore, west coast of India. Indian J. Mar. Sci. 18 (3), 170—173. http://nopr.niscair.res.in/handle/123456789/38360.

Senthilkumar, S., Santhanam, P., Perumal, P., 2002. Diversity of phytoplankton in Vellar estuary, southeast coast of India. In: Ayyappan, S., Jena, J.K., Mohan, J.M. (Eds.), Proc. 5th Indian Fisheries Forum, AFSIB, Mangalore & AeA, Bhubaneswar, India, 245—248.

Senthilkumar, B., Purvaja, R., Ramesh, R., 2008. Seasonal and tidal dynamics of nutrients and chlorophyll *a* in a tropical mangrove estuary, southeast coast of India. Indian J. Mar. Sci. 37 (2), 132—140.

Shannon, C.E., Wiener, W., 1949. The Mathematical Theory of Communication. Univ. Illinois Press, Urbana, 125 pp.

Shashi Shekhar, T.R., Kiran, B.R., Puttaiah, E.T., Shivaraj, Y., Mahadevan, K.M., 2008. Phytoplankton as index of water quality with reference to industrial pollution. J. Environ. Biol. 29 (2), 233—236.

Sin, Y., Wetzel, L.R., Anderson, C.I., 1999. Spatial and temporal characteristic of nutrient and phytoplankton dynamics In the York

River Estuary, Virginia. Analysis of long-term data. Estuaries 22 (2), 260—275, http://dx.doi.org/10.2307/1352982.

Siva Sankar, R., Padmavathi, G., 2012. Species composition, abundance and distribution of phytoplankton in the harbour areas and coastal waters of Port Blair, South Andaman. Int. J. Oceanogr. Mar. Ecol. Syst. 1 (3), 76—83, http://dx.doi.org/10.3923/ijomes.2012.76.83.

Skejić, S., Bojanić, N., Matijević, S., Vidjak, O., Grbec, B., Ninčević-Gladan, Ž., Šestanović, S., Šantić, D., 2014. Analysis of the phytoplankton community in the vicinity of domestic sewage outflow during stratified conditions. Mediterr. Mar. Sci. 15 (3), 574—586, http://dx.doi.org/10.12681/mms.866.

Smayda, T.J., 1980. Phytoplankton species succession. In: Morris, I. (Ed.), Physiological Ecology of Phytoplankton. Univ. California Press, Berkeley, 493—570.

Smith, D.L., 1977. A Guide to Marine Coastal Plankton and Marine Invertebrate Larvae. Kendal/Hunt Publ. Co., Dubuque, 16 pp.

Soundarapandian, P., Preamkumar, T., Dinakaran, G.K., 2009. Studies on the phyisco- chemical characteristics and nutrients in the Uppanar estuary of Cuddalore, south east coast of India. Curr. Res. J. Biol. Sci. 1 (3), 102—105.

Spatharis, S., Danielidis, D.B., Tsirtsis, G., 2007. Recurrent *Pseudo-nitzschia calliantha* (Bacillariophyceae) and *Alexandrium insuetum* (Dinophyceae) winter blooms induced by agricultural runoff. Harmful Algae 6 (6), 811—822, http://dx.doi.org/10.1016/j.hal.2007.04.006.

Sridhar, R.T., Thangaradjou, S., Senthil Kumar, Kannan, L., 2006. Water quality and phytoplankton characteristics in the Palk Bay, Southeast coast of India. J. Environ. Biol. 27 (3), 561—566.

Steinhart, G.S., Likens, G.E., Soto, D., 2002. Physiological indicators of nutrient deficiency in phytoplankton in southern Chilean lakes. Hydrobiologia 489 (1—3), 21—27.

Strickland, J.D.H., Parsons, T.R., 1972. A Practical Hand Book of Seawater Analysis, 2nd ed. Fish. Res. Board Canada, Ottawa, 310 pp.

Su, J., Tian, T., Krasemann, H., Schartau, M., Wirtz, K., 2015. Response patterns of phytoplankton growth to variations in resuspension in the German Bight revealed by daily MERIS data in 2003 and 2004. Oceanologia 57 (4), 328—341, http://dx.doi.org/10.1016/j.oceano.2015.06.001.

Subramanian, B., Mahadevan, V., 1999. Seasonal and diurnal variations of hydro biological characters of coastal waters of Chennai (Madras) Bay of Bengal. Indian J. Mar. Sci. 28 (4), 429—433.

Subramanyan, R.A., 1946. Systematic account of marine plankton diatoms of Madras Coast. Proc. Indian Acad. Sci. 24 (4), 85—197, http://www.ias.ac.in/j_archive/procb/24/4/85-197/viewpage.html.

Sukumaran, M., Muthukumaravel, K., Sivakami, R., 2013. Seasonal variation in physico-chemical characteristics of Agniar Estuary, Southeast Coast of India. Asia Pac. J. Res. 2 (8), 108—120, http://apjor.com/files/1376844720.pdf.

Thangaradjou, T., Vijayanaskara, S.G., Raja, S., Poornimaa, D., Shanthia, R., Balasubramaniana, T., Babub, K.N., Shuklab, A. K., 2012. Influence of environmental variables on phytoplankton floristic pattern along the shallow coasts of southwest Bay of Bengal. Algal Res. 1 (2), 143—154, http://dx.doi.org/10.1016/j.algal.2012.07.005.

Thangaradjou, T., Sarangi, R.K., Shanthi, R., Poornima, D., Raja, K., Saravanakumar, A., 2013. Changes in nutrients ratio along the central Bay of Bengal coast and its influence on chlorophyll distribution. J. Environ. Biol. 35 (3), 467—477.

Thillai Rajsekar, K., Perumal, P., Santhanam, P., 2005. Phytoplankton diversity in the Coleroon estuary, southeast coast of India. J. Mar. Biol. Assoc. India 47 (2), 127—132.

Vengadesh Perumal, N., Rajkumar, M., Perumal, P., Thillai Rajasekar, K., 2009. Seasonal variations of plankton diversity in the Kaduviyar estuary, Nagapattinam, southeast coast of India. J. Environ. Biol. 30 (6), 1035—1046.

Venkataraman, G.A., 1939. Systematic account of some South Indian diatoms. Proc. Indian Acad. Sci. 10, 293—368.

Vinayachandran, P.N., Murty, V.S.N., Ramesh Babu, V., 2002. Observations of barrier layer formation in the Bay of Bengal. J. Geophys. Res. 107 (12), 1—14, http://drs.nio.org/drs/handle/2264/1362.

Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag, New York, 213 pp., http://dx.doi.org/10.1007/978-0-387-98141-3.