

Influence of Coastal and Backwaters Coupling on Sustenance of High Nutrients and Organic Production along the Southeast Arabian Sea

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Abstract The diversity, abundance, size fraction phytoplankton biomass and primary productivity in the shelf waters of six transects along the southern Kerala coast were studied in relation to the prevailing hydrological conditions. Southwest coastal waters of India (Arabian Sea) especially have a special environmental importance due to the formation of mudbanks, upwelling and coupling of these waters with adjacent watershed through backwaters. These coupling provides perennial source of nutrients to the adjacent coastal waters and supporting rich primary production. Result indicated that primary productivity and phytoplankton standing crop were directly tuned with chlorophyll *a* and nutrient concentrations. About 105 species of phytoplankton were identified in the neritic waters of southern Kerala coast. Among these, 75 species belonged to diatoms (Bacillariophyceae) and 25 to dinoflagellate (Dinophyceae). Haptophyceae was represented by two species while blue-green (Cyanophyceae), greens (Chlorophyceae), and silicoflagellate (Chrysophyceae) were represent by one species each. Phytoplankton diversity (Margalef richness d' , Shannon-Wiener H' , Pielou's evenness J'), abundance and biomass in the waters of Paravur, Neendakara and Alleppy transects were observed to be higher relative to southern transect Veli. The nanoplankton (2-20 μm) community formed the major fraction of chlorophyll *a* and primary production followed by micro- (>20 μm) and pico- (0.2-2 μm), respectively. The study suggested that phytoplankton abundance; biomass and community structure played a crucial role on organic production available to the marine food web and was significantly influenced by the enrichment of nutrients from the catchment discharge and hydrographical conditions.

Keywords Community structure, Nanoplankton, Nutrients, Phytoplankton, Primary production, Kerala coast, Southwest coast of India

1. Introduction

The Arabian Sea is a highly complex oceanic basin, strongly influenced by industrial establishments and human settlements along the west coast of India necessitate an evaluation of the type and quantum of inputs to the regional assimilative capacities. During summer monsoon, wind-driven upwelling occurs along a broad region parallel to the coast, which brings cooler but nutrient rich water into the euphotic zone, inducing a strong coupling between physical and biological processes in these waters [1]. The semi-annual

reversal of coastal currents in the Arabian Sea introduces a high degree of seasonality in the physico-chemical environment [2]. The south west monsoon is the time of an equatorward current along the west coast and results upwelling [3]. During the period of upwelling that lasts from May-June to October-November and by which denser nutrient rich water is brought to the surface, leads to marked increase in phytoplankton growth thereby increasing chlorophyll *a* and gross primary productivity [4, 5].

Phytoplankton size structure plays a crucial role in controlling the fate of biogenic carbon (C) in pelagic ecosystems [6]. In any aquatic environment, phytoplankton growth and abundance are primarily regulated by both abiotic and biotic interactions [7]. The constant nutrient supply always supports the rich phytoplankton production, but generally nitrogen (N) and phosphorous (P) have been

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considered as the potentially limiting nutrients for phytoplankton growth in the aquatic ecosystems[8]. In addition to nutrients, physical properties such as salinity[9], turbidity and light availability[10] are also found to play major roles in the regulation of phytoplankton growth and their distribution in the coastal systems. In the coastal waters size of planktonic organisms largely determines their interactions and hence, the rate of biological processes [11,12]. The size and structure of phytoplankton is very important as it changes with the environmental conditions [13], reflecting the pathways of carbon cycling in the pelagic food chain[14]. Generally nutrient enrichment favors the growth of large phytoplankton[15], while the production of small phytoplankton (nano-) are mainly controlled by microzooplankton (ciliates and flagellates) grazing[16,17].

Any possible threat to the well being of the living resources of EEZ of India, then the coastal waters of southwest coast of India, and in particular, southern Kerala coast is the prime location prone to trigger it. The 16 major and several minor industries situated in the upstream region of the backwaters discharge nearly $0.105 \text{ Mm}^3 \text{ d}^{-1}$ of effluents[18]. The fertilizer consumption in Kuttanad region (the main agricultural field draining to Cochin backwater) alone is reported to be $20,239 \text{ t y}^{-1}$ [19]. Conventional understanding of coastal waters of southeastern Arabian Sea is that the activation of mudbanks by monsoon forcing triggers intense geochemical processes leading to high productivity[20]. Mudbanks are unique in their formation and functions, and have turned out to be economically important for its rich biological resources. The holistic understanding of factors determining marine productivity requires detailed knowledge of the marine ecosystem. In this regard the present study examines changes in the environmental conditions and their influence on the diversity and distribution of different size fractions of phytoplankton ($>20 \mu\text{m}$, $2-20 \mu\text{m}$ and $<2 \mu\text{m}$) in the coastal waters of southern Kerala in an integrated manner.

2. Materials and Methods

2.1. Study Area

A range of mountains *viz.* the Western Ghats on eastern side and the Arabian Sea on the Western side borders the state of Kerala. The total land area of the state is estimated as 38863 km^2 in which the coastal line of the Arabian Sea sprawling on the western part is 590 km. The inshore sea area falling within the territorial limit of the state (22 km) is about $13,000 \text{ km}^2$ and the continental shelf area of the sea adjoining the Kerala state is 39139 km^2 . The estimated marine fishery potential of the state is 7.95 lakh tonnes. Fisheries contribute to about ~3% to the economy of the state. The coastal low land fringing the sea extending over 590 km covers about 16.4% of the state's total area. The 41 west flowing rivers of the state carry nearly $45,060 \text{ M m}^3$ of water per year in to the sea. There are about 27 estuaries and 7 lagoons or Kayals in Kerala and hence well known for the

occurrence of mud banks which is a unique phenomenon. Almost 30% of the total population lives in the coastal area. The average marine production from Kerala is about 25% of the country. About 300 medium to large and about 2000 small scale industries are discharging effluents directly in to the marine and fresh water bodies. It is estimated that about one million m^3 of sewage is generated per day in coastal areas and about 30000 m^3 of this reaches the surface water bodies. A chain of water bodies locally known as Kayals running parallel to the coastline is a characteristic feature of Kerala coast. These are mostly interconnected by natural or manmade canals facilitating internal navigation along the entire coast.

The 690 km long Kerala coast faces the Arabian Sea and the coastline of Kerala is more or less straight trending in NNW-SSE direction from north till Thangasserry headland near Kollam. The coastal orientation south of Thangasserry is in the NW-SW direction. The offshore continental shelf bathymetry is steeper to the south while the 100 m contour is at a distance of around 40 km off of Thiruvananthapuram from the shore; it is 58 km off Kasargode. The variation in the slope of inner shelf is more pronounced. This change in bottom slope has lot of implications in the hydrodynamic and sedimentological characteristics of the inner shelf of the state. The hydrodynamic regime of the coastal marine zone of Kerala depicts the typical features of a monsoon dominated tropical coast. Like the other parts of the west coast, the coastal marine zone of the Kerala coast is known for the occurrence of upwelling, which is strong during monsoon. During the southwest monsoon period when the sea is very rough, very calm sea conditions prevail in the mudbank zones adjoining the shorelines. Some of the locations well known for the occurrence of the mudbank are Koilandy, Njarakkal, Puthuvypene, Alleppey and Purakkad. Their transient nature, unpredictable periodicity, calmness and turbid nature of the water column are unique. Ramachandran and Malik[21] reported an offshore sediment source and rapid sedimentation in the mudbank region during monsoon period.

2.2. Sampling Strategy

Six transects were selected for the study along southern Kerala coast between latitudes $9^\circ 57' \text{ N}$ and $8^\circ 29' \text{ N}$ and longitudes $76^\circ 14' \text{ E}$ and $76^\circ 53' \text{ E}$ stretching from north to south. The transect I (Kochi), transect II (Alleppey), transect III (Kayamkulam), transect IV (Neendakara), transect V (Paravur), and transect VI (Veli) respectively are stretching from north to south (Figure 1). Four stations, on each of these transects were selected for sampling *viz.* near shore, 2 km, 5 km and 10 km offshore across the coast. The samples were collected during the CRV *Sugar Purvi*, cruise programme from May-June 2005.

2.3. Materials and Methods

The water samples were collected using 5 litre Niskin bottles. The samples for dissolved oxygen (DO) were fixed onboard

and the remaining water samples were collected in 2 litre PVC bottles kept in deep freezer till the analysis. Total suspended matter (TSM mg L^{-1}) was determined gravimetrically on Millipore membrane filters (pore size $0.45 \mu\text{m}$) after drying at 70°C for 6-8 hours to reduce water content before weighing. Salinity was determined using a Digi Auto Salinometer (Model TSK, accuracy ± 0.001) and the pH using an ELICO LI 610 pH meter (accuracy ± 0.01). Dissolved oxygen (DO) was estimated according to Winkler's method[22]. Samples for nutrients (ammonia, nitrate, nitrite, phosphate and silicate) were analysed following the standard methods[22].

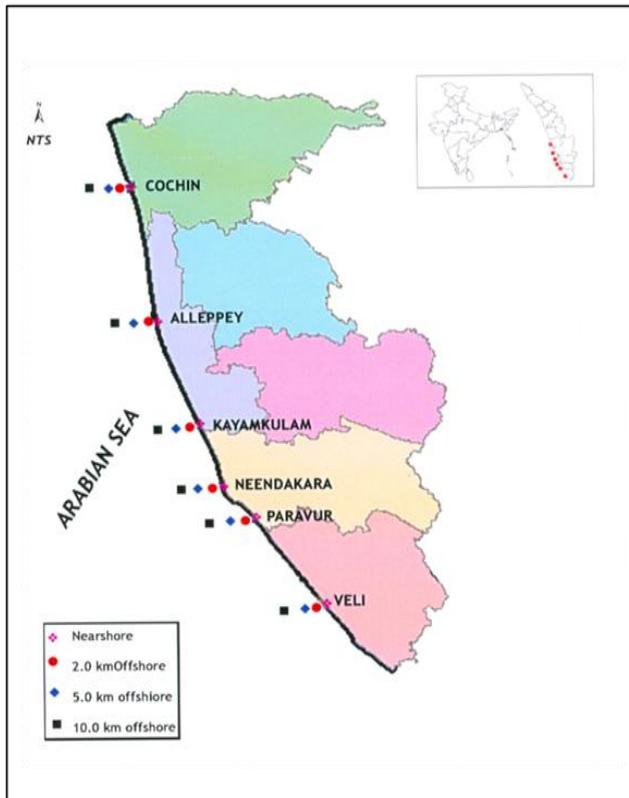


Figure 1. Sampling sites along southern Kerala coast

Size fractionated phytoplankton pigments (chlorophyll *a*) were carried out by sequential filtering of 500 ml water, initially through $20 \mu\text{m}$ nylon sieve and subsequently through $2 \mu\text{m}$ and $0.2 \mu\text{m}$ polycarbonate filters. The cells retained by the $20 \mu\text{m}$ sieve are the microplankton whereas those retained by 2 and $0.2 \mu\text{m}$ filters constitutes the nano- and pico- fractions, respectively. After filtration, pigments were extracted in 90% acetone for 24 h in the dark at 4°C and pigment concentration was determined spectrophotometrically (UV-VIS Spectrophotometer, Model-1650PC, Shimadzu). Similarly, the size fractionated primary production was determined by running simulated deck incubations with the ^{14}C isotope maintaining *in situ* temperature. Four 300 ml acid washed BOD glass bottles (3 light and 1 dark bottles) were filled with water collected from the surface and bottom. Each bottle was inoculated with 1 ml $5\mu\text{Ci NaH}^{14}\text{CO}_3$ and incubated for 6 hours starting at noon.

At the end of incubations, samples were sequentially filtered through $20 \mu\text{m}$ nylon mesh and 2 and $0.2 \mu\text{m}$ polycarbonate filters. The phytoplankton cells concentrated in the $20 \mu\text{m}$ mesh were washed with filtered (through $0.2 \mu\text{m}$ polycarbonate filters) seawater and again concentrated on GF/F filters (nominal pore size- $0.7 \mu\text{m}$). The filters were used for subsequent analysis in the liquid scintillation counter after treatment with concentrated HCl fumes to remove inorganic carbon. The primary production rate was calculated according to the equation described in the protocol of UNESCO[23].

2.4. Cluster and Species Diversity Index Analysis

Multi-linkage cluster analysis using group linkage method was used for identifying the similarities between stations. Diversity indices (Species Richness (d'); Evenness Index (J') and Shannon-Wiener (H')) were estimated on species abundance using PRIMER.

3. Results

3.1. Hydrographic Conditions

Coastal belt of Kerala experiences a warm humid climate. Average atmospheric temperature ($29.78 \pm 1.06^\circ\text{C}$) was higher ($27.15 \pm 0.87^\circ\text{C}$) than the water temperature (Figure 2a & b). Salinity showed wide variation between the nearshore and the offshore waters (Figure 2c). The distribution of total suspended matter (TSM) was found to be more or less similar in distribution with elevated values recorded at estuarine transects (Figure 2d). Similarly, the coastal waters remained fairly saturated with respect to DO except at station Veli (Figure 2e). pH was always high in the offshore waters as compared to the estuarine and nearshore stations (Figure 2f). The nitrogenous nutrients were recorded high at estuarine transect such as Paravur, Neendakara and Kochi except for the southern transect, Veli. The phosphate concentrations did not show any spatial variation except Veli, but higher concentrations of ammonia, nitrate and silicate were observed at selected regions in the near shore regions and decreased gradually towards offshore (Figure 2g-l). The Nitrate-N concentrations pointed towards a clear source between Paravur to Kochi, where it peaked up to $>10 \mu\text{M}$ and decreased towards offshore. A slight shift but with a similar trend was observed for ammonia-N with the source centered on Neendakara and Kochi. It may be assumed that the ammonia released were either rapidly utilized by phytoplankton or oxidized within the system itself where the waters were saturated with dissolved oxygen. Distribution of silicate-Si was similar to that of nitrate and ammonia and was higher than the corresponding values reported for the waters of southeastern Arabian Sea[24]. The input of these nutrients supported high primary production (peak surface production of $597.8 \pm 230.8 \text{ mg C m}^{-3} \text{ d}^{-1}$) and was represented by high chlorophyll *a* up to $5.60 \pm 2.31 \text{ mg m}^{-3}$ which was approximately two times greater than the peak values

reported so far from these waters[25]. A correlation matrix is produced to investigate the relationship among the water quality variables are illustrated in Table 1.

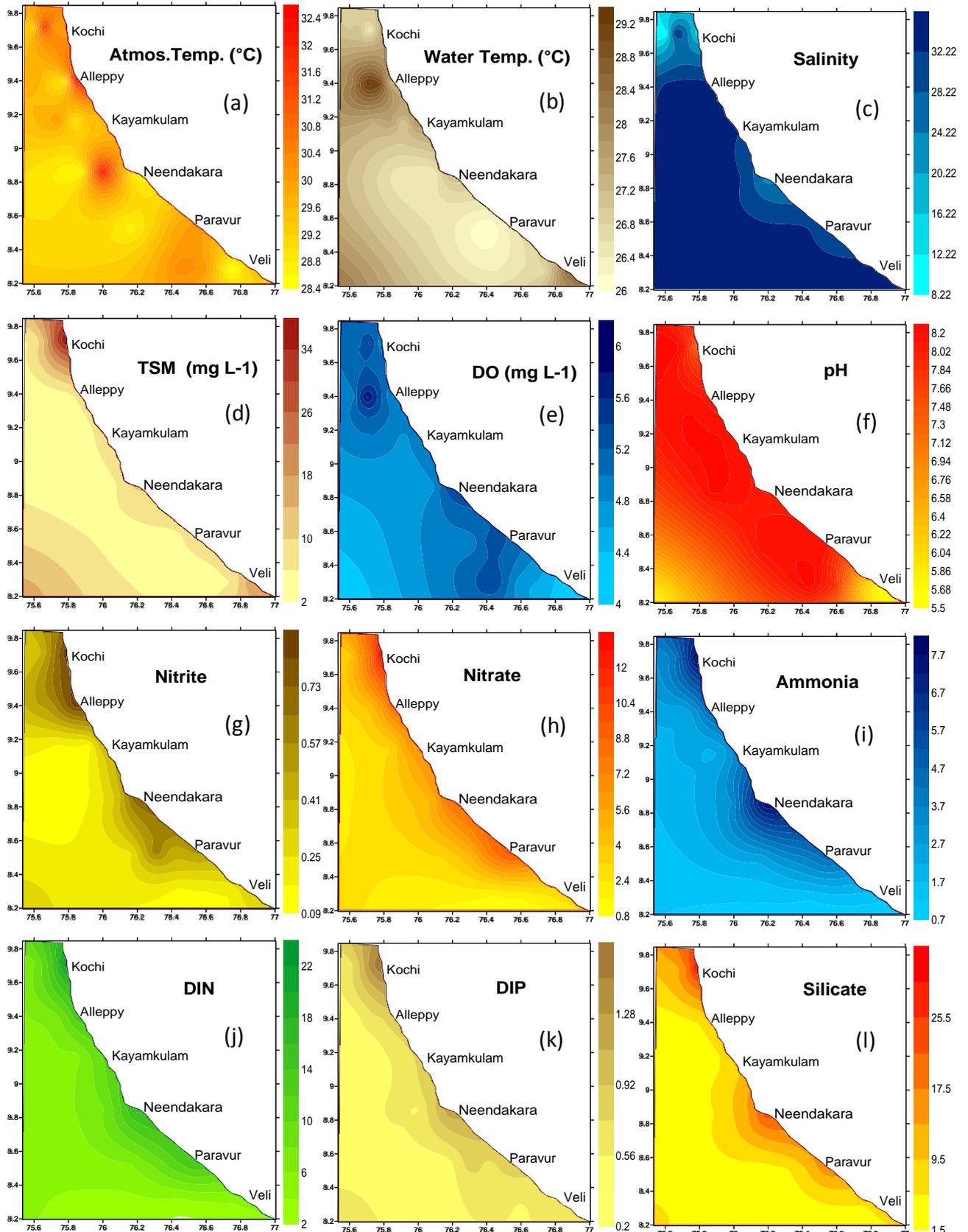


Figure 2. Spatial variation in (a) atmospheric temperature °C, (b) water temperature °C, (c) salinity, (d) TSM mg L⁻¹, (e) DO mg L⁻¹, (f) pH, (g) nitrite-N (µM), (h) nitrate-N (µM), (i) ammonia-N (µM), (j) DIN (µM), (k) DIP (µM), (l) DISi (µM) along southern Kerala coast

The N/P ratio for these coastal waters was recorded well below 16 (Redfield ratio), possibly due to the disproportionate release of P from mudbank sediments. However, a band of N/P ratio close to 16 was noticed from Paravur to Kochi region, which indicated an 'external source' of nitrogenous compounds into these coastal waters. Submarine discharges of groundwater or backwater discharge with high N:P ratios (>15) have been reported to cause P-limitation in coastal waters [26]. These present observations indicated the presence of nutrient sources between Paravur and Kochi. Though this region represents mudbanks, the release of nitrogenous compounds could be attributed to the release from sediments. Further, the addition of nutrients in the non-monsoon months was observed when mudbanks were passive. This could be explained by considering the direct or indirect influence of backwaters such as Vembanad Lake, Ashtamudi Kayal and Paravur Kayal on the coastal waters. Developmental activities in Vembanad Lake over the past century have included urbanization, reclamation, drainage of wetlands and agriculture. One of the recent estimates showed that in spite of receiving $42.4 \times 10^3 \text{ mol d}^{-1}$ of inorganic phosphate and $37.6 \times 10^3 \text{ mol d}^{-1}$ of inorganic nitrate from Periyar estuary, a major share of these nutrients are exported to the coastal waters [27]. The dendrogram provided a sequence of group plot for the same location based on the hydrographical condition for the same stations, which provided a fairly convincing four groups (Paravur and Kayamkulam transect form one group, Alleppy and Kochi another group and Veli and Neendakara for two separate groups) with respect to hydrobiological condition prevailing in that region (Figure 3).

3.2. Chlorophyll *a* and Primary Production

Chlorophyll *a* (chl *a*) contained in the pico-(0.2–2 μm), nano-(2–20 μm) and micro- (>20 μm) fractions showed significant variations with maximum concentrations recorded at transect Alleppy (Figure 4). The total chl *a* was higher in the nearshore, as compared to the coastal waters. Among size fraction, nanoplankton chl *a* was dominant ($3.06 \pm 1.26 \text{ mg m}^{-3}$, 55.02 \pm 5.5%) over micro- ($1.62 \pm 0.83 \text{ mg m}^{-3}$, 28.5 \pm 4.7%) and pico- ($0.91 \pm 0.37 \text{ mg m}^{-3}$, 16.5 \pm 2.8%). Similar to the distribution of chl *a*, primary production (total and size fractions) also exhibited considerable variation along the coastal transects, with higher values at Neendakara and Alleppy transects. The nanoplankton primary production was the dominant fraction ($470.6 \pm 200.6 \text{ mg C m}^{-3} \text{ d}^{-1}$, 77.05 \pm 9.3%) of the total primary production, followed by micro- ($89.16 \pm 44.1 \text{ mg C m}^{-3} \text{ d}^{-1}$, 16.10 \pm 6.7%) and pico- ($4.71 \pm 2.6 \text{ mg C m}^{-3} \text{ d}^{-1}$, 1.19 \pm 1.45%) fraction (Figure 5). The high chl *a* and primary production contributed by the nanoplankton in the coastal waters of southern Kerala was an evidence, depicting the dominance of this community as compared to the autotrophic pico- and microplankton as reported earlier [28]. Normally nutrient enrichment favours the

proliferation of large-sized phytoplankton in the coastal waters (>20 μm ; Agawin et al., [29]) and also they need high light intensity for saturating photosynthetic activities [30, 31], however in the present study relatively higher nanoplankton was observed even in presence of higher nutrients. This could be due to light limitation associated with high TSM discharged from the backwaters and wind induced re-suspension which ultimately lead to limit the growth of large-sized micro phytoplankton by enhancing water column turbidity [32].

3.3. Phytoplankton Abundance and Composition

Among the stations, maximum phytoplankton standing crop ($8260 \text{ cells L}^{-1}$) was recorded at Paravur 2 km offshore whereas, Veli nearshore recorded minimum standing crop of 326 cells L^{-1} . Variations in phytoplankton standing crop at various transect were illustrated in (Figure 6). About 105 species of phytoplankton were identified in the neritic waters of six transects along southern Kerala coast. Out of these 105 species recorded, 75 species belongs to diatoms (Bacillariophyceae) and 25 species to dinoflagellate (Dinophyceae). Haptophyceae was represented by two species while one species from each of blue-green (Cyanophyceae), green (Chlorophyceae), and silicoflagellate (Chrysophyceae) were identified (Table 2). Among the Bacillariophyceae, centrales were the predominant (55 centrales to 20 pennales). The species number represented by each transects (Table 3) was in the order of, Alleppey (101) > Kayamkulam (94) > Neendakara (90) > Paravur (90) > Kochi (75) > Veli (51). The species were dominated by Bacillariophyceae (34-73) and Dinophyceae (15-23) in all the stations. Higher number of Haptophyceae (2) was observed at transect Alleppey and Neendakara, whereas Cyanophyceae, Chrysophyceae, Chlorophyceae, contributed one species each at all transect except Kochi, Kayamkulam, Neendakara and Veli. Out of the 105 species, 75 species belong to Bacillariophyceae (40 genera, 75 species), 25 species to Dinophyceae, (9 genera, 25 species), 2 species to Haptophyceae (2 genera, 2 species) and one species to each group of Cyanophyceae, Chrysophyceae, and Chlorophyceae.

The genera observed with relatively higher richness in species were, *Rhizosolenia* (8), *Coscinodiscus* (6), *Chaetoceros* (6), *Bacteristrum* (4), *Ceratium* (10), and *Protoperdinium* (6). Among 5 taxonomic groups, percentage composition of diatoms were dominant over other groups (96.84%) followed by Dinoflagellate (3.15%), Blue-greens (0.49%) Greens (0.11%) and Silicoflagellate (0.009%). The prominent species observed at transect Kochi were *Asterionella japonica* (39.34%), *Chaetoceros lorenzianus* (26.93%) and *Skelitonema coastatum* (14.60%), at Alleppey were *Asterionella japonica* (35.80%), *Chaetoceros lorenzianus* (26.02%), *Fragilaria oceanica* (17.90%) and *Bacteriastrium varience* (5.11%), at Kayamkulam were *Asterionella japonica* (38.87%),

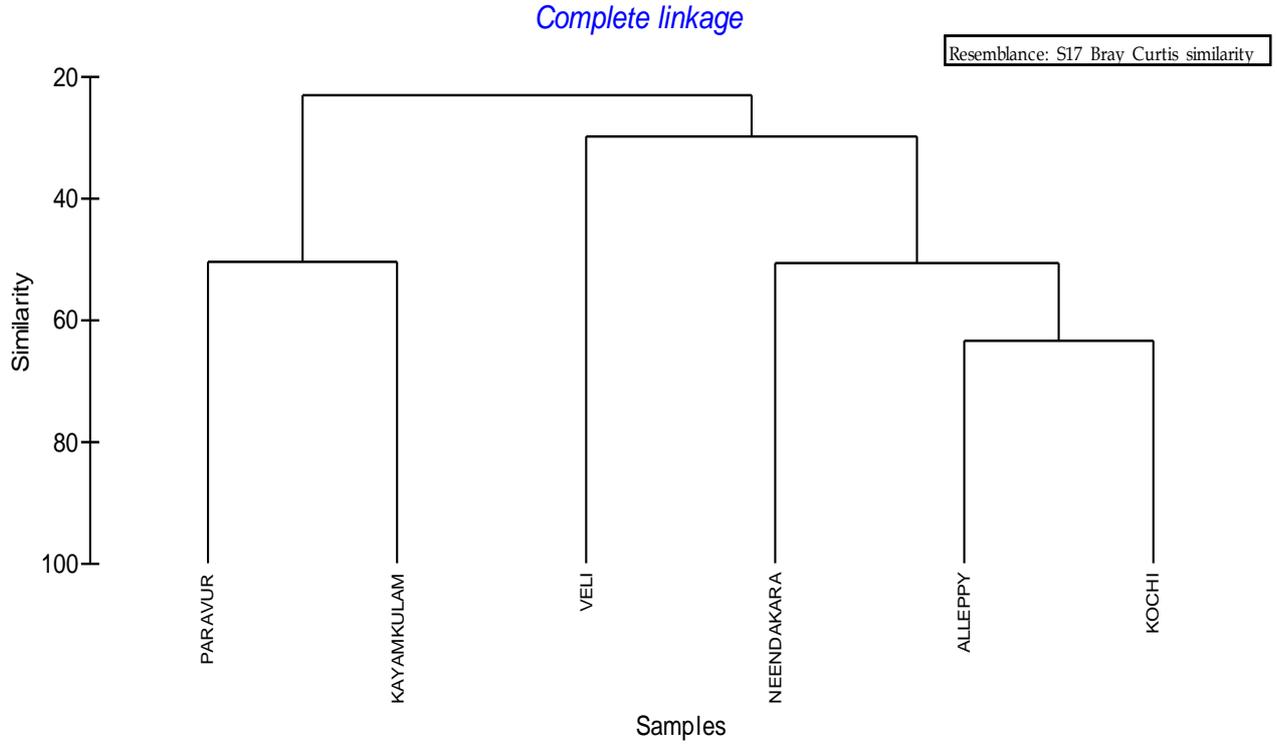


Figure 3. Group average clustering from euclidean distances based calcification of various transects with respect to hydrographic conditions

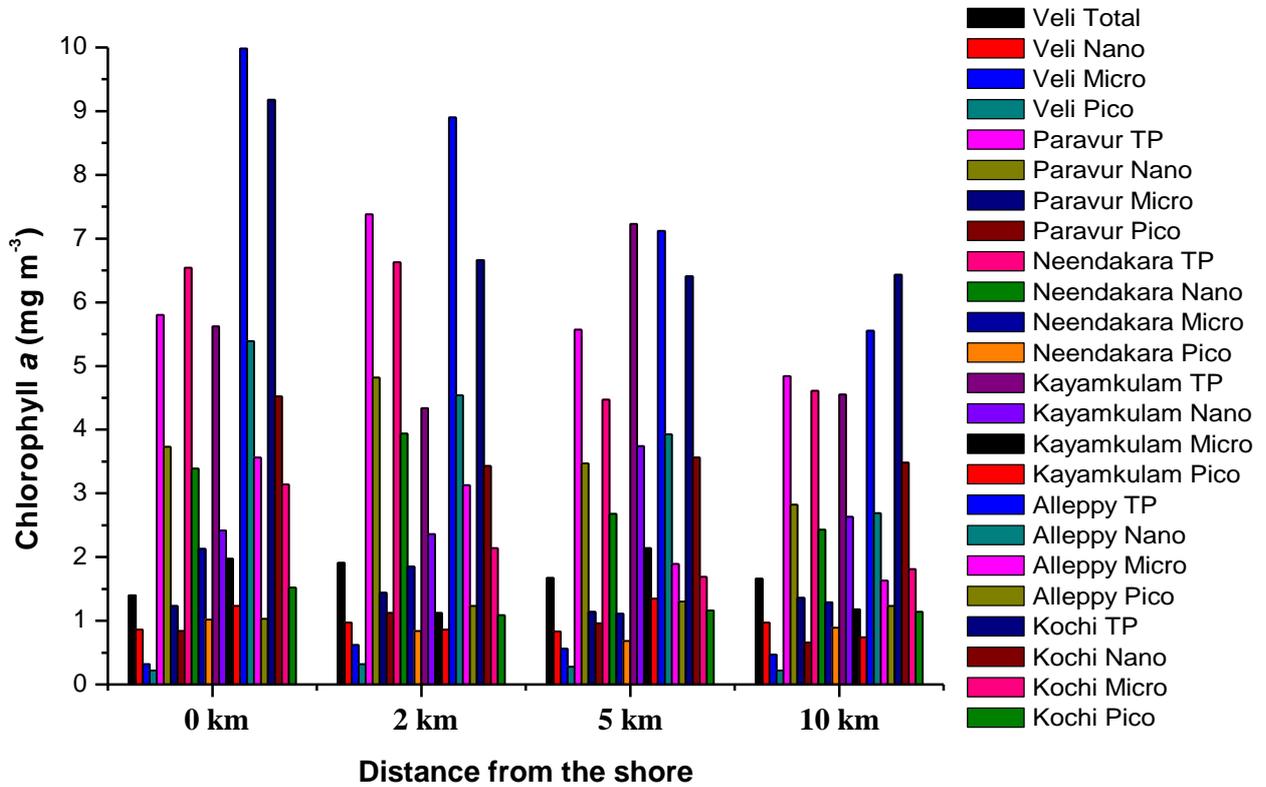


Figure 4. Distribution of size fractionated chlorophyll a (pico- (0.2–2 μm), nano- (2–20 μm) and micro- (>20 μm) and (total) along the various transects of southern Kerala coast

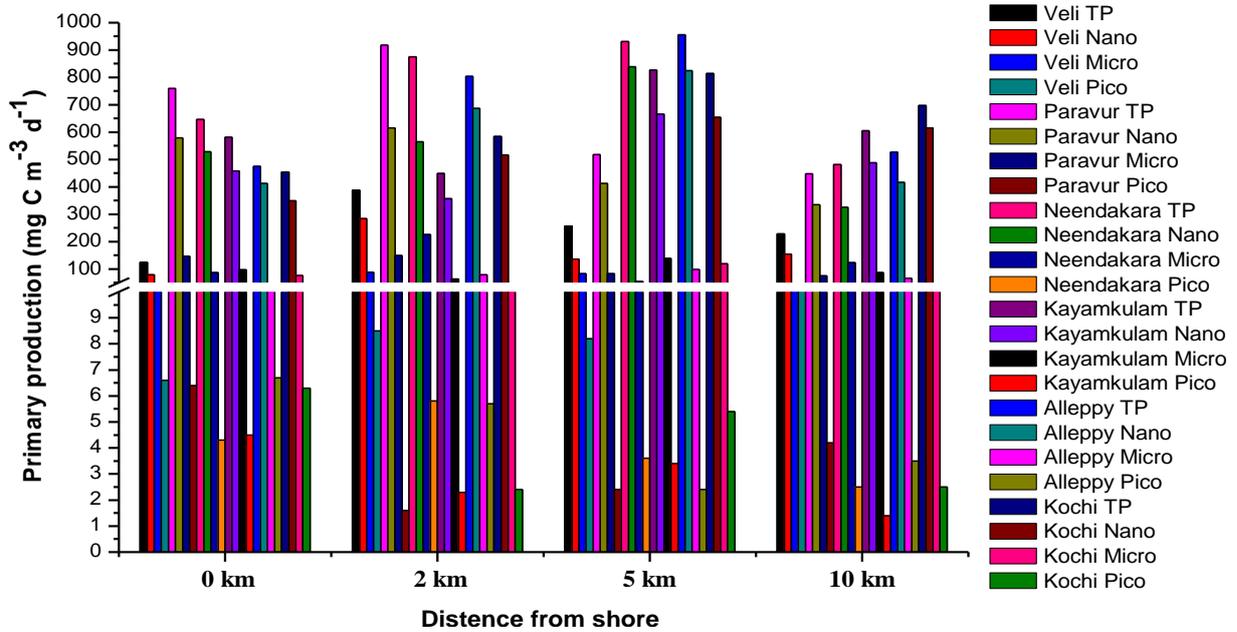


Figure 5. Distribution of size fractionated primary production (pico- (0.2–2 μm), nano- (2–20 μm) and micro- (>20 μm) and (total) along the various transects of southern Kerala coast

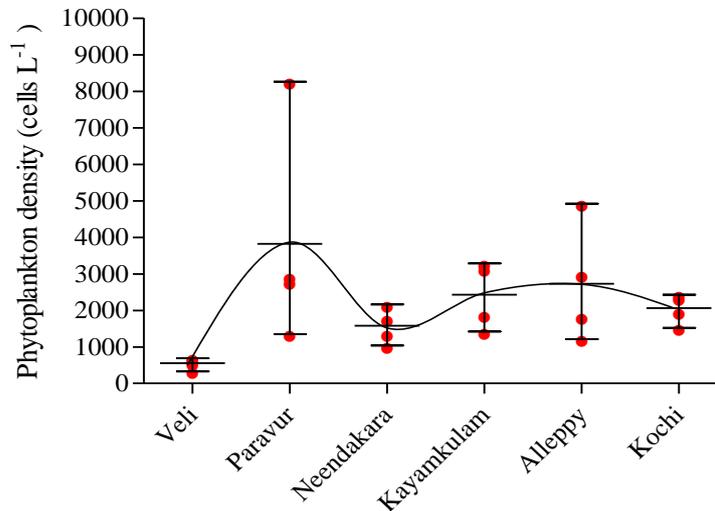


Figure 6. Phytoplankton density along the various transects of southern Kerala coast

Table 1. Simple correlation co-efficient (r) for the physico-chemical variables along the southern Kerala coast

	A.T	W.T	Salinity	TSM	DO	pH	NO ₂ ⁻ -N	NO ₃ ⁻ -N	DIP	T.Chl	Phyto	(d')	(J')	(H')
A.T	1													
W.T	-.192	1												
Salinity	.084	.026	1											
TSM	.116	.057	-.538**	1										
DO	-.004	.131	-.145	.028	1									
pH	.218	-.182	-.009	-.327	.565**	1								
NO ₂ ⁻ -N	.125	-.084	-.614**	.803**	.251	-.067	1							
NO ₃ ⁻ -N	.241	-.001	-.460*	.708**	.181	.009	.882**	1						
DIP	.134	.075	-.567**	.851**	.241	-.023	.910**	.875**	1					
T.Chl	-.047	-.253	.078	-.156	-.017	.112	-.152	-.124	-.118	1				
Phyto	.064	-.244	.064	-.135	-.005	.177	-.136	-.099	-.123	.939**	1			
(d')#	.337	-.424*	-.216	.103	.175	.343	.144	.161	.199	.382	.286	1		
(J')#	-.332	.027	-.405*	.116	-.018	.061	.218	.191	.224	.092	-.097	.276	1	
(H')#	.059	-.335	-.321	.092	.097	.279	.146	.157	.198	.411*	.261	.900**	.634**	1

** Correlation is significant at the 0.01 level ($P < 0.01$), * Correlation is significant at the 0.05 level ($P < 0.05$), #Species richness (d'), #Evenness index (J'), #Shannon Wiener (H')

Table 2. Checklist of phytoplankton species recorded along southern Kerala coast

No	Name of the species	Kochi	Alleppey	Kayamkulam	Neendakara	Paravur	Veli
BACILLARIOPHYCEAE							
Order : Centriales							
Family : Melosiraceae							
1	<i>Stephanophysis palmmeriana</i>	+	+	+	+	+	-
Family : Thalassiosiraceae							
2	<i>Skeltonema coastatum</i>	++	+++	+++	+++	+++	+
3	<i>Thalassiosira coramendelina</i>	-	+	+	+	+	-
4	<i>Thalassiosira subtilis</i>	+	+	+	+	+	+
5	<i>Cyclotella striata</i>	+	+	+	+	+	+
6	<i>Planktonella sol</i>	+	+	+	+	+	-
Family : Coscinodiscus							
7	<i>Coscinodiscus eccentricus</i>	+	++	++	++	++	-
8	<i>Coscinodiscus rothii</i>	+	+	+	+	+	-
9	<i>Coscinodiscus gigas</i>	+	+	+	+	+	-
10	<i>Coscinodiscus iridis</i>	+	+	+	+	+	-
11	<i>Coscinodiscus marginatus</i>	-	+	+	+	+	-
12	<i>Coscinodiscus asteromphalus</i>	+	+	+	+	+	-
Family : Actinodisceae							
13	<i>Actinotychus undulatus</i>	+	+	+	+	+	+
14	<i>Asteromphalus flagellatum</i>	-	+	-	+	-	+
15	<i>Asteromphalus wyvillei</i>	-	+	+	+	+	+
Family : Eupodisceae							
16	<i>Gosleria tropica</i>	-	+	+	-	-	+
Family : Solenia							
17	<i>Corethron hystrix</i>	+	+	+	+	+	+
18	<i>Lauderia annulata</i>	+	+	+	+	+	-
19	<i>Schoderella delicatula</i>	+	+	+	+	+	+
20	<i>Leptocylindrus danicus</i>	++	++	++	++	++	+
21	<i>Leptocylindrus minimus</i>	+	+	+	+	+	+
22	<i>Guinardia flaccida</i>	+	+	+	+	+	+
23	<i>Rhizosolenia cylindrus</i>	-	+	+	+	+	-
24	<i>Rhizosolenia stouterfothii</i>	+	+	+	+	+	-
25	<i>Rhizosolenia robusta</i>	+	+	+	+	+	-
26	<i>Rhizosolenia imbricata</i>	+	++	+	+	+	-
27	<i>Rhizosolenia styliformis</i>	+	+	+	+	+	-
28	<i>Rhizosolenia setigera</i>	+	+	+	+	+	-
29	<i>Rhizosolenia castracanei</i>	+	+	+	+	+	-
30	<i>Rhizosolenia alata</i>	++	++	++	++	++	-
Family : Chaetocereae							
31	<i>Bacteristrum delicatulum</i>	-	-	+	-	-	+
32	<i>Bacteristrum hyalinum</i>	+	++	++	++	++	-
33	<i>Bacteristrum varians</i>	+++	+++	+++	+++	+++	-
34	<i>Bacteristrum cosmorum</i>	+	+	+	+	+	+
35	<i>Chaetoceros coarctatus</i>	+	+	+	+	+	-
36	<i>Chaetoceros penicillatus</i>	+	+	+	+	+	-
37	<i>Chaetoceros lorenzians</i>	+++	+++	+++	+++	+++	-
38	<i>Chaetoceros diversus</i>	-	+	+	+	+	-
39	<i>Chaetoceros messanensis</i>	+	+	+	+	+	-
40	<i>Chaetoceros curvisetus</i>	++	++	++	++	++	+
Family : Biddulphiaceae							
41	<i>Eucampia zoodicus</i>	+	+	+	+	+	+
42	<i>Eucampia cornata</i>	+	+	+	+	+	+
43	<i>Climacodium frauenfeldianum</i>	+	+	+	+	+	+
44	<i>Streptotheca indica</i>	+	+	+	+	+	-
45	<i>Bellerophon malleus</i>	+	+	+	+	+	-
46	<i>Ditylum brightwellii</i>	+	+	+	+	+	+
47	<i>Ditylum sol</i>	-	+	+	+	+	-
48	<i>Lithodesmium undulatum</i>	+	+	+	+	+	-
49	<i>Triceratium faves</i>	+	+	+	+	+	-
50	<i>Biddulphia sinensis</i>	+	+	+	+	+	-
51	<i>Biddulphia mobiliensis</i>	+	++	++	+	+	+
52	<i>Biddulphia heteroceros</i>	-	+	-	-	+	+
Family : Hemiaulaceae							
53	<i>Hemiaulus sinensis</i>	-	+	+	+	+	+
54	<i>Cerataulina bergonii</i>	-	+	-	-	+	-

	Family : Eodiace						
55	<i>Hemidiscus hardmannianus</i>	-	+	+	+	-	+
	Order Pennales						
	Family : Fragilarioideae						
56	<i>Fragilaria oceanica</i>	++	+++	+++	+++	+++	-
57	<i>Synedra fomosa</i>	-	+	--	-	-	-
58	<i>Talassionema nitzschioides</i>	++	++	++	++	++	-
59	<i>Talassiothrix longissima</i>	-	+	+	-	+	-
60	<i>Talassiothrix frauenfeldii</i>	++	+++	+++	+++	+++	+
61	<i>Asterionella japonica</i>	+++	+++	+++	+++	+++	++
	Family : Naviculoidae						
62	<i>Gyrosigma balticum</i>	+	+	+	+	+	-
63	<i>Pleurosigma elongatum</i>	+	+	+	+	+	+
64	<i>Pleurosigma nomanii</i>	+	+	+	+	+	+
65	<i>Pleurosigma angulatum</i>	+	+	+	+	+	+
66	<i>Diploneis weissflogii</i>	-	-	+	+	-	+
67	<i>Diploneis robustus</i>	-	+	-	+	+	-
68	<i>Navicula longa</i>	+	+	+	+	+	+
69	<i>Navicula clavata</i>	-	+	+	+	-	-
70	<i>Pinnularia alpina</i>	-	+	+	-	-	+
71	<i>Amphora lineolata</i>	+	+	+	+	+	+
	Family : Bacillariaceae						
72	<i>Bacillaria paradoxa</i>	++	++	+	+	+	+
73	<i>Nitzschia sigma</i>	+	+	+	+	+	+
74	<i>Nitzschia longissima</i>	-	+	-	+	-	-
75	<i>Nitzschia seriata</i>	+	++	+	+	++	+
	DINOPHYCEAE						
	Order : Proocentrales						
76	<i>Proocentrum micans</i>	+	+	+	-	-	+
	Order : Dinophysiales						
77	<i>Dinophysis pedunculata</i>	+	+	+	+	+	+
78	<i>Dinophysis milis</i>	-	+	+	+	+	+
79	<i>Ornithocercus thumi</i>	-	+	+	-	-	+
80	<i>Ornithocercus stenii</i>	+	+	+	+	+	+
	Order: Peridinales						
81	<i>Noctiluca miliaris</i>	+	+	+	+	+	-
82	<i>Pyrophacus horologicum</i>	+	+	+	+	+	-
83	<i>Protoperidinium ovatum</i>	+	+	+	+	+	-
84	<i>Protoperidinium pedunculatum</i>	+	+	+	+	+	-
85	<i>Protoperidinium brochii</i>	-	-	+	-	-	-
86	<i>Protoperidinium conicum</i>	+	+	+	+	+	-
87	<i>Protoperidinium depressum</i>	+	+	+	+	+	+
88	<i>Protoperidinium oceanicum</i>	+	+	+	+	+	+
89	<i>Goniaulax birostris</i>	-	+	-	-	+	+
90	<i>Ceratium furca</i>	+	+	+	+	+	+
91	<i>Ceratium inflatum</i>	+	+	+	+	+	+
92	<i>Ceratium fusus</i>	+	+	+	+	+	+
93	<i>Ceratium extensum</i>	-	-	+	+	-	-
94	<i>Ceratium tripos</i>	+	+	+	+	+	+
95	<i>Ceratium pulchellum</i>	+	+	-	+	+	-
96	<i>Ceratium breve</i>	+	+	+	+	+	+
97	<i>Ceratium azoricum</i>	-	+	-	-	+	-
98	<i>Ceratium macroceros</i>	+	+	+	+	+	+
99	<i>Ceratium trichoceros</i>	-	+	+	-	+	+
100	<i>Oxytoxum scolopx</i>	-	+	+	-	-	-
	CYNOPHYCEAE						
101	<i>Trichodesmium erythraea</i>	+	+	+	+	+	+
	HAPTOPHYCEAE						
102	<i>Coccolithus</i> sp.	+	+	+	+	+	+
103	<i>Discosphaera</i> sp.	-	+	-	+	-	-
	CHRYSOPHYCEAE						
104	<i>Distephanes speculum</i>	-	+	-	-	+	-
	CHLOROPHYCEAE						
105	<i>Chlorella marina</i>	+	+	+	+	+	-

“+” Denotes presence, “++” Denotes less abundant, “+++” Denotes abundant, “-” Denotes absence

Table 3. Taxonomic composition and proportional representation of phytoplankton species among transects

Taxonomic group	Kochi	Alleppy	Kayamkulam	Neendakara	Paravur	Veli
Bacillariophyceae	55	73	69	68	66	34
Dinophyceae	17	23	22	18	20	15
Cynophyceae	1	1	1	1	1	1
Haptophyceae	1	2	1	2	1	1
Chrysophyceae	0	1	0	0	1	0
Chlorophyceae	1	1	1	1	1	0
TOTAL	75	101	94	90	90	51

Table 4. Information (range and mean) on the diversity indices of phytoplankton in the shelf southern Kerala coast

Diversity indices	Kochi	Alleppy	Kayamkulam	Neendakara	Paravur	Veli
cells L ⁻¹ (<i>N</i>)	1520-430	1215-4920	1420-3285	1035-2165	1345-8260	325-685
Species Richness (<i>d'</i>)	2.42-3.08	2.48-3.15	2.65-3.56	2.82-3.15	2.34-2.68	1.23-1.80
Evenness Index (<i>J'</i>)	0.74-0.92	0.68-0.85	0.62-0.84	0.56-0.95	0.43-0.86	0.61-0.84
Shannon- Wiener (<i>H'</i>)	2.38-2.60	2.16-2.40	2.35-2.56	2.23-2.69	2.18-2.38	1.34-1.85

Chaetoceros lorenzianus (28.74%) and *Bacteriastrium varians* (5.55%), at Neendakara were *Chaetoceros lorenzianus* (51.17%), *Asterionella japonica* (12.78%) and *Talassiothrix frauenfeldii* (4.01%), at Paravur were *Chaetoceros lorenzianus* (37.69%), *Asterionella japonica* (5.52%), *Talassiothrix frauenfeldii* (5.04%) and *Chaetoceros curvisetus* (4.46%) and at Veli transect were *Chaetoceros lorenzianus* (19.40%), *Asterionella japonica* (5.73%), *Skelitonema coastatum* (5.11%) and *Bacteriastrium varians* (4.05%), respectively. The percentage contribution of phytoplankton groups was in decreasing order as follows, Diatom>Dinoflagellates>Haptophyceae>Cyanophyceae>Chlorophyceae>Chrysophyceae. In all the stations diatoms were the major contributor than that of other groups, and its overall relative abundance reached up to 96.84%. Diatom were the dominant forms, while *Skelitonema coastatum*, *Coscinodiscus eccentricus*, *Leptocylindrus danicus*, *Rhizosolenia alata*, *Bacteriastrium varians*, *Chaetoceros lorenzianus*, *Chaetoceros curvisetus*, *Fragilaria oceanica*, *Talassionema nitzschoides*, *Talassiothrix frauenfeldii* and *Asterionella japonica* were the dominant phytoplankton species encountered most of the stations. Among the stations, maximum phytoplankton standing crop of 8260 cells L⁻¹ was recorded at Paravur 5 km offshore, whereas Veli nearshore recorded minimum standing crop of 326 cells L⁻¹. Phytoplankton diversity (Margalef richness *d'*, Shannon-Wiener *H'*, Pielou's evenness *J'*), abundance and biomass in the waters of Paravur, Neendakara and Alleppy transects were observed to be higher relative to southern transect Veli. (Table 4). The low phytoplankton count and diversity encountered at Veli transect might be due to the high pH, suspended particulate matter and low dissolved oxygen. However grazing pressure from zooplankton is not a matter of fact in the case of low phytoplankton production. This result is ratified by various earlier observations [33,34,35,36]. In the present study nutrients are not much significant in phytoplankton standing crop. High standing crop was recorded at offshore stations compared to nutrient rich near

shore waters. This might be due to marginal salinity stress from the fresh water input. The high phytoplankton density at Paravur might be due to combined optimal conditions like temperature, salinity, nutrient level and light which might enhance the quick multiplication of phytoplankton cells. Similar observations were also made by Ananthan, [37] from Pondicherry coast and Rajashree and Panigrahy [38] from Gopalpur coastal waters. The physical factors related to water movements, horizontal or vertical, in turn were influenced by seasonal and climatic factors, perennial catchment discharge through backwaters and nutrient leaching from mudbanks, lead to control over organic production, biomass and its community structure.

4. Conclusions

From this study, it is obvious that the variations in the water quality play a significant role on phytoplankton community structure along the coastal waters. The predominant nanoplankton community along the Southeast Arabian was largely involved in the conversion of the inorganic nutrients into phytoplankton biomass and sustained autotrophy. Preponderance of favorable environmental conditions (optimum nutrients and light) prevailing beyond surf zone, enhanced the abundance of nanoplankton community in these waters, whereas in the nearshore stations, light limitation due to high turbidity reduced the nanoplankton growth and abundance, even though existence of high nutrient level. Variation in the nutrient stoichiometry suggested, these coastal waters are very sensitive to further increase in nutrient loading. The study provides baseline knowledge on the productivity, pigment concentration, phytoplankton community structure and the quantity of phytoplankton biomass available for marine food web with respect to various environmental conditions, which could give a new insight to the future ecological assessment along coastal and shelf waters of southern Kerala.

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