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Seasonal variation of physico-chemical parameters and phytoplankton diversity in the Muthukuda mangrove environment, southeast coast of India

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Original Article

Abstract

Physico-chemical characteristics and phytoplankton diversity of three Stations *viz.,* Open sea, mangrove and freshwater zone of Muthukuda region of Palk Strait, southeast coast of India for the period of two years from January 2012 to December 2013 were analyzed. The seasonal results showed high concentration all nutrients (phosphate, nitrate, nitrite, ammonia and silicate) at Station 3 (freshwater zone). Similarly, high Chl *a*, phytoplankton density and species richness values were noticed at open sea (Station 1), high species diversity values were observed at Station 2 (mangrove) while high species evenness were found at Station 1. Rotation mode varimax factor analyses were applied separately to open sea (Station 1), mangrove (Station 2) and freshwater zone (Station 3) data sets due to existing stratification in the water column caused by river water inflow. This helped us to understand the interrelationships between the variables and to identify the probable source components to explain the environmental status of the area. Four factors (each for Station1 and Station 3) and five factors (Station 2) were found responsible for variance (79.7% in Station 1, 80% in Station 2 and 77.6% in Station 3) in the Palk Strait coastal waters of Muthukuda region.

Keywords: *Physico-chemical characteristics, Muthukuda mangrove environment, phytoplankton, diversity, rotation mode factor analysis.*

Introduction

Mangroves are essential ecosystem for fisheries and other activities (Kawabata *et al*., 1993). In between land and sea, mangroves serve as an intermediary zone (Bardarudeen *et al.,* 1996). Phytoplankton is one of the biological components from which the energy is transferred to primary consumers like zooplankton and secondary consumers like shellfish and finfish through food chain (Saravanakumar *et al.,* 2008a; Mathivanan *et al.,* 2007). The pelagic algal communities make an important contribution to the smooth functioning of coastal ecosystem. Plankton in mangrove habitats contributes from 20 to 50% total fish productivity (Robertson and Blabber, 1992). Productivity and health of mangrove environment is manifested through productivity of the phytoplankton and zooplankton as primary and secondary producers. Phytoplankton species distribution shows wide-ranging of spatio-temporal variations due to the discrepancy effect of hydrographical factors on individual species and they serve as good indicators of water quality and pollution (Liu *et al.,* 2004).

High productivity and larval maintenance in mangrove-lined estuaries have generally been attributed to the abundant planktonic food supply (Robertson and Blabber, 1992). Larval and juvenile stocks can sustain by using primary food source of organic materials originating from decay of mangrove leaf. Kannan and Vasantha (1992) have suggested that variation of physical and chemical characteristics on planktonic communities in mangrove waters are more prominent than the near shore coastal environment, resulting in seasonal changes of planktonic species composition and densities. The same time periodic shift of planktonic communities is an important biological factor in the mangrove ecosystem.

In India, the Palk Bay has landmarks between the Point Calimere and Rameshwaram island as northern and southern borders, respectively. The eastern part of the bay is connected with Srilanka whereas the western part of the bay is the border of the Indian subcontinent. The Palk Bay region, especially Muthukuda coastal area near Mimisal, has not been paid much attention in the literature.

Vasudevan *et al.* (2012) only made an attempt on short term investigations on vertical distribution of physico-chemical and phytoplankton biomass in Pambanar estuary. Though, considerable attention has been paid in the recent years to study the physicochemical parameters of the coastal waters around India in order to ascertain the water quality and biodiversity of plankton, very little information is available on these aspects of the Muthukuda region of Palk Bay. Hence, the present study was undertaken on the water quality and phytoplankton diversity analyses for 24 months (2012-2013).

Material and methods

Study area, sampling and analyses

Muthukuda (Lat. 9º 51′ 48″ N; Long 79º 7′ 15″ E) is a coastal village located near the town of Mimisal in the Palk Bay region of the Pudukottai district of Tamil Nadu. The samples (surface water samples) were collected from the three Stations and the Station 1 is open sea (9º 51′ 37″ N, 79º 8′ 0.02″ E) with low waves activities; Station 2 are mangrove zone (9º 51′ 38″ N, 79º 8′ 1.57″ E) with various habitats like mangroves, seagrass bed; and Station 3 are freshwater zone (9º 51′ 39″ N, 79º 8′ 49.4″ E) received huge amount of enriched water during monsoon season. The water samples (2 l) were collected in three Stations by using clean polythene bottles and kept in an ice box and transported immediately to the laboratory for analyses of physico-chemical, nutrients and biological characteristics. The atmosphere and surface water temperature was measured using the centigrade thermometer and the pH was measured using a portable bench top electrode pH meter. Water transparency was analyzed by using Secchi disk. Hardness of water is a measure of the total concentration of the calcium and magnesium ions expressed as calcium carbonate by using EDTA as a titrant. Dissolved Oxygen (DO) was measured by Winkler's titrimetric method (Grasshoff *et al.*, 1999).The precipitate of fixed dissolved oxygen was broken down by acidification and the liberated iodine was titrated with standard sodium thiosulphate solution, where the end point was marked using starch as an indicator.

The water samples were filtered using a millipore filtering system (MFS) and analyzed for inorganic nutrients. The inorganic nutrients ($PO^{3+}{}_{4}$, NO^{-3}, NO^{-2}, NH^{+3}, SiO_{3}^{2-}) in the water were analyzed according to Strickland and Parsons (1972) and Jenkins and Medsker (1964). Phosphate was measured by the treatment of water sample with acidified molybdate reagent to give phospho-molybdate complex which was then reduced to a highly colored blue compound (phospho molybdenum blue) using ascorbic acid as a reducing reagent. For the analyses of nitrate, the reaction between the alkaloid, brucine, and nitrate in acid medium produces a yellow color measured by standard spectrophotometric procedures (Jenkins and Medsker, 1964). The nitrite was determined after diazotising it with sulfanilamide and coupling with N (1-Naphthyl)-ethylene diamine-dihydrochloride. Ammonia—Nitrogen was determined by the indophenol blue method based on the principle that in a moderately alkaline medium, ammonia was allowed to react with hypochlorite in catalytic amounts of nitroprusside to form indophenol blue. The determination of Silicate-Silicon was estimated by the formation of a yellow silicomolybdic acid, when a nearly acidic sample was treated with a molybdate reagent. The yellow silicomolybdic acid was reduced to an intensely blue coloured complex using ascorbic acid as the reductant.

Collection of phytoplankton were carried out from the surface water, by towing the phytoplankton net (mouth diameter 0.35 m) made up of bolting silk cloth (No. 28, mesh size 48 μm), for half an hour. The collected samples were preserved in 5% neutralized formalin for further analysis. For the quantitative analysis of phytoplankton, the settlement method described by Sukhanova (1978) was adopted. Numerical plankton analysis was carried out by using light microscope (Magnus MLX-B). Phytoplankton was identified using the standard methods (Desikachary, 1987; Taylor, 1976; Anand *et al.*, 1986). The phytoplankton diversity, richness and evenness were analyzed using PRIMER (Ver. 6.1.11) bio-diversity software. The following standard formulas are used to calculate species indices: species diversity (H′) was calculated according to Shannon and Wiener (1949) formula: $H' = \Sigma p_{i} \log 2\ p_{i}$, where pi = is the quantity of the plankton samples related to the ith species. Species richness (S) has been calculated following formula derived by Simpson (1949): ($S-1$)/LogeN, where is S= total number of phytoplankton species; N= the natural logarithm of the total number of individuals of all the species in the phytoplankton sample. Species evenness was calculated using following formula derived by Pielou (1996): $J' = H'$/Log2S, where is, H'= Phytoplankton diversity index and S=Total number of phytoplankton species.

Statistical analyses

Correlation coefficients (r) were calculated for phytoplankton density and physico-chemical parameters were made for hydrological parameters in relation to Stations and months. The data collected was subjected to statistical analysis to understand the influence of various parameters on phytoplankton diversity of the system. The statistical approaches such as Principle Component Analysis (PCA), also called the Factor analysis have been used by several researchers for deriving the significance of specific parameters among the data generated (Helena *et al.,* 2000; Wunderlin *et al.*, 2001; Simenova *et al.,* 2003; Singh *et al.,* 2004 and Shirodkar *et al.,* 2009). Rotation mode (sorted) factor analysis resulted in Eigen values, percentage of variance and cumulative percentage for total Stations in the system, allowing inter parameter relation and variation at one Station to another Stations. Factor analyses of the present data set of the mangrove water from Muthukuda were further sorted by contribution of less significant variables (<0.4 factor score). A varimax rotation of different varifactors with factor loading was calculated using eigen value greater than 1 and sorted by the results having values greater than 0.4, based on significant influence (Sahu *et al.,* 1998; Panigraghy *et al.,* 1999 and Rath*et al.,* 2000). Rotation of the axis defined by factor analyses produced a new set of factors, each one involving primarily a sub set of the original variables with a little overlap as possible so that original variables are divided into groups. The factor loading was classified as per Liu *et al.* (2003), who categorized the factor loadings as "strong", "moderate" and "weak" corresponding to absolute loading values of >0.75 as "strong", of 0.75-0.5 as "moderate" and of 0.50 – 0.40 as "weak". All the statistical analyses were made using SPSS software (Version 16.0 for windows, SPSS, Chicago, IL, USA).

Results

Physico-chemical characteristics

Environmental factors play a key role and it influences

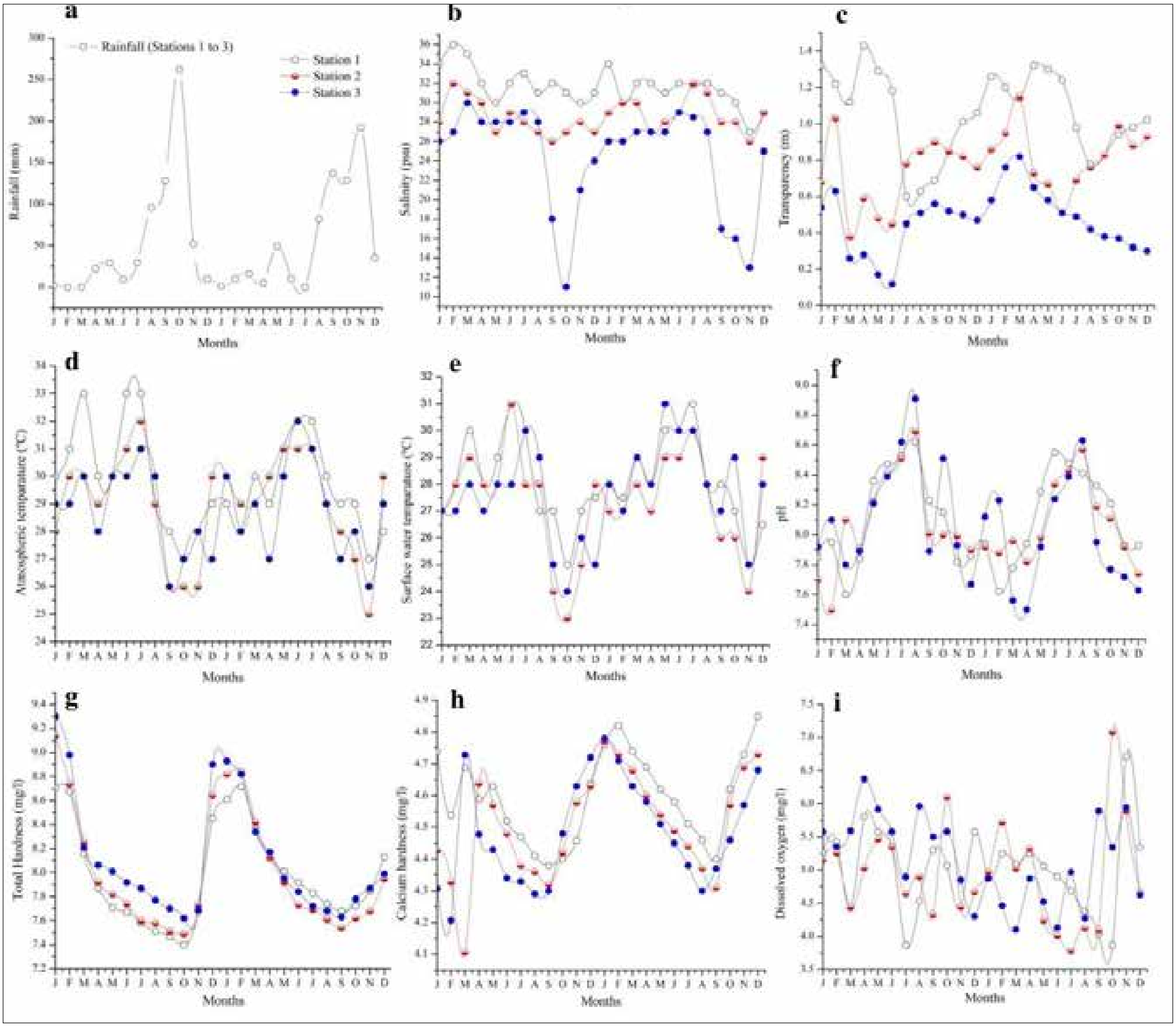

Fig.1. Seasonal variations of physico-chemical parameters during post monsoon 2012 to monsoon 2013

growth, abundance and diversity of phytoplankton in the marine environment and also showed wide temporal and spatial differences. Variations in physico-chemical characteristics of the Muthukuda seawater from surface are shown in Fig. 1 (a–i).The recorded rainfall was between 0.66 and 118.66mm with the lowest rainfall noticed during 2012 post monsoon season and the highest during 2013 monsoon season. Salinity ranged between 18 and 35psu recording the maximum (35psu) during 2012 post monsoon season at Station 1 and minimum (18psu) during 2013 monsoon season at Station 3 (Fig. 1b). Water transparency varied from 0.19 to 1.3m, and the minimum (0.19m) was recorded at Station 3 in 2012 summer season while the maximum (1.3m) in 2012 summer season at Station1 (Fig. 1c). Atmospheric temperature varied from 27.33 to 31.33ºC. The maximum (31.33ºC) was notice at Station 1 in 2012 post monsoon season and minimum (27.33ºC) in 2012 monsoon season at Station 2 and 3 (Fig. 1d). The highest surface water temperature (29.67ºC) was recorded during 2013 summer season at Station 3 whereas the lowest (25ºC) in 2012 monsoon season at Station 3(Fig. 1e).

The maximum (8.47) pH was recorded at Station 3 during 2012 pre monsoon season and minimum (7.71) at Station 3 in 2013 monsoon season respectively (Fig. 1f). Total water hardness varied from 7.52 to 8.83 (mg/l) with maximum (8.83mg/l) in 2012 post monsoon season at Station 3 and minimum (7.52mg/l) at Station 1 in 2012 pre monsoon season (Fig. 1g) while the calcium hardness varied from 4.29 to 4.77 (mg/l) with minimum (4.29 mg/l) at Station 2 and maximum (4.77mg/l) at Station 1 during 2012 post monsoon season and 2013 post monsoon season respectively (Fig. 1h). The recorded variation in dissolved oxygen content ranged from 4.00 to 5.96mg/l with minimum in 2013 pre monsoon season at Station 2 and the maximum in 2012 at Station 2 (Fig. 1i).

The concentrations of inorganic nutrients viz., phosphate (4.16-13.98µmol L-1), nitrate (7.43-20.55µmol L-1), nitrite (0.15-1.86µmol L-1), ammonia (0.27-3.47µmol L-1) and silicate (20.31-48.52µmol L-1) varied independently. The minimum concentration of inorganic phosphate (4.16µmol L-1) was recorded during 2012 summer season at Station 1 and maximum (13.98µmol L-1), during 2013 monsoon season at Station 3 (Fig. 2a). The maximum (20.55µmol L-1) nitrate was recorded in 2013 monsoon season at Station 3 and minimum (7.43µmol L-1), in 2012 summer season at Station 1 (Fig. 2b), while the nitrite content recorded the minimum (0.15µmol L-1) during 2012 post monsoon at Station 2 and maximum (1.86µmol L-1) during 2013 pre monsoon season at Station 3 (Fig. 2c). The maximum (3.47µmol L-1) concentration of ammonia was recorded during 2012 pre monsoon season at Station 3 and minimum (0.27µmol L-1) during 2012 pre monsoon season at Station 2 (Fig. 2d). The reactive silicate concentration registered its maximum (48.52µmol L-1) in November 2013 monsoon season at Station 3 and minimum (20..31µmol L-1) in 2013 post monsoon season at Station 1 (Fig. 2e).

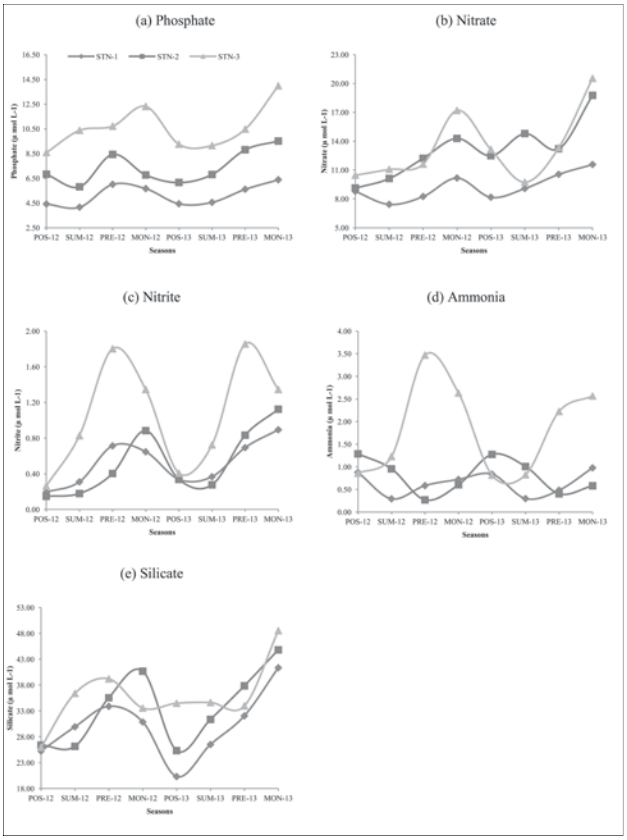

Fig.2. Seasonal variations of nutrients concentrations during post monsoon 2012 to monsoon 2013

Phytoplankton diversity

In the present investigation, totally 64 species of phytoplankton

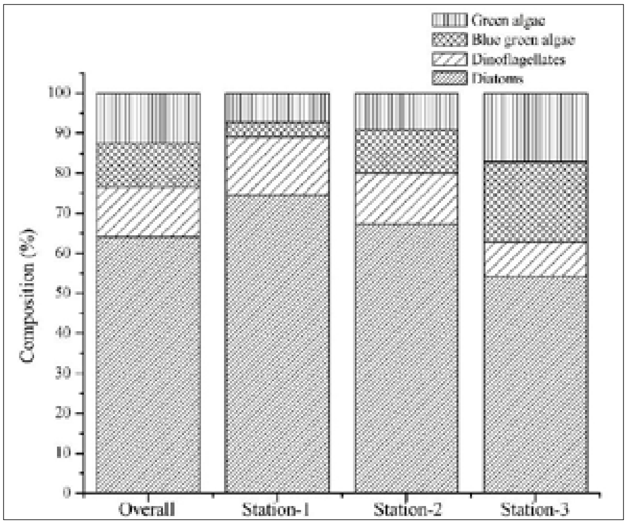

Fig. 3. Percentage composition of phytoplankton in Muthukuda coastal waters during post monsoon 2012 to monsoon 2013

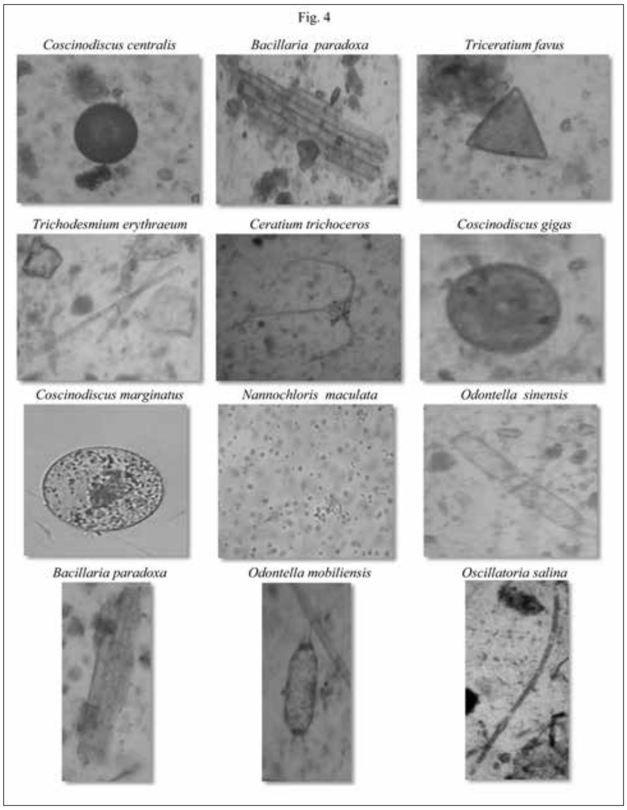

Fig.4. Some photographs of observed phytoplankton in Muthukuda coastal water

were recorded for the period of two years. Of these, 64% composed by diatoms, 12 % by dinoflagellates, 11% by blue green algae and 13% by green algae (Fig. 3). At Station 1, total of55 species were recorded, among these 75% were diatoms, 14% by dinoflagellates, 4% by blue green algae and 7% by green algae (Fig. 4). 67% of diatoms, 13% by dinoflagellates, 11% by blue green algae and 9% species by green algae with total of 55 species were recorded at Station 2. Only 35 species were recorded at Station 3, consisting of 54% by diatoms, 9% species by dinoflagellates, 20% by blue green algae and 17% by green algae.

Among the recorded phytoplankton, species such as *Coscinodiscus centralis, C. gigas, Amphora* sp., *Nitzschia longissima, Odontella mobiliensis, Bacillaria paradoxa, Ceratium tripos, Trichodesmium erythraeum, Oscillatoria salina, Chlorella marina, Picochlorum maculatum (Nannochloris maculate)*, *Chlorella vulgaris* were found to be abundant (Table 1). The recorded ranges of phytoplankton density (cells/l) were 48, 783-75,796;47, 149-73,996 and 13,576-37,562 at Station 1, 2 and 3 respectively (Fig. 5a). The minimum (13,576 cells/l) population density was recorded at Station 3 during 2013 monsoon season and maximum (75,796 cells/l) at Station 1 during 2012 summer season. Percentage contribution of each group of phytoplankton was in the following order: Bacillariophyceae> Chlorophyceae> Dinophyceae> Cyanophyceae. Among the three Stations, the species diversity, species richness and species evenness was noticed between 1.01-3.42, 0.42-0.90 and 0.73-0.96 (Fig. 5b-

Table 1. List of phytoplankton species recorded in Muthukuda mangrove environment during January 2012-December 2013

Species Name	St.			Species Name	St.		
	1	2	3		1	2	3
BACILLARIOPHYCEAE				*Stephanopyxis palmeriana*	+	-	-
Amphora sp.	+	+	+	*Stephanopyxis* sp.	+	+	-
Asterionellopsis glacialis	+	+	+	*Thalassiosira reticulatum*	+	+	-
Bacillaria paradoxa	+	+	+	*T. mobilienis*	+	-	-
Bacteriastrum sp.	+	+	+	*Thalassiothix longissima*	+	+	-
Bacteriastrum delicatulum	+	+	-	*T. frauenfeldii*	+	+	-
Bellerochea malleus	+	+	-	*Triceratium favus*	+	+	+
Biddulphia aurita	+	+	+	*Triceratium s*p.	+	+	-
Coscinodiscus gigas	+	-	-	DINOPHYCEAE (Dinoflagellates)			
C. longissima	+	+	+	*Ceratium furca*	+	+	-
C. centralis	+	+	-	*C. tripos*	+	+	+
Chaetoceros affinis	+	+		*C. trichoceros.*	+	+	-
Cyclotella striata	+	+	-	*Dinophysis caudata*	+	+	-
Ditylum brightwelli	+	+	-	*Noctiluca scintillans*	+	-	-
D. sol	+	+	-	*Prorocentrum depressum*	+	+	+
Fragillaria sp.	+	+	-	*P. micans*	+	+	-
Gyrosigma balticum	+	-	-	*Protoperedinium venustum*	+	+	+
Hemidiscus hardmannianus	+	+	+	CYANOPHYCEAE (Blue-Green Algae)			
Leptocylindrus danicus	+	+	-	*Anabena* sp.	-	+	+

Leptocylindrus sp.	+	+	+	*Lyngbya* sp.	-	+	+
Navicula sigma	+	+	+	*Oscillatoria salina*	+	+	+
N. forcipata	+	+	+	*Spirulina subsalsa*	+	-	+
*Navicula s*p.	+	+	+	*Synechococcus* sp.	+	-	+
Nitzchia sp.	+	+	+	*Trichodesmium erythraeum*	+	+	+
Nitzschia longissima	+	+	+	*Microcystis aeruginosa*	-	-	+
Odontella sinensis	+	+	+	CHLOROPHYCEAE (Green Algae)			
O. mobiliensis	+	+	-	*Chlorella* sp.	+	+	+
Planktoniella sol	+	+	+	*C. marina*	+	+	+
Pleurosigma angulatum	+	+	+	*Chlorococcum* sp.	-	-	+
P. elongatum	+	+	+	*Dunaliella* sp.	+	+	-
Rhizosolenia alata	+	+	-	*Nannochloris maculata*			
(*Picochlorum maculatum*)	+	+	-				
R. styliformis	+	+	-	*Pediastrum simplex*	-	+	+
R. robusta	+	+	-	*Scenedesmus bijugatus*	-	-	+
Skeletonema costatum	+	+	+	*Volvox* sp.	-	-	+

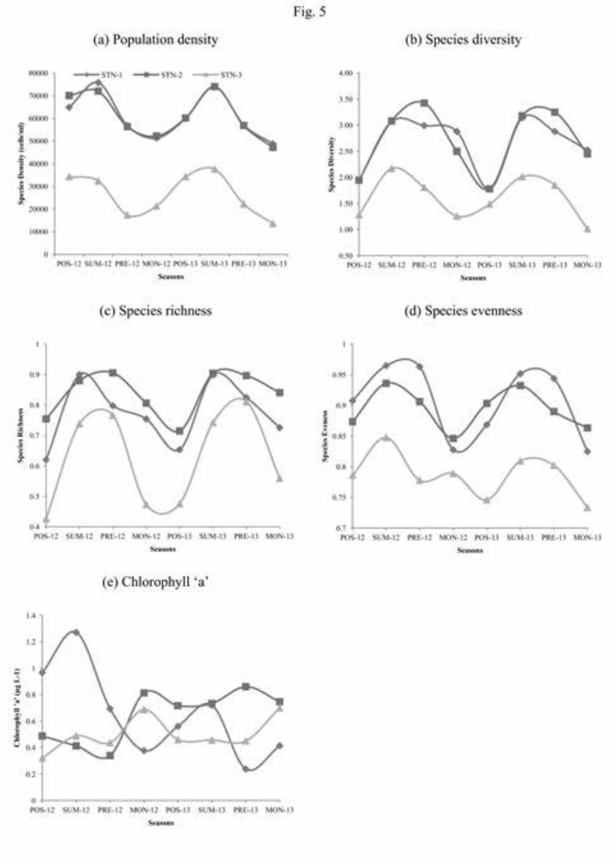

Fig. 5. Seasonal variations of phytoplankton cell density, diversity, richness, evenness and chlorophyll 'a' during post monsoon 2012 to monsoon 2013at Station 1, 2 and 3

d).Chlorophyll 'a' content was ranged from 0.23 to 1.27 μg L-1 with the lowest and highest concentration of chlorophyll 'a' were observed in Station 1 during 2013 pre monsoon season and 2012 summer season respectively (Fig. 5e).

Statistical analyses

The R-mode varimax factor analyses were executed on the assigned data set. For the data interpolation, the eigen values which contains greater than 1 is considered. Different physico-chemical and biological variables includes (population density, diversity, evenness and richness) was subjected to R-mode varimax factor rotation. The whole data set of the R-mode varimax factor analyses were yielded 4, 5 and 4 factors for Station 1, 2 and 3 respectively. The highest (80.01%) percentage of cumulative values was observed in Station 2 and lowest (77.67%) were found in Station 1. 79.71% of cumulative values were observed in Station 1. The ordination of the variables against the components is shown in Fig. 6 and the factor loadings for the variables are presented in Table 2.

The correlation coefficients were subjected to physico-chemical and biological variables were relation to Station and months. The positive values (+) greater than 0.5 termed as strong positive and negative (-) values greater than 0.5 termed as strong negative. The lower values lesser than 0.5 termed as weak. In Station 1 rainfall positively correlated with all major nutrients like phosphate, nitrate, nitrite and silicate; negatively correlated with temperature, water hardness and transparency, phytoplankton density and evenness. In Station 2, salinity, water hardness and ammonia negatively correlated with rainfall; phosphate positively correlated with nitrate and nitrite. In Station 3, positive correlation was observed between

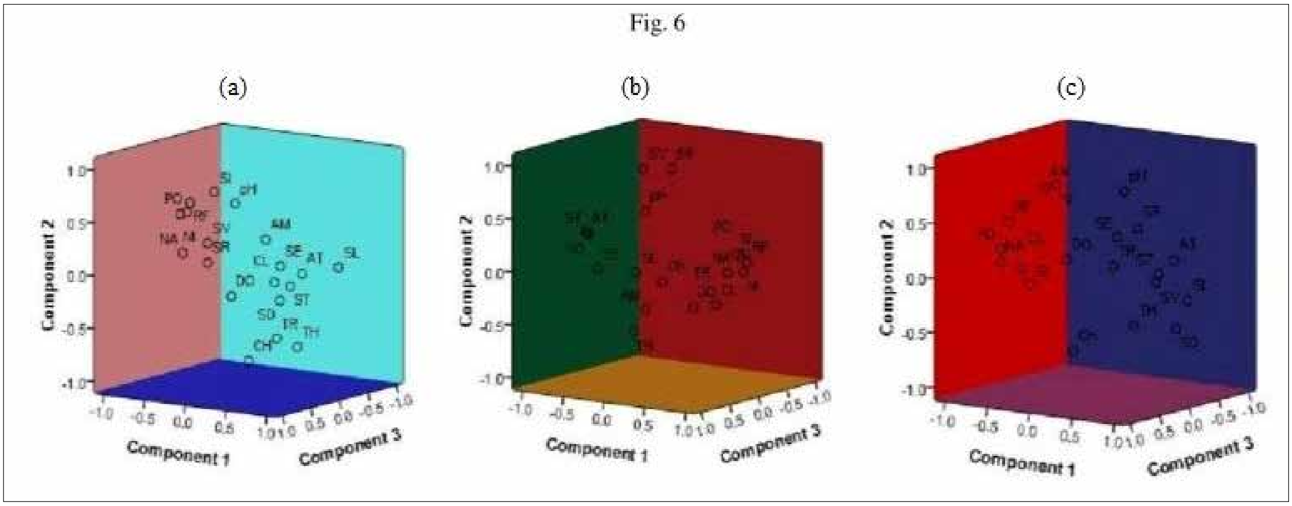

Fig. 6. Components plots in rotated space

temperature and species diversity and richness. Negative correlation was observed between nutrients (nitrate, nitrite and ammonia) and salinity. The detailed correlation matrix was given in Table 3, 4 and 5.

Discussion

Rainfall plays a vital role in tropical countries and influenced on hydrographical characteristics changes in estuarine and

Table 2. R-mode varimax sorted factor analysis of physico-chemical and biological parameters of Muthukuda mangrove environment

	(a) Station -1				(b) Station - 2					(c) Station - 3			
Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 1	Factor 2	Factor 3	Factor 4
Rainfall	-.780	.551			.922					-.733	.443	.402	
pH		.721	.474			.617	.553				.753		
Salinity	.780		-.463		-.407				.810	.880			
Atmosphere Temperature	.833				-.771					.847			
Surface water Temperature	.804		.419		-.761					.844			
Total Hardness		-.768	-.472		-.562	-.700					-.573	-.622	
Calcium Hardness		-.872						.889			-.694		
Transparency		-.617		.537			-.587					-.465	-.695
Dissolved Oxygen				.797				.517					.845
Phosphate	-.779	.469			.737					-.738		.546	
Nitrate	-.834				.711			.441		-.812		.428	
Nitrite	-.799	.463			.878						.821		
Ammonia			-.764		-.519	-.509				-.408	.770		
Silicate	-.576	.656			.905							.802	
Chlorophyll 'a'	.482			.627	.659				.500	-.596			
PopulationDensity	.712		.469		-.876					.667	-.503	-.413	
Species Diversity			.780			.929				.791			
Species Richness			.896			.908				.715	.519		
Species Evenness	.586					.	.797						.703
Eigen value	6.292	3.764	3.317	1.774	6.929	3.424	1.849	1.643	1.358	6.38	3.612	2.693	2.074
% variance	33.11	19.80	17.45	9.339	36.46	18.01	9.734	8.648	7.146	33.58	19.00	14.17	10.91
Cumulative %	33.11	52.92	70.38	79.71	36.46	54.48	64.22	72.87	80.01	33.58	52.59	66.76	77.67

Table 3. Correlation matrix among the physico-chemical and biological characteristics of Muthukuda mangrove waters, Southeast coast of India at Station – 1.

	Rain fall	pH	Salinity	AT	ST	TH	CH	Trans parency	Do	Phosphate	Nitrate	Nitrite	Ammonia	Silicate	Chl- a	Population Density	Species Diversity	Species Richness	Species Evenness
Rain fall	1.00																		
pH	0.20	1.00																	
Salinity	-0.49*	-0.07	1.00																
AT	-0.59***	0.33	0.59***	1.00															
ST	-0.65****	0.34	0.43*	0.90****	1.00														
TH	-0.60***	-0.65****	0.37	0.02	0.02	1.00													
CH	-0.43*	-0.63****	-0.10	-0.09	-0.05	0.73****	1.00												
Trans parency	-0.55***	-0.46*	0.19	0.16	0.23	0.61***	0.61***	1.00											
Do	0.005	-0.35	-0.27	-0.31	-0.29	0.28	0.41*	0.47**	1.00										
Phosphate	0.88****	0.22	-0.49**	-0.54	-0.63****	-0.56***	-0.38	-0.63****	-0.11	1.00									
Nitrate	0.72****	-0.11	-0.54	-0.55	-0.58***	-0.21	-0.07	-0.28	0.09	0.71	1.00								
Nitrite	0.82****	0.31	-0.62***	-0.54***	-0.56***	-0.59***	-0.37	-0.71****	-0.05	0.86	0.68****	1.00							
Ammonia	0.36	-0.28	-0.05	-0.46*	-0.53***	0.19	0.0002	-0.10	0.16	0.28	0.30****	0.29	1.00						
Silicate	0.83****	0.26	-0.35	-0.42*	-0.52**	-0.51***	-0.41*	-0.39	0.10	0.70	0.58****	0.69***	0.44*	1.00					
Chl- a	-0.38	0.01	0.21	0.30	0.28	0.08	0.19	0.42*	0.20	-0.45	-0.50*	-0.56***	-0.42*	-0.19	1.00				
Population Density	-0.68****	0.29	0.23	0.65****	0.70****	0.16	0.18	0.44*	0.06	-0.68	-0.64****	-0.64****	-0.47**	-0.56***	0.61***	100			
Species Diversity	0.07	0.56*	-0.34	0.27	0.37	-0.62***	-0.41*	-0.18	-0.05	0.07	0.008	0.16	-0.45*	0.04	0.21	0.38	1.00		
Species Richness	0.004	0.58*	-0.28	0.29	0.43*	-0.55***	-0.22	-0.01	-0.01	-0.04	-0.13	-0.005	-0.71****	-0.09	0.29	0.46*	0.67****	1.00	
Species Evenness	-0.46*	0.28	0.23	0.50**	0.57***	-0.04	-0.12	0.04	-0.001	-0.43	-0.44*	-0.35	-0.22	-0.35	0.23	0.47	0.24	0.4364*	1.00

*P<0.05; **P<0.02; ***P<0.01; ****P<0.001

Table 4. Correlation matrix among the physico-chemical and biological characteristics of Muthukuda mangrove waters, Southeast coast of India at Station – 2.

	Rainfall	pH	Salinity	AT	ST	TH	CH	Transparency	Do	Phosphate	Nitrate	Nitrite	Ammonia	Silicate	Chl - a	Population Density	Species Diversity	Species Richness	Species Evenness
Rainfall	1.00																		
pH	0.11	1.00																	
Salinity	-0.52***	0.00	1.00																
AT	-0.75	0.25	0.46*	1.00															
ST	-0.76	0.29	0.57***	0.88	1.00														
TH	-0.59***	-0.63	0.29	0.21	0.18	1.00													
CH	-0.13	-0.36	-0.17	-0.05	-0.05	0.28	1.00												
Transparency	0.30	-0.34	-0.05	-0.41*	-0.46*	0.14	0.32	1.00											
Do	0.35	-0.30	-0.28	-0.40	-0.39	0.11	0.34	0.30	1.00										
Phosphate	0.68	0.09	-0.27	-0.62***	-0.53***	-0.49**	-0.21	0.35	0.18	1.00									
Nitrate	0.70	-0.16	-0.53***	-0.56***	-0.56***	-0.38	0.21	0.45*	0.40	0.57***	1.00								
Nitrite	0.85	-0.01	-0.31	-0.69	-0.68	-0.46*	0.04	0.36	0.28	0.63****	0.61***	1.00							
Ammonia	-0.52***	-0.57***	0.46*	0.18	0.17	0.64	0.26	0.01	0.25	-0.41*	-0.26	-0.44*	1.00						
Silicate	0.84	0.17	-0.41*	-0.70	-0.66	-0.65	-0.10	0.26	0.20	0.70	0.66	0.75	-0.54***	1.00					
Chl - a	0.49*	-0.09	-0.01	-0.35	-0.44*	-0.14	0.14	0.17	0.16	0.22	0.52***	0.56***	-0.04	0.52***	1.00				
Population Density	-0.78	0.08	0.48*	0.81	0.82	0.29	-0.03	-0.45*	-0.35	-0.59*	-0.67	-0.71	0.40	-0.75	-0.54***	1.00			
Species Diversity	-0.05	0.70	-0.08	0.46*	0.44*	-0.60***	-0.22	-0.35	-0.45*	0.00	-0.11	-0.19	-0.46*	0.05	-0.34	0.39	1.00		
Species Richness	0.17	0.46*	-0.08	0.20	0.23	-0.60****	-0.25	-0.14	-0.29	0.16	0.07	0.07	-0.37	0.16	-0.33	0.26	0.79	1.00	
Species Evenness	-0.31	0.36	0.19	0.47*	0.54***	0.01	-0.01	-0.37	-0.13	-0.13	-0.39	-0.27	-0.15	-0.34	-0.22	0.42*	0.16	0.06	1.00

*$P<0.05$; **$P<0.02$; ***$P<0.01$; ****$P<0.001$

Table 5. Correlation matrix among the physico-chemical and biological characteristics of Muthukuda mangrove waters, Southeast coast of India at Station – 3.

	Rainfall	pH	Salinity	AT	ST	TH	CH	Trans parency	Do	Phosphate	Nitrate	Nitrite	Ammonia	Silicate	Chl - a	Population Density	Species Diversity	Species Richness	Species Evenness
Rainfall	1.00																		
pH	0.14	1.00																	
Salinity	-0.89	0.19	1.00																
AT	-0.56***	0.47*	0.74	1.00				+											
ST	-0.49**	0.21	0.66	0.80	1.00														
TH	-0.55***	-0.27	0.31	0.02	-0.12	1.00													
CH	-0.18	-0.53***	-0.02	-0.15	-0.13	0.26	1.00												
Transparency	-0.11	-0.09	0.03	-0.10	0.05	0.37	0.13	1.00											
Do	0.37	0.11	-0.28	-0.26	-0.32	-0.17	-0.36	-0.54	1.00										
Phosphate	0.92	0.01	-0.85	-0.62***	-0.52***	-0.48*	-0.01	-0.27	0.38	1.00									
Nitrate	0.64	0.25	-0.54***	-0.24	-0.44*	-0.21	-0.01	0.07	0.14	0.50**	1.00								
Nitrite	0.63	0.40	-0.53***	-0.16	-0.16	-0.68	-0.43*	-0.23	0.12	0.47*	0.30	1.00							
Ammonia	0.66	0.41*	-0.57***	-0.25	-0.29	-0.59***	-0.38	-0.17	0.23	0.55***	0.28	0.84	1.00						
Silicate	0.46*	-0.07	-0.40	-0.31	-0.02	-0.31	0.05	-0.26	0.14	0.58***	0.07	0.23	0.31	1.00					
Chl - a	0.69	-0.01	-0.61***	-0.47*	-0.49*	-0.32	0.13	-0.06	0.24	0.69	0.73	0.22	0.29	0.39	1.00				
Population Density	-0.90	-0.18	0.81	0.50**	0.40	0.58***	0.21	0.21	-0.44*	-0.87	-0.40	-0.69	-0.76	-0.47*	-0.47**	1.00			
Species Diversity	-0.45*	0.20	0.63	0.50**	0.54***	-0.13	-0.15	-0.20	-0.07	-0.46*	-0.33	-0.08	-0.35	-0.12	-0.37	0.45*	1.00		
Species Richness	-0.18	0.53***	0.40	0.60***	0.59***	-0.45*	-0.42	-0.33	-0.14	-0.24	-0.24	0.41*	0.18	0.05	-0.24	0.13	0.67	1.00	
Species Evenness	0.12	0.32	0.00	0.29	0.14	-0.31	-0.39	-0.30	0.41*	0.02	0.22	0.22	0.01	-0.27	-0.02	-0.10	0.40	0.29	1.00

*P<0.05; **P<0.02; ***P<0.01; ****P<0.001

coastal waters. In the present investigation, the high values of rainfall were recorded during the monsoon month of October. Rajkumar *et al.* (2009) has described that, the rainfall is largely influenced by two monsoons, viz., the southwest monsoon on the west coast, northern and northeastern India, and the northeast monsoon on the southeast coast of India. Kinne (1971) suggested that, for functional physiology and reproductive activity of the marine organisms, water salinity is the main influencing factor and in the present study, salinity was higher during the post monsoon and summer seasons (January and February, 2012 and 2013). This is might be due to the continuous evaporation of water during these seasons (Sampathkumar and Kannan, 1998; Sridhar *et al.,* 2006). Low salinity during monsoon season could be attributed to high rainfall leading to more land drainage (Ashok Prabhau *et al*., 2008; Damotharan *et al*., 2010; Nedumaran and Perumal, 2012).

The water transparency mainly ruled by wave action, tides, wind agitation and freshwater discharges, by stirring up the bottom thereby re-suspending the settled particles and fine sand or mud particles in shallow areas as that of the present study area. The lowest water transparency was recorded during July to October 2012 and July to November 2013 could be attributed to the turbid nature of the coastal waters caused by the land runoff and the findings were agreed by Kannan and Kannan (1996) and Sridhar *et al.* (2006) from the Palk Bay. The surface water and atmospheric temperature showed an increasing trend from December to April and was influenced by the intensity of solar radiation, evaporation, freshwater influx and cooling and mix up with ebb and flow from adjoining neritic waters (Govindasamy *et al.,* 2000). The water temperature during October 2012 and November 2013 was low because of rainfall caused by the northeast monsoon at Muthukuda. The similar trend has been reported by Sampathkumar and Kannan (1998) from the Tranquebar-Nagapatinam coast, Subramanian and Kannan (1998) from Tuticorin region and Sridhar *et al.* (2006) from Kattumavadi region.

Hydrogen ion concentration (pH) in surface water remained alkaline throughout the study period at three Stations with maximum values during the pre-monsoon and the minimum during post-monsoon. Generally, its seasonal variation is attributed to factors like removal of CO_2 by photosynthesis through bicarbonate degradation, dilution of seawater by freshwater influx, low primary productivity, reduction of salinity and temperature, and decomposition of organic matter (Bragadeeswaran *et al.,* 2007; Paramasivam and Kannan, 2005).

Saravanakumar *et al.* (2008b) has been described that the temperature and salinity affect the dissolution of oxygen. The high and lower values of DO observed during monsoon (October) and pre-monsoon (July) season respectively and reason behind this, swelling effect of higher wind velocity, a heavy rainfall, and the freshwater mixing (Rajasegar, 2003). The low DO could be due to the gradual saline water incursion and increasing temperature which cause higher evaporation besides low dissolute of oxygen saline water (Govindasamy *et al.,* 2000) and seasonal variation of dissolved oxygen mainly due to the freshwater flow and to the terrigenous impact of the sediments (Paramasivam and Kannan, 2005).

Vengadesh Perumal *et al.* (2009) have suggested that, nutrients are considered as one of the most important parameters in the estuarine and coastal environment influencing growth, reproduction and metabolic activities of marine species. Distribution of nutrients is mainly based on the season, tidal conditions and freshwater flow from land source. The recorded highest phosphate values during monsoon (November, 2013) season could be mainly due to the organic materials received from agricultural area (Das *et al.,* 1997). The addition of super phosphates applied in the agricultural fields as fertilizers and alkyl phosphates used in households, as detergents can be other sources of inorganic phosphates during the season (Bragadeeswaran *et al.,* 2007). The summer season has been recorded low value of phosphate could be attributed to the limited flow of freshwater, high salinity and utilization of phosphate by phytoplankton (Rajasegar, 2003).

The higher values of nitrate were recorded during monsoon season due to freshwater inflow, mangrove leaves (litter fall) decomposition and terrestrial run-off (Santhanam and Perumal, 2003) and through oxidation of ammonia form of nitrogen to nitrite formation (Rajasegar, 2003). The low values were recorded at summer season may be due to its utilization by phytoplankton as evidenced by high phytoplankton population and also due to the neritic water dominance, which contained only negligible amount of nitrate (Govindasamy *et al.,* 2000). Further, significant inverse relationship between rainfall and nutrients indicated that freshwater flow constituted the main source of the nutrients in the estuaries and coast neritic waters (Vengadesh Perumal *et al.,* 2009).

The recorded higher value of nitrite values, during pre-monsoon season could be due to the increased phytoplankton excretion, oxidation of ammonia and reduction of nitrate and by recycling of nitrogen and also due to bacterial decomposition of planktonic detritus present in the environment (Govindasamy *et al.,* 2000). The low nitrite value during post and pre-monsoon seasons noticed may be due to less freshwater inflow and high salinity (Mani and Krishnamurthy, 1989). The higher values of ammonia were recorded during pre-monsoon season and lower values during summer season clearly indicated that the mineralization of ammonia from the mangrove litter fall beside dead seagrass and an organic matter oxidation of dead plant and animal mater associated with mangrove vegetation along the banks of Pambanar estuary (Segar and Hariharan, 1989; Vasudevan *et al.,* 2012). The higher values of silicate that were recorded during monsoon season could be due to the large influx of freshwater derived from agricultural and aquaculture land drainage carrying silicate through river flow and also from the bottom sediment (Saravanakumar *et al.,* 2008a). The lower values of silicate was recorded during summer season and the reason behind this low silicate content could be attributed to the absorption by biological activity of phytoplankton especially diatoms or co-precipitation with humic compounds and iron (Rajasegar, 2003).

Phytoplankton species composition was comparatively more in Station 2 (Mangrove zone) than in Station 1 (Open Sea) and Station 3 (Freshwater zone). Generally, diatoms were found to be dominant in Muthukuda mangrove water, which could well thrive in widely changing hydrographical conditions (Gopinathan *et al.,* 2001; Gowda *et al.,* 2001; Senthilkumar *et al.,* 2002; Vengadesh Perumal *et al.,* 2009). Presently observed high population density and species diversity during post monsoon, summer and pre-monsoon season might be due to the predominance of diatoms *viz*.: *Asterionellopsis glacialis, Bacillaria paradoxa, Bacteriastrum* sp., *Bacteriastrum delicatulum, Coscinodiscus gigas, Leptocylindrus danicus, Navicula sigma, Navicula s*p., *Nitzschia longissima, Odontella sinensis, O. mobiliensis, Pleurosigma angulatum, Pleurosigma elongatum* and *Triceratium favus*. Among the four seasons, summer season with higher phytoplankton density could be attributed to the favorable salinity, pH, temperature and light penetration (Saravanakumar *et al.,* 2008b).

The low abundance of phytoplankton during monsoon months might be due to the heavy rainfall, high turbidity caused by run-off, reduced salinity, decreased temperature and pH.Ei-Gindy and Dorghan (1992) has suggested that phytoplankton and their growth depend on several environmental factors, which are variable in different seasons and regions. The recorded lowest values of phytoplankton diversity were noticed during monsoon season, but the diversity was higher during other periods. A total of 64 species of phytoplankton were identified in Muthukuda region of Palk Strait and nearby mangrove wetland. They often contributed significantly to the total abundance of phytoplankton as reported in other regions (Gowda *et al.,* 2001; Senthilkumar *et al.,* 2002).

During summer, the phytoplankton density was found to be high and it could be attributed to more stable hydrographical conditions prevailed during that period. Phytoplankton density negatively correlated with nutrients, reason behind this could be due to utilisation of nutrients by phytoplankton. In three Stations, species richness was found minimum during post monsoon season and maximum during summer season and this could be correlated with higher and lower salinity and pH as reported by Mani (1992).

A higher values of chlorophyll 'a' was recorded during summer (May, 2012) and lower during pre-monsoon season (Aug, 2013). The higher chlorophyll 'a' noticed during the summer season coincided with the maximum phytoplankton population density. The strong negative correlation between the phytoplankton population density and nutrients indicates the utilization of nutrients by the phytoplankton. Low concentration of chlorophyll 'a' during pre-monsoon season could be due to the anthropogenic activity, discharges from the rivers causing turbidity and less availability of light (Thillai Rajasekar *et al.,* 2005; Vengadesh Perumal *et al.,* 2009).

R-mode Varimax factor analyses

Station – 1

Rotation mode factor analyses were plotted in Fig 6. During the sampling period in Station 1, the R-mode varimax factor analyses of the data indicated a total of 4 factors responsible for 79.71% of the variance (Fig.6a) (Table. 2). Factor 1 accounted for 33% of the total variance due to strong positive loadings of salinity, atmospheric and surface water temperature, moderate positive loading of population density and evenness, weak positive loading of chlorophyll 'a' and strong negative loading of rainfall and nutrients (Phosphate, Nitrate, Nitrite and silicate). In this factor, the nutrients significantly correlated with rainfall (Table. 3), suggesting rainfall is a main source for nutrients. They correlated negatively with salinity, temperature, water hardness, population density and species evenness. Previous studies confirmed that nutrients were the main factors determining the concentrations of phytoplankton community in coastal waters (San Diego-McGlone *et al.,* 1995; Malone *et al.,* 1996; Hidalgo-GonzALez and Alvarez-Borrego, 2001) therefore represents a riverine influence that the nutrients are contributed by rivers. Hence, Factor 1 can be termed as the Riverine Factor.

Factor 2 explains 53% of the total variance and associated with moderate positive loading of rainfall, pH and silicate, weak positive loading of phosphate and nitrite, strong negative loading of total and calcium hardness, moderate negative loading of water transparency. In this case rainfall positively correlates with all the nutrients except ammonia. Similarly water transparency positively correlates with population density and negatively correlates with phosphate and nitrite. While the relationship between rainfall and water transparency is significant, indicate that the contribution of rainfall to water transparency is associated with river or water influx by rainfall. On other hand, a significant positive correlation of water transparency with chlorophyll 'a' and population density indicates that the water transparency isa factor of chlorophyll production and increasing level of population density. The factor 2 can therefore be called a rainfall factor.

Factor 3 explains 70% of total variance and was associated with strong positive loadings of species diversity and species richness, weak positive loading of pH, population density and surface water temperature, strong negative loading of ammonia, weak negative loading of total hardness and salinity. In this case, species diversity and species richness correlate positively with each other, while species diversity is positively correlated with pH and is negatively correlated with total hardness, calcium hardness and ammonia. Species richness is positively correlated with pH, population density, species diversity and is negatively correlated with total hardness and ammonia. Hence, higher species diversity recorded at Station 1 due to maximum light penetration contributes to the higher plankton production and distribution. Moreover, low freshwater influx and species mortality resulted positive loading of surface water temperature and negative loading of ammonia. This factor can therefore be termed as the plankton distribution factor.

Factor 4 explains 70% of total variance and is associated with 80% total variance and is associated with strong positive loading of dissolved oxygen and moderate positive loading of chlorophyll 'a' and transparency. Dissolved oxygen positively correlates with transparency and calcium hardness. Water transparency enhances the primary production and the dissolved oxygen balance, and this factor is termed as the productivity factor.

Station – 2

In Station 2, water exhibited different scenario. Altogether five factors account for 80% of the total observed variance in Station 2 (Fig. 6b) (Table 2). Factor 1 explains 36% of total variance and strongly loaded positively with rainfall, silicate and nitrite, moderately loaded positively with phosphate, nitrate and chlorophyll 'a', strong negative loadings of population density, surface water temperature and atmospheric temperature, moderate negative loadings of ammonia, total hardness and weak negative loadings of salinity. Rainfall positively correlates with inorganic nutrients except ammonia (Table 4). But rainfall negatively correlates with salinity, total hardness and ammonia. This suggests that contribution of rainfall to the nutrients level increases in mangrove environment. This factor is termed as nutrient factor.

Factor 2 explains 54% of total variance and is strong positive relationship with species diversity and species richness, moderately loaded positively with pH, moderately loaded negatively with total hardness and ammonia. Species diversity was positively correlated with atmospheric and surface water temperature and was negatively correlated with total hardness and ammonia. Species richness positively correlates with pH and negatively correlates with total hardness. Species diversity and richness mainly ruled by temperature. So factor 2 is termed as an environment factor.

Factor 3 is called the alkaline factor which explains 64% of the total variance and indicates strong positive loading of species evenness and moderately positive loading of pH, moderately negative loading of transparency. pH positively correlate with species diversity and species richness negatively correlate with total hardness and ammonia. Generally the pH was varied due to biological activity of phytoplankton.

Factor 4 explains 73% of total variance and shows strong positive loadings of calcium hardness and moderate positive loading of dissolved oxygen and nitrate. Dissolved oxygen negatively correlates with species diversity. Higher calcium was dominated mainly due to influx of freshwater and excretion of minerals from the river associated rocks and substrates. So factor 4 is termed as a mineral factor. Factor 5 explains 80% of total variance and is loaded strongly positively with salinity and moderately positively with chlorophyll 'a'. Salinity positively correlates with atmosphere temperature and population density; negatively correlates with nitrate and silicate. Higher loading of salinity might be due to low rainfall, higher rate of water evaporation and dominance of neritic water. In this case factor 5 can therefore be termed as environmental factor.

Station – 3

In the case of Station 3, total 4 factors explain about 78% of the total variance (Fig. 6c) (Table. 2). Factor 1 explains 34% of total variance and is associate with strong positive loadings of salinity, atmospheric temperature, surface water temperature and species diversity, moderate positive loadings of species richness and population density, strong negative loading of nitrate, moderate negative loading of rainfall, moderate negative loading of phosphate and chlorophyll 'a' and weak negative loading of ammonia. The strong positive loading of salinity, temperatures and population density explain significant relationship between both of them and moderate positive loading of species richness and density positively related with species diversity and temperature. This factor could be associated with environmental factor such as salinity and temperature.

Factor 2 is responsible for 53% of total variance and shows a strong positive loading of nitrite, ammonia and pH, moderate positive loading of species richness with weak positive loading of rainfall, moderate negative loading of total hardness, calcium hardness and population density. The strong positive loading of nitrite negatively correlated with salinity, calcium and total hardness and positively correlates with rainfall and phosphate

(Table 5). This shows that high nitrite loading could be due to oxidation of ammonia and reduction of nitrate and recycling of the nitrogen. So, factor 2 is called the nitrogen factor.

Factor 3 explains 67% of total variance and shows strong positive loading of silicate, moderate positive loading of phosphate, weak positive loading of nitrate and rainfall, moderate negative loading of total hardness, weak negative loading of transparency and population density. The higher silicate loading could be due to leaching of silicate from rocks and also from the bottom sediment with help of freshwater influx. This factor 3 therefore is the silicate affected factor. Factor 4 contributes to 78% of total variance and shows a strong positive loading of dissolved oxygen, moderate positive loading of species evenness and moderate negative loading of transparency. Higher loading of dissolved oxygen could be due to the cumulative effect of high wind velocity and heavy rainfall. In this case dissolved oxygen positively correlates with species evenness and negatively correlates with population density. This factor can be termed as productivity factor.

The Muthukuda region is subjected to seasonal fluctuations in physico-chemical parameters depending upon the season and freshwater influx resulting in a constant exchange of organic, inorganic, plant, animal and aquaculture practices waste materials. This mangrove water supports rich phytoplankton population and diversity. Rotation mode factor analyses were applied separately for the data sets of Station 1, 2 and 3 to understand the environmental status of the area and to sketch the sources. The factor analyses indicated 4 factors explaining 79.7% of the total variance in Station 1, 5 factors explaining 80.01% of the total variance in the Station 2 and 4 factors explained 77.6% of the total variance. The study revealed that the phytoplankton production caused by the addition of nutrients with help of weathering, rainfall and carried by rivers. In Muthukuda (open sea, mangrove waters and freshwater region), diatom was the dominant group. From the present findings it is concluded that the Muthukuda mangrove waters and adjacent neritic waters are fertile for phytoplankton productivity.

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