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Distribution and species diversity of phytoplankton in the inshore waters of Tuticorin in relation to the physicochemical variables

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Original Article

Abstract
A study was conducted to evaluate the phytoplankton community structure and its relationship with selected physicochemical variables in the inshore waters of Tuticorin during January to December 2008. Water and plankton samples from the surface waters at two depths (5m and 10m) were collected on board the research vessel *Cadalmin-IV*. Standard methods were followed for phytoplankton identification, enumeration and estimation of physicochemical variables. The present study recorded 69 species of phytoplankton with 85.5% dominance of diatoms followed by 14.5% of dinoflagellates. The overall density of phytoplankton was comparatively higher at 10 m with a mean of $2.14 \times 10^4 \pm 0.4 \times 10^4$ cells L^{-1} and $3.37 \times 10^4 \pm 0.9 \times 10^4$ cells L^{-1} at 5 m and 10 m depth respectively. The analysis indicated that 10 m depth, especially during the monsoon season, is rich in diversity of algal species than at the same depth during post-monsoon. It is confirmed that the population density of phytoplankton is more influenced by seasonal fluctuation of the physicochemical variables especially due to the effect of northeast monsoon in the inshore waters of Tuticorin.

Keywords*: Phytoplankton, physicochemical variables, inshore waters, northeast monsoon*

Introduction

Phytoplankton is an essential component in marine life and plays fundamental role in the biodiversity, bio-productivity and biogeochemical cycle of marine ecosystem. Besides being a primary producer, phytoplankton serves the energy needs of planktivorous organisms and is helpful in predicting the fishery potential of the region (Falkowski *et al*., 1998). Distribution of phytoplankton species shows spatiotemporal variations due to hydrographical factors and serves as indicators of water quality of the environment (Liu *et al*., 2004). The study of phytoplankton community structure in response to environmental variables is considered very useful for evaluating ecosystem changes of both the long-term and short-term scales (Kannan and James, 2009; Biswas *et al*., 2010).

Information is available on phytoplankton abundance and the influencing physicochemical parameters in Indian water (Perumal *et al*., 1999; Govindsamy *et al*., 2000; Rajasegar *et al*., 2000; Rajasegar, 2003; Madhav and Kondalarao, 2004; Thillairajasekar *et al*., 2005; Ashok Prabhu *et al*., 2008; Saravanakumar *et al*., 2008; Rajkumar *et al*., 2009, Vengadesh Perumal *et al*., 2009; Rajkumar *et al*., 2012; Amarnath *et al*., 2013). Tuticorin, located at the southern tip of Gulf of Mannar, is facing rapid changes in the hydrobiological characteristics due to effluent discharge from various industries located nearby, which was studied in detail by Marichamy and Siraimeetan (1979) and Asha and Diwakar (2007). Information on the phytoplankton species availability in the inshore waters of Tuticorin has been summarised by Gopinathan and Rodrigo (1991). Similarly, Santhanam *et al.* (1994) elucidated the impact of *Trichodesmium* sp. bloom on the phytoplankton and productivity of Tuticorin inshore waters, and Kavitha *et al.* (2016) dealt with the plankton production of the fishing grounds off Tuticorin. In the present study, phytoplankton community structure and its relationship with selected physicochemical variables in the inshore waters of Tuticorin were analyzed.

Material and methods

Phytoplankton samples were collected from the surface waters every month between 06.30 – 10.00 hours from two stations employing the research vessel *Cadalmin- IV* during the period January to December 2008. The first station (St.1) was fixed at 5 m depth (N8°47.478'; E078°13.078') and the second station (St.2) at 10m depth (N08°47.286'; E078°14.257') in the inshore fishing ground of Tuticorin. Seawater samples (1000ml) were collected and preserved with Lugol's iodine solution, and phytoplankton was allowed to settle overnight. 100 ml of the settled samples were used for identification and quantification using a light microscope (make-Nikon Eclipse). Species identification was done based on relevant literature (Desikachary, 1959, 1987; Tomas, 1997). Cells of identified species present in 1ml sample of a counting chamber are enumerated in triplicate and calculated the density following the standard formula,

$$N = n \times v/V$$

Where N= mean cell number in 1ml of sample, v = volume of concentrate and V=volume of seawater filtered. The relative abundance of phytoplankton groups in percentage of the total number of plankton cells was then calculated from the total density and the density of each group.

Standard procedures were adopted for estimating the physicochemical parameters. In situ measurement of air and water temperatures were made using a high precision thermometer. Salinity was determined by Mohr's titration method (Grasshoff, 1983). Dissolved oxygen content and chlorophyll were estimated by Winkler method (Winkler, 1888). Nutrients were determined using Spectrophotometer (Genesis 5 model) as per the procedure of Grasshoff *et al.* (1999). Primary production was estimated by dark and light bottle method, and Winkler's method was employed for the estimation of oxygen, and the same was converted into carbon equivalent using a PQ of 1.25 for obtaining the gross production. Chlorophyll was estimated and calculated according to Parsons *et al.* (1984). Rainfall data were obtained from Tuticorin centre of Indian Meteorological Department. For convenience, data were pooled to four different seasons of three months each like summer (April, May and June); pre-monsoon (July, August, and September); monsoon (October, November, and December) and post-monsoon (January, February and March).

Species-wise, family-wise and class-wise variation in phytoplankton density and month-wise, season-wise variations in physicochemical variables were analysed using MS-excel. The statistical analysis, one-way analysis of variance ANOVA and correlation between all possible combinations of the physicochemical variables were tested using SPSS software (version 20; Chicago, USA). The diversity indices Shannon diversity index, H' (log2) (Shannon and Wiener, 1963); Margalef's richness index, d (Margalef, 1958) and Pielous evenness index, J' (Pielou, 1975) were applied to compare the phytoplankton diversity between season and depth. Recent taxonomic and phylogenetic diversity indices–taxonomic diversity index, Δ; average taxonomic distinctness index, Δ^*; and total phylogenetic diversity index, sPhi+ were also performed (Clarke and Warwick, 2001). The phytoplankton diversity data were fourth root transformed before analysis. The physicochemical variables were log transformed and normalized before calculating the resemblance using Euclidean distance for matching these with the phytoplankton. A dendrogram was drawn based on the Bray-Curtis similarity for knowing the grouping of phytoplankton diversity between season and depth (Clark,1999). Relationships between the seasonal abundance of phytoplankton and physicochemical variables were analyzed by correlation-based Principal component analysis (PCA). The component matrix with the value of eigenvector ($> \pm 0.45$) was selected and taken in the interpretation of results. All the univariate and multivariate analyses of data were done using PRIMER (Plymouth Routines in Multivariate Ecological Research) v.6.1.12 package developed by the Plymouth Marine Laboratory, UK (Clarke and Gorley, 2001) using the software.

Results and discussion

Phytoplankton species distribution and diversity

The seasonal and depth wise variation in the distribution of phytoplankton species in the inshore waters of Tuticorin are represented in Table 1. The present study recorded 69 species of phytoplankton (21 orders, 34 families, and 40 genera). Of these, 59 species (85.5%) were diatoms (18 orders, 29 families, and 35 genera) and ten species (14.5%) were dinoflagellates (3 orders, five families, and ten genera). Among the diatoms, the centric groups were dominating (62.7%) followed by pennate groups (37.3%). Classes Bacillariophyceae (9 orders, 13 families,

Table 1. Seasonal variation in the density (cells.L^{-1}) of phytoplankton species in the inshore waters of Tuticorin

Plankton species	Summer		Pre monsoon		Monsoon		Post monsoon	
	5m	10m	5m	10m	5m	10m	5m	10m
Bacillariophyceae								
Asterionella japonica	-	1x10^{3}	-	-	-	1x10^{3}	-	-
Thalassiothrix longissima	5x10^{3}	-	-	-	7x10^{3}	-	-	1x10^{3}
T. frauenfeldii	5x10^{3}	-	-	-	-	-	2x10^{3}	-
Pleurosigma elongatum	-	-	3x10^{3}	-	-	3x10^{3}	3x10^{3}	-
P. directum	4x10^{3}	-	2x10^{3}	-	-	-	2x10^{3}	-
Navicula distans	3x10^{3}	-	-	-	-	-	1x10^{3}	4x10^{3}
N. clavate	-	-	-	-	-	-	-	3x10^{3}
Surirella fluminensis	-	-	-	-	-	2x10^{3}	3x10^{3}	-
Mastogloia exilis	-	3x10^{3}	-	-	2x10^{3}	2x10^{3}	2x10^{3}	-
Striatella delicatula	2x10^{3}	1x10^{3}	-	-	1x10^{3}	2x10^{3}	-	2x10^{3}
Grammatophora undulata	2x10^{3}	-	-	-	-	-	-	-
Cocconeis littoralis	-	-	1x10^{3}	-	-	-	1x10^{3}	-
Gyrosigma balticum	-	-	5x10^{3}	-	-	-	-	-
Diploneis puella	-	-	4x10^{3}	-	2x10^{3}	-	-	-
Bacillaria paradoxa	5x10^{3}	-	-	-	4x10^{3}	3x10^{3}	5x10^{3}	-
Nitzschia sigma	-	-	-	-	1x10^{3}	4x10^{3}	-	-
N. longissima	5x10^{3}	-	-	-	-	5x10^{3}	4x10^{3}	-
N. closterium	-	-	-	-	2x10^{3}	1x10^{3}	3x10^{3}	-
N. seriata	-	-	-	-	-	-	1x10^{3}	-
Campylodiscus iyengarri	-	-	-	-	-	-	2x10^{3}	-
Rhaphoneis discoides	-	-	-	-	-	-	7x10^{3}	-
R. amphiceros	-	-	-	-	-	7x10^{3}	-	-
Rhabdonema spp	-	-	-	5x10^{3}	-	-	-	-
Mediophyceae								
Skeletonema costatum	-	1x10^{3}	1x10^{3}	1.4x10^{4}	-	7x10^{3}	-	6x10^{3}
Bellerochea malleus	-	1x10^{3}	-	-	-	1x10^{3}	-	-
Eucampia cornuta	-	-	3x10^{3}	4x10^{3}	1x10^{3}	-	-	2x10^{3}
Ditylum brightwellii	-	5x10^{3}	-	-	1x10^{3}	1x10^{3}	-	3x10^{3}
Hemiauls chinensis	-	2x10^{3}	-	-	-	-	-	-
Bacteriastrum varians	-	-	2x10^{3}	-	3x10^{3}	-	-	-
Cyclotella striata	-	-	1x10^{3}	5x10^{3}	5x10^{3}	3x10^{3}	-	-
Lauderia annulata	-	-	1x10^{3}	-	-	-	-	-
Bacteriastrum hyalinum	-	-	-	-	1x10^{3}	-	-	-
Leptocylindrus danicus	-	-	-	-	-	3x10^{3}	-	-
Lithodesmium undulatum	1x10^{3}	2x10^{3}	5x10^{3}	-	-	-	-	-
Biddulphia chinensis	-	2x10^{3}	-	8x10^{3}	8x10^{3}	3x10^{3}	-	-
B. mobiliensis	1x10^{4}	6x10^{3}	3x10^{3}	-	1x10^{4}	2x10^{3}	-	-
B. pulchella	-	1x10^{3}	3x10^{3}	-	-	-	-	-
Chaetoceros lorenzianus	2x10^{3}	3x10^{3}	-	2x10^{3}	-	-	-	-
C. peruvianus	-	2x10^{3}	5x10^{3}	-	-	-	-	-
C. indicus	1x10^{3}	4x10^{3}	-	7x10^{3}	-	-	-	1x10^{3}
C. didymus	3x10^{3}	2x10^{3}	2x10^{3}	6x10^{3}	-	-	-	-
C. affinis	2x10^{3}	1x10^{3}	3x10^{3}	-	-	-	-	5x10^{3}

C. diversus	4x10^{3}	1x10^{3}	-	6x10^{3}	-	1x10^{3}	-	-
C. subtilis	-	-	4x10^{3}	1.9x104	-	5x10^{3}	-	
Planktoniella sol	1x10^{3}	-	2x10^{3}	7x10^{3}	-	-	-	-
Ceratulina pelagica	1x10^{3}	-	-	1.1x104	-	-	-	-
Coscinodiscophyceae								
Actinoptchcus undulates	-	6x10^{3}	-	5x10^{3}	-	-	-	-
Triceratium dubium	-	-	4x10^{3}	-	-	2x10^{3}	-	-
T. alternans	-	-	-	-	-	3x10^{3}	-	-
Coscinodiscus concinnus	-	-	-	-	-	1x10^{3}	-	-
C granii	-	-	-	1x10^{3}	-	-	-	2x10^{3}
C. lineatus	-	-	-	7x10^{3}	5x10^{3}	3x10^{3}	-	-
C. marginatus	-	-	-	2x10^{3}	6x10^{3}	5x10^{3}	4x10^{3}	-
Rhizosolenia alata	-	-	3x10^{3}	-	4x10^{3}	-	-	-
R. cylindrus	-	-	4x10^{3}	6x10^{3}	-	-	-	-
R. imbricate	-	6x10^{3}	-	-	-	-	-	2x10^{3}
R. robusta	-	-	4x10^{3}	4x10^{3}	-	-	-	2x10^{3}
R. stolterfothii	-	7x10^{3}	2x10^{3}	-	-	-	2x10^{3}	3x10^{3}
Aulacodiscus sp.	-	2x10^{3}	-	1x10^{3}	-	2x10^{3}	1x10^{3}	+
Dinophyceae								
Amphidinium cateri	1.1x10^{4}	-	-	2x10^{3}	-	-	-	-
Ceratium candelabrum	-	-	-	1x10^{3}	-	-	1x10^{3}	-
C.tripos	-	-	-	4x10^{3}	-	-	5x10^{3}	-
C.tripos var. ponticum	-	-	-	2x10^{3}	-	-	2x10^{3}	-
C. buceros	-	-	-	2x10^{3}	-	-	-	-
C. fusus	2x10^{3}	-	-	2x10^{3}	-	-	-	-
C. furca	-	-	-	-	-	1x10^{3}	-	-
Amphisolenai sp.	-	-	-	3x10^{3}	-	-	3x10^{3}	-
Podolampus spinifera	-	-	+	-	1x10^{3}	2x10^{3}	-	-
Diplopsalopsis bomba	-	-	-	-	1x10^{3}	-	-	-

16 genera and 23 species) and Mediophyceae (6 orders, 11 families, 14 genera and 23 species) were the dominant group constituting 33.3% each of the total phytoplankton. 18.84% of the phytoplankton belonged to the class Coscinodiscophyceae (13 species) and Dinophyceae constituted 14.49% of the population, comprising ten species was the least represented class (Fig.1). The overall density of the phytoplankton was comparatively higher at 10 m depth with a mean of 2.14x10^{4}±0.4x10^{4}cells.L^{-1} and 3.37x10^{4}±0.9x10^{4}cells.L^{-1} at 5 m and 10m depth respectively.

The 69 numbers of phytoplankton species reported in the present study is much higher than the 46 species reported earlier form the offshore waters of Tuticorin (Kavitha *et al.*, 2016) and is in concordance with the 69 species observed in Palk Bay (Sithik *et al.*, 2009). In the present study, the dominance of diatom (85.5%) was noticed among the phytoplankton population. The dominance of diatoms in the inshore waters of Gulf of Mannar and Palk Bay area have been reported earlier (Subramanyan *et al.*, 1975; Anbhazhagan, 1988; Gopinathan and Rodrigo, 1991; Sampathkumar, and Kannan, 1998; Jayasiri and Priyadharshini,

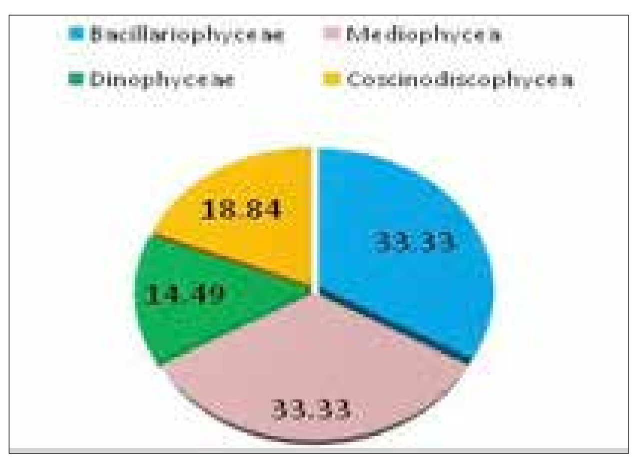

Fig. 1. Relative abundance (%) of phytoplankton classes in the inshore waters of Tuticorin

2007; Sithik *et al.*, 2009; Choudhary and Pal, 2010 and Kavitha *et al.*, 2016).

The phytoplankton population exhibited distinct seasonal variations, in both diversity and density, following the seasonal changes in physicochemical variables. 43 numbers of phytoplankton species were noticed during the pre-monsoon season followed by 40 numbers during the monsoon period. During summer and the post-monsoon months, phytoplankton species were 39 and 37 numbers respectively. Among the various classes, Dinophyceae, Mediophyceae, and Coscinodiscophyceae species abundance were higher during the pre-monsoon periods, whereas Bacillariophyceae flourished more during the post-monsoon months (Fig. 2). The mean density of phytoplankton was highest ($1.49x10^5 \pm 770.1$ cells.L^{-1}), noticed at 10 m depth during the pre-monsoon followed by $6.9x10^4 \pm 499.3$ cells.L^{-1} at 5 m depth during the summer months.

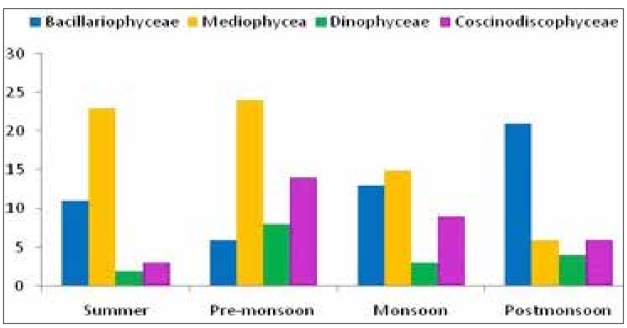

Fig. 2. Seasonal variation in the phytoplankton class-wise distribution

The results of the phytoplankton diversity analysis to discern the species status for different season and depth are given in Table 2. The Shannon diversity index, H'(Log2) provides the realistic estimate of biodiversity, and it was found to be highest during the monsoon season at 10m depth (4.51) followed by 4.37 at 5 m depth during the pre-monsoon season. The lowest diversity index was of 3.39, reported during the monsoon season at 5 m depth. This result was supplemented by Pigou's evenness or equitability J' was highest during the pre-monsoon season at 5m depth (0.97). The Simpson index, (l-lambda) gave information on the dominance of the species and was found to be maximum (0.11) at 10 m depth during the post-monsoon season. The species richness index, Margalef's richness (d) was highest (2.32) during the monsoon season at 10 m depth and lowest of 1.06 during the post-monsoon season at 10 m depth. The analysis was done with the newly introduced biodiversity indices, which have an additional statistical framework for comparison of one sample with another. Accordingly, the highest values of various indices like taxonomic diversity index (92.25), the total phylogenetic diversity index (1760), the average taxonomic distinctness index (2490.8) were noticed during the monsoon months at 10m depth and lowest seen during the post-monsoon months at 10 m depth. As per the conventional as well as the newly introduced biodiversity analysis, 10 m depth station, especially during the monsoon season is more stable due to the richness in bio-diversity of algal species and the same station during post-monsoon are less stable due to the lowest diversity indices.

As per the Bray-Curtis similarity coefficient analysis, the highest similarity was found during monsoon season between 5m depth and 10 m depth with 50.6% similarity among themselves, and the low of 15.37% was found between monsoon and post–monsoon at 10m depth (Table 3). The cluster analysis (dendrogram) revealed grouping of phytoplankton species with respect to season, into three major clusters, i.e., between 5 m and 10 m during monsoon. The highest grouping (50.6%) was noticed between the phytoplankton species occurring during monsoon irrespective of depth (Fig. 3).

In the present study, as per the analysis of diversity indices, monsoon season was found to be the favourable season for phytoplankton growth and reproduction. This phenomenon might occur probably due to the congenial physicochemical conditions especially moderate temperature, light intensity, salinity and high nutrient content of sea water. This observation is in concordance with the findings of Iyengar and Subrahmanyan (1944) and Subramanyan (1959) on

Table 2. Diversity indices of phytoplankton species in the inshore waters of Tuticorin

Depth	Season	S	N	d	J'	H'(log2)	l-Lambda	Delta+	sDelta+	sPhi+
5m	SUMa	19	69000	1.62	0.92	3.89	0.08	87.49	16662.2	1180
5m	PRMb	23	67000	1.98	0.97	4.37	0.05	87.51	2012.73	1280
5m	MONc	19	65000	1.62	0.90	3.83	0.08	92.16	1751.11	1260
5m	POMd	20	57000	1.74	0.95	4.09	0.07	87.68	1753.68	1260
10m	SUMa	20	48000	1.76	0.93	4.04	0.07	82.84	1656.84	1140
10m	PRMb	28	149000	2.27	0.93	4.45	0.06	88.41	2475.56	1400
10m	MONc	27	73000	2.32	0.95	4.51	0.05	92.25	2490.77	1760
10m	POMd	12	33000	1.06	0.95	3.39	0.11	90.61	1087.27	840

a: Summer; b: Pre-monsoon; c: Monsoon; d: Post-monsoon

Table 3. Bray-Curtis similarity for phytoplankton species during different seasons and depths.

Season	5m Summer	5m Pre-monsoon	5m Monsoon	5m Post-monsoon	10m Summer	10m Pre-monsoon	10m Monsoon	10m Post-monsoon
5m Summer								
5m Pre- monsoon	26.92							
5m Monsoon	22.00	27.36						
5m Post-monsoon	25.41	18.32	20.91					
10m Summer	38.63	35.57	25.12	9.44				
10m Pre-monsoon	31.20	33.63	21.26	27.73	35.34			
10m Monsoon	21.49	19.02	50.55	33.84	39.87	24.60		
10m Post-monsoon	30.33	27.53	22.85	5.55	35.28	32.71	15.37	

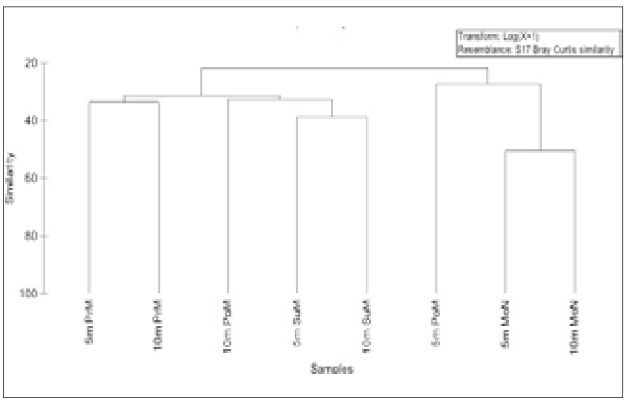

Fig. 3. Dendrogram of phytoplankton species recorded during different seasons

the ideal physicochemical conditions (fall in temperature to optimum levels from 32-33°C to 24-25°C; salinity from 35 to 31 ppt, besides high nutrients) for the reproduction and multiplication of phytoplankton. Levy *et al.* (2007) also indicated higher phytoplankton productivity during the cooling monsoon season in their studies. Cloern *et al.* (1985) also appraised that freshwater influence associated with monsoon is known to have a profound effect on phytoplankton biomass, productivity, and community composition. Similarly, Gopinathan and Rodrigo (1991); Gomes *et al.* (2000); Madhu *et al.* (2002); Madhupratap *et al.* (2003) and Madahav and Kondalaro (2004) also indicated that nutrient inputs from river runoff during monsoon as the reason for increased phytoplankton production in the coastal waters of Bay of Bengal.

Among the phytoplankton species, the class mediophyceae were the prominent group in Tuticorin inshore waters as the class was represented by the first four major species. *Biddulphia amobiliensis* was the most dominant species with the highest density of 3.1x10^4 cellsL^{-1} observed throughout the study period. *Skeltonema costatum*, *Chaetoceros subtilis*, and *Biddulphia chinensis* were the second, third and fourth primary species with a density of 2.9 x10^4 cellsL^{-1}, 2.8 x10^4cells.L^{-1} and 2.1 x10^4 cells.L^{-1} respectively. Kavitha *et al.* (2016) also reported the dominance of *Biddulphia* sp. and *Skeltonema costatum* in the offshore waters of Tuticorin.

In the present study, it was observed that the species composition of phytoplankton community varied based on the physicochemical variables of the prevailing ecosystem. The predominance of species like *Pleurosigma directum*, *Biddulphia mobiliensis, Amphidinium cateri*, *Ditylium brightwelli* and *Actinoptchcus undulates* were noticed during summer months. Species such as *Coscinodiscus marginatus*, *Thalassiothrix longissima*, *Cyclotella striata* were dominant during the monsoon months. Many species like, *Planktoniella sol, Rhizosolenia stolterfothii*, *Rhizosolenia imbricate*, *Skeltonema coastatum*, *Biddulphia chinensis*, *Coscinodiscus lineatus*, *Ceratulina pelagica* and *Cyclotella striata* aggregated more during pre-monsoon months and *Thalassiothrix frauenfeldii*, *Pleurosigma elongatum*, *Bacillaria paradoxa*, *Rhaphoneis discoides* gathered during post-monsoon months. Seasonal variation in the species composition observed in the present study is based on species level adaptation to the changes in physicochemical variables as indicated by Sampathkumar *et al.* (2015). Robertson and Blabber (1992) also indicated that shift in species composition and dominance of phytoplankton could be altered by a range of mechanisms including environmental and biological variables.

Physicochemical variables and influence on phytoplankton

The seasonal variations in the mean values of the physicochemical variables obtained in the inshore waters of Tuticorin are given in Table 4. Not much variation was observed in the air and sea surface temperature between the two depths. At 5 m depth, the air, as well as the sea surface temperatures (SST), were minimum (25 and 27°C) during the post-monsoon period and maximum (31 and 30.8°C) during the pre-monsoon season. At 10 m depth, summer months recorded the minimum of both air and water temperatures (26.2 and 27°C), and the highest air temperature (31.2°C) was reported during pre-monsoon period and sea surface temperatures of (31°C) during monsoon months. The seasonal difference was statistically significant for both air and water temperatures ($P<0.001$). In the present study, the SST has been influenced by the air temperature and a high positive correlation was also noticed between the air and water temperatures ($P<0.01$). This observation is in concordance with the findings of Rajapandian *et al.* (1990); Sridhar *et al.* (2006); Yogesh and Geetha (2012) and Kavitha *et al.* (2016) in Gulf of Mannar area.

The influence of northeast monsoon was more evident at 5 m depth, as the salinity was comparatively lower with wider fluctuations. Salinity varied between 25.51 and 37 ppt at 5 m depth and between 28.69 to 35.5 ppt at 10 m depth. The mean salinity was 31.4±1.13 ppt and 32.01±0.8 ppt at 5 m and 10 m depths respectively (Table 4). Significant difference was noticed in the seasonal variation at both depths ($P<0.001$). The lower salinity, especially during monsoon season, was reported in many of the previous studies (Sampathkumar and Kannan, 1998; Asha and Diwakar, 2007; Kavitha *et al.*, 2016). pH was comparatively lower at 5 m depth and more or less standard at 10 m depth. The lowest pH of 7.5 at 5 m depth was recorded during monsoon season and highest of 8.27 at 10 m depth during pre-monsoon. The fluctuation in pH during monsoon might be due to freshwater influx into the shallow inshore water of Tuticorin (Asha and Diwakar, 2007 and Bradeeswaran *et al.*, 2007). At both the stations, dissolved oxygen was comparatively better during monsoon season and lower during post-monsoon season. The mean value was 3.71±0.28 $ml.L^{-1}$ and 3.96±0.32 $ml.L^{-1}$ at 5 m and 10 m depth respectively. The seasonal variation was statistically significant ($P<0.001$).

The gross primary productivity was comparatively higher at 5m depth with the highest of 4.03mg C $m^{-3}day^{-1}$ during December. The mean value was 0.67 ±0.12mg C $m^{-3}day^{-1}$ at 5 m depth and 0.03±0.01mg $Cm^{-3}day^{-1}$ at 10 m depth. At both stations, higher values of chlorophyll were recorded during monsoon months with the highest of 2.18 $mg.m^{-3}$ and 1.62 $mg.m^{-3}$ recorded at 5 m and 10 m depth respectively. Nitrite concentration was greater during the monsoon and post-monsoon season at 5 m depth and lower during the summer months at both depths. Phosphate level was higher during the summer and the post-monsoon period and lower during the monsoon season. Silicate concentration was higher at both depths during pre-monsoon season and lower during monsoon season. In general, all the nutrients except nitrite were comparatively lower during the monsoon period. The higher concentration of phosphate during summer reported in the present study might be due to the release of phosphate from sediments or by the decaying matter as reported by Sridhar *et al.* (2006). Comparatively higher nitrite during monsoon might have resulted from the terrigenous input of land runoff during monsoon (Asha and Diwakar, 2007). The lower silicate during monsoon indicate the utilization of silicate for phytoplankton growth. The increased chlorophyll concentration and primary productivity during monsoon in the present study also suggest the favourable environmental conditions for phytoplankton growth during the monsoon season. Fisher *et al.* (1992) appraised that the limiting nutrient concentration varies with season, location and community structure. The mean nutrient values recorded were highest 4.97±2.4 $\mu gL^{-1}$for nitrite at 5m depth during the post-monsoon season, 1.37±0.56 μgL^{-1} for phosphate at 10 m depth during summer and 3.5±2.5 μgL^{-1} for silicate at 10m depth during pre-monsoon season respectively. Only the variation in phosphate concentration was statistically significant for different season ($P<0.001$). Comparatively higher silicate content than that of other nutrients noticed in the present study is similar to the observation made by Sampathkumar *et al.*, 2015. The silicate concentration has significantly affected the growth of phytoplankton in the inshore waters of Tuticorin ($P<0.01$). Gopinathan and Rodrigo (1991) and Mishra *et al.* (1993) also reported the utilization of silicate especially by the diatoms in Tuticorin waters, during the monsoon season. In the present

Table 4. Seasonal variations in the mean (±SE, n=12) values of the physicochemicalparameters in the inshore waters of Tuticorin

Hydrological parameters	Summer		Pre-monsoon		Monsoon		Post- monsoon	
	5m	10m	5m	10m	5m	10m	5m	10m
AT (°C)	29±0.57	27.6±1.14	30.5±0.28	31.1±0.1	29.3±0.89	30.2±0.78	26.5±0.9	27.2±1.01
SST(°C)	29.7±0.67	27.4±0.33	29±0.6	29.5±0.5	29.9±0.52	31±0.9	27.1±0.06	27.4±0.4
D.O (ml L^{-1})	4.12±0.27	4.58±0.04	4.61±0.2	4.45±0.23	3.56±0.7	3.87±0.8	2.53±0.05	2.316±1.8
Salinity	31.9±3.05	33.5±1.47	32.9±2.2	32.8±2.8	28.1±1.3	29.6±0.72	32.9±2.2	33.5±1.9
P^H	7.5±0.02	8.2±0.07	8.0±0.06	8.1±0.17	7.8±0.17	8.15±0.03	7.9±0.07	8.18±0.09
GPP (mg C $L^{-1}day^{-1}$)	0.81±0.41	0	0.13±0.01	0.15±0.08	1.47±1.3	0	0.24±0..2	0
Total Chlorophyll ($\mu g.L^{-1}$)	0.19±0.06	0.20±0.02	0.62±0.31	0.46±0.21	0.81±0.7	0.78±0.43	0.35±0.18	0.204±0.03
Nitrite ($\mu g.L^{-1}$)	0.57±0.19	0.95±0.02	0.213±0.09	0.075±0.002	2.3±1.9	0.220±0.08	4.97±2.4	0.95±0.01
Phosphate ($\mu g.L^{-1}$)	1.13±0.26	1.37±0.56	0.83±0.08	0.76±0.51	0.3±0.18	0.353±0.10	1.13±0.45	1.36±0.56
Silicate ($\mu g.L^{-1}$)	2.9±0.7	2.5±1.5	3.0±0.6	3.5±2.5	1.92±0.04	1.67±0.3	2.3±0.3	2.5±1.5

study, the higher relative abundance of diatom throughout the sampling period could be due to the relatively high silicate concentration and faster growth rate of diatoms as indicated by Egge and Aksnes (1992). The rainfall data showed maximum showers during monsoon months of October–November months followed by February and March.

As per the principal component analysis, the extracted PC1, PC2, PC3, PC4 & PC5 explained 39.0%, 31.7%, 14.6%, 7.1% and 4.2% of variation in physicochemical parameters and phytoplankton abundance (Table 5). The correlation matrix loading of the significant principal components for the four seasons are shown in Table 6. The result of the PC1 revealed that atmospheric temperature, sea surface temperature, rainfall, dissolved oxygen are positively influencing the phytoplankton. The variables, like salinity, pH, NO_2, PO_4, and SiO_3 are negatively impacting explained by 39.0% of the total variance along the first principal axis (Table 6). The result of the PC2 revealed that rainfall, NO_2, PO_4, are positively influencing the phytoplankton, whereas variables like atmospheric temperature, sea surface temperature, salinity, dissolved oxygen, pH, and SiO_3 are negatively affecting the phytoplankton, which is well explained by the 31.7% of the total variance (Table 6). Sampathkumar *et al.* (2015) also indicated that variables like sea surface temperature and dissolved oxygen influence the seasonal pattern of phytoplankton population in the south-east coast of India. The present study also reports the role of sea surface temperature, dissolved oxygen and rainfall on phytoplankton distribution and diversity in the inshore waters of Tuticorin. Less spatial variation in the phytoplankton productivity was observed in the present study, however it is confirmed that the population density of phytoplankton is more impacted by the seasonal fluctuation in the physicochemical variables especially due to the influence of northeast monsoon in Tuticorin inshore waters. Owing to the rising industrial growth in and around Tuticorin coastal belt, the study also warrants the need for continuous assessment of the phytoplankton population characteristics and the physicochemical variables influencing them.

Table 5. Eigen values and percentages of explained variability

PC	Eigen values	% variation	Cum % variation
1	4.68	39.0	39.0
2	3.80	31.7	70.6
3	1.75	14.6	85.2
4	0.85	7.1	92.3
5	0.499	4.2	96.5

Table 6. Correlation based principal component analysis for physicochemical variables.

Variable	PC1	PC2	PC3	PC4	PC5
Plankton density	-0.063	-0.366	-0.085	0.685	0.176
AT	0.245	-0.425	-0.062	0.066	0.04
SST	0.386	-0.223	-0.004	-0.177	0.3
Salinity	-0.447	-0.092	-0.061	0.016	-0.066
Rainfall	0.253	0.378	-0.246	0.164	0.245
DO	0.058	-0.417	0.154	-0.298	-0.59
pH	-0.121	-0.048	-0.699	0.045	-0.179
NO_2	-0.039	0.395	0.183	0.452	-0.521
PO_4	-0.442	0.079	0.11	-0.183	0.129

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