

Seasonal distribution of phytoplankton and its association with physico-chemical parameters in coastal waters of Malvan, west coast of India

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Abstract Malvan coast is one of the Marine Protected Area (MPA) of Maharashtra because of its rich coral reef and biodiversity. The study investigated on phytoplankton assemblage and their diversity with respect to physico-chemical parameters covering protected and unprotected area of Malvan coast. Physico-chemical parameters such as salinity, nitrite, nitrate, and ammonia did not display seasonality due to inadequate fresh water influx and allochthonous nutrient input. Positive correlation of phosphate ($r = 0.96$, $p < 0.0001$) and silicate ($r = 0.91$, $p < 0.0001$) with Total Suspended Solids (TSS) confirmed their autochthonous origin as a result of resuspension of bottom sediments during monsoon. A total of 57 phytoplankton species were identified mostly dominated by Bascillariophyceae (40 species), followed by Dinophyceae (9 species), Chlorophyceae (5 species), Cyanophyceae (2 species), and Dictyochophyceae (1 species) from Malvan coast. Canonical correspondence analysis (CCA) revealed that water temperature and TSS were the most significant parameters influencing the distribution and seasonal shift in phytoplankton species such as *Skeletonema costatum* and *Chaetoceros* sp. during pre-monsoon and *Pseudo-nitzschia* sp., *Streptotheca thamensis*, *Eucampia zodiacus*, and *Lithodesmium undulatum* during post-monsoon. Silicate and phosphate had minor

influence on phytoplankton distribution. Shannon-Wiener diversity index as a pollution index suggested that the study area was incipiently polluted except at bay stations. Despite of various human interventions the water quality and phytoplankton assemblage of this area has not reached to an alarming situation. The current study provides a valuable baseline data on phytoplankton assemblage from Malvan coast.

Keywords Marine protected area · Phytoplankton · Biomass · Community structure · Diversity index · Malvan

Introduction

Coastal zone encompasses diverse and productive areas such as coral reefs, mangroves, and sea grasses. These ecosystems have considerable share in global food production and support variety of economic activities in the form of fishery, aquaculture, tourism, recreation, and transportation. These activities have decreased the resilience of coastal ecosystem by unsustainable uses of its resources and increasing their vulnerability to anthropogenic pressures and climate change effects (Bijlsma et al. 1995). Furthermore, the natural process of particular coastal area has its own unique characteristics, structured by water exchange with adjacent areas, topology of the coastline, rainfall, and river discharge (Ilyash et al. 2015). Therefore, the natural processes together with anthropogenic activities result in the formation of gradient in abiotic and biotic factors which has strong

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impact on phytoplankton species composition, succession, and abundance (Biswas et al. 2015).

Phytoplankton acts as a primary producer and represents themselves as a direct food source for heterotrophic aquatic organisms (Price 2001). Their composition and abundance are considered as natural bio-indicator of water quality because of their sensitivity and rapid response to change in environmental conditions (light intensity, temperature, salinity, and nutrient load) (Gharib et al. 2011). These environmental parameters often vary seasonally, and, thus, it is noteworthy to study the community structure, spatio-temporal distribution, relative abundance, and diversity of this aquatic biota as indicator of environmental health or biological integrity of a particular water body.

Malvan coast extends from 16° 00' to 16° 05' N Latitude and 73° 25' to 73° 30' E Longitude and forms a part of the Western Ghats where the Sahyadri ranges abruptly meet the Arabian Sea. It has been declared as a marine sanctuary or Marine Protected Area (MPA) because of relatively rich marine diversity and coral reefs (Pawar and Lavate 2015). In addition to this, Sindhudurg Fort, which is an attractive tourist spot, is also located at a fortified island on the south side of the entrance of the Malvan coast. The socio-economic status of Malvan coastal villages is mainly dependent on fishing and tourism. According to a report published by Integrated Coastal Marine Area Management (ICMAM) (2001), the total annual fish catch of year 1999–2000 was 13,433 t. Therefore, a combined effect of all these activities may have adverse effects on marine biota due to human interventions in this pristine environment. The study made by Ramaiah et al. 2002 in Malvan coast taking direct viable count of bacteria as a proxy, categorized Malvan coast under moderately polluted area.

Highly dynamic nature of coastal ecosystem due to heterogeneity in physical, chemical, and biological factors makes it more difficult to determine the limiting factors or the environmental drivers of phytoplankton assemblage. Considering the ecological significance of phytoplankton, numerous studies have been carried out on phytoplankton community from west coast of India such as from Cochin backwater (Madhu et al. 2007, 2010; Martin et al. 2013), Mandovi-Zuari (Patil and Anil 2011, Mochemadkar et al. 2013; Pednekar et al. 2014; Patil and Anil 2015), and Mumbai waters (Ramaiah et al. 1998; Jaiswar et al. 2013). All these studies were mostly focused on estuarine system and provided several mechanistic approaches on the

seasonal shift, effect of monsoon, oil spill, and eutrophication on community structure of phytoplankton. Even though Malvan is a marine protected area and has socio-economic importance, it received less scientific attention and very few information is available on phytoplankton species assemblages (Dehadrai and Bhargava 1972; Integrated Coastal and Marine Area Management, ICMAM, 2001).

The above discussion clearly reveals absence of information on the spatial and temporal distribution of phytoplankton assemblage and their environmental drivers from the diverse and protected ecosystem of the Malvan coast. The current paper is the first report on the phytoplankton abundance, community structure, and spatio-temporal distribution of phytoplankton from Malvan coast. The study emphasizes on the influence of changing environmental conditions on phytoplankton species abundance, apart from that, it also provides the checklist of phytoplankton species during three major seasons namely pre-monsoon, monsoon, and post-monsoon. In addition to this, Shannon-wiener diversity index (H') was used as a pollution index to determine the pollution status of Malvan coast with respect to anthropogenic activities.

Methods and methodology

Study period and site description

Sampling was carried from six pre-selected stations covering protected (buffer and core zone of MPA) and unprotected area of Malvan coast (Fig. 1). The choices of stations were made to study the seasonal changes and human interventions in the MPA with respect to phytoplankton assemblages. Stations were divided as, bay stations (M1 and M2), near shore stations (M5 and M6), and outer stations (M3 and M4) with average depth of 5, 3, and 20 m, respectively. Bay stations M1 and M2 are in the buffer zone of MPA where maximum anthropogenic activities like fish landing (harbor) and passenger jetties for tourists have been operated. This forming an important platform for all fishing activities of the town and movement of ferry boats to the fort. While near stations M5 and M6, which is also in the buffer zone but with limited human impact. Outer stations M3 is in the core zone of MPA, and in the vicinity of Sindhudurg Fort, while M4 is located outside the boundary of MPA with negligible anthropogenic

activities and can be treated as a control site. The study region is with inadequate freshwater influx as there is no perennial river or creek joining the bay. However, some minor influence of Kalavali River approximately 4 km in the north and Karli River 10.5 km in the south is possibly under the prevailing tidal circulation. Though domestic waste water from the town entered the bay through non point sources, there was no known industrial and domestic point source releases in the MPA of Malvan coast.

The study was carried out over a year—from March 2012 to February 2013, during three seasons namely Pre-monsoon, February–May; Monsoon, Jun–September; and Post-monsoon, October–January. The seasons are classified on the basis of southwest monsoon which has profound influence on the west coast India. Thus, pre-monsoon is the period with least rainfall followed by monsoon that brings bountiful rainfall with post-monsoon as the interphase between the two. Rainfall data for the study period (2012 and 2013) were acquired from the Meteorological Department (IMD), Pune, and given Fig. 2.

Physico-chemical parameters

The present study was carried out in a power boat with eco-sounder (Grainin, GNX 20), and samples were collected during the day time irrespective of tide. Water samples from surface and near bottom were collected using a 5-L Niskin water sampler (Hydro-Bios, Kiel-Holtenau, Germany). Water temperature was measured by hand held standard mercury thermometer (BRANNAN Brand, U.K.) of accuracy ± 0.1 °C. Salinity and dissolve oxygen (DO) were estimated by Mohr titration and Winkler's method, respectively, as recommended by Grasshoff (1983). Total suspended solid (TSS) (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 h before weighing (APHA, American Public Health Association, 2005). Inorganic dissolved nutrients like nitrite (NO_2), nitrate (NO_3), ammonia (NH_4), phosphate (PO_4), and silicate (SiO_4) were collected in clean polyethylene bottles and kept in an ice box. In laboratory, these water samples were filtered through Millipore filter paper ($0.45 \mu\text{m}$) and analyzed by spectrophotometric procedure within 6 h of collection as described by Grasshoff, 1983.

Phytoplankton biomass estimation, identification, and enumeration

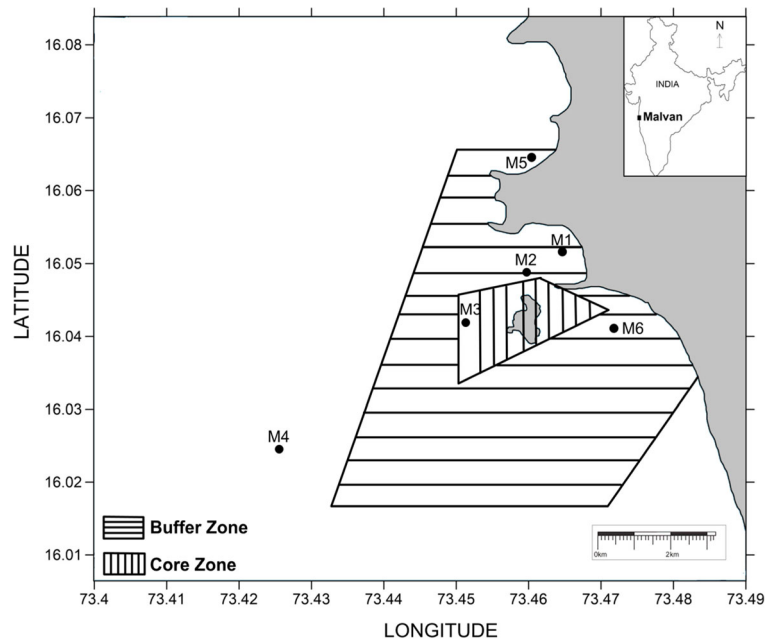
For the estimation of phytoplankton biomass (Chlorophyll *a*), water sample was collected using Niskin water sampler from surface and near bottom and dispensed directly into 500 ml amber colored plastic bottle and transported to the laboratory by keeping in ice box. Thereafter, these samples were filtered through GF/F filter paper (pore size $0.7 \mu\text{m}$ and diameter 47 mm). The filtrate was extracted by keeping in 90% acetone for 24 h in the dark at 4 °C and pigments measured using fluorometer (Turner Trilogy Model 7200, USA) before and after acidification following standard protocol (Strickland and Parsons, 1972).

For the study of phytoplankton, abundance and composition 500 ml of surface and near bottom water sample was fixed with 2% Lugol's iodine (acidic solution prepared using acetic acid glacial). Samples were allowed to settle for 2 days and concentrated to 10 ml by carefully siphoning the top layer of the sample with silicon tubing without disturbing the bottom layer. Using Sedgwick Rafter chamber (PYSER- SGI Ltd. UK) 1 ml of above concentrated sample was taken for taxonomic identification and enumeration under compound microscope (MOTIC BA 410, 400 magnifications). Phytoplankton were identified up to species level where ever possible using standard taxonomic keys (Subrahmayan, 1946; Desikachary 1959; Tomas, 1997). The numbers of phytoplankton cells present in all 1000 grids were counted, and phytoplankton density (cells L^{-1}) was calculated according to standard protocol (UNESCO 1994).

Statistical analysis

Different statistical software such as canonical correspondence analysis (CCA), Pearson's correlation matrix (r), Shannon-Wiener diversity index ($H' \log_2$), and Pielou evenness (J') were applied to find out diversity and environmental drivers of phytoplankton assemblages while CCA was mainly used to examine the environmental variables influencing the phytoplankton community. Significant environmental variables were selected by forward selection with program CANOCO (version 4.5) and assessed for its statistical significance axes using Monte

Fig. 1 The map of Malvan showing the station location



Carlo permutation test (499 permutations at a significance level 0.05). Person's correlations were computed using XLSTAT 2016 to assess correlation between the environmental variables and phytoplankton communities. Phytoplankton species diversity index (H') and evenness (J') were calculated using primer version 5 (Clarke and Warwick 1994) according to:

Species diversity (H') = $\sum (P_i \log_2 (P_i))$, Shannon Weaver, (1963).

Species evenness (J') = $H' / \log_2(S)$, Pielou, (1975).

Where $P_i = n_i/n$ (proportion of the sample belonging to the i^{th} species. 'S' is the number of species

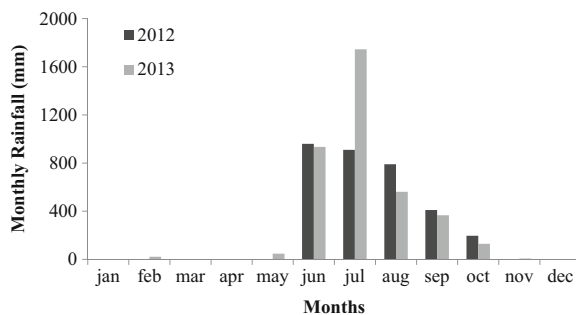


Fig. 2 Monthly rainfall data for the period of 2012–2013

Results

Spatio-temporal variation in physico-chemical parameters

The results were represented as a single data set (average of surface and bottom) since there was no depth wise variation which is depicted in standard deviation as given in Table 1. Temporal and spatial variation in salinity (35.63 ± 0.39) was not appreciable in MPA of Malvan coast due to inadequate freshwater influx (Fig. 3a). As expected for tropical coast, the temporal variability in water temperature was relatively low with seasonal maximum ($av. 30.91 \pm 0.41$ °C) during pre-monsoon and minimum ($av. 27.37 \pm 0.58$ °C) during monsoon (Fig. 3b). Seasonality in TSS was evident with high content during monsoon ($av. 83.78 \text{ mg L}^{-1} \pm 12.64$) and low in post-monsoon ($av. 20.89 \pm 2.11 \text{ mg L}^{-1}$) and pre-monsoon ($av. 28.50 \pm 6.81 \text{ mg L}^{-1}$) (Fig. 3c). DO varied between 5.52 and 7.69 mg L^{-1} ($av. 6.55 \pm 0.62$) (Fig. 3d) with the absence of spatio-temporal trends. Likewise, inorganic nutrients like nitrite, nitrate, and ammonia did not reveal remarkable seasonal variation though phosphate and silicate showed noticeable seasonal variation with higher levels of phosphate in monsoon ($>1.0 \text{ } \mu\text{M}$) which decreased during post-monsoon and pre-monsoon

Table 1 The average values and standard deviation of physico-chemical parameters measured in the study region. Values for standard deviation are given (in parenthesis)

Locations/seasons	Parameters								
	Temperature °C	TSS mgL ⁻¹	Salinity	DO mgL ⁻¹	NO ₂ µgL ⁻¹	NO ₃ µgL ⁻¹	NH ₄ µgL ⁻¹	PO ₄ µgL ⁻¹	SiO ₄ µgL ⁻¹
Pre-monsoon									
M1	31.08 (±0.29)	27.16 (±1.35)	35.63 (±0.11)	7.69 (±0.54)	0.06 (±0.02)	0.76 (±0.46)	1.15 (±0.36)	0.75 (±0.32)	0.86 (±0.29)
M2	30.65 (±0.81)	25.67 (±4.31)	36.41 (±0.09)	7.14 (±0.16)	0.17 (±0.07)	1.38 (±0.41)	0.62 (±0.09)	0.98 (±0.31)	3.06 (±1.30)
M3	30.43 (±0.17)	22.34 (±6.20)	35.36 (±0.15)	7.29 (±0.16)	0.15 (±0.05)	1.60 (±0.81)	1.12 (±0.37)	0.48 (±0.09)	3.39 (±0.18)
M4	30.6 (±0.120)	23.83 (±2.27)	35.45 (±0.11)	6.75 (±0.18)	0.12 (±0.02)	0.98 (±0.15)	0.63 (±0.22)	0.51 (±0.13)	3.5 (±0.37)
M5	31.20	41.00	35.40	6.60	0.18	3.09	1.75	0.74	3.40
M6	31.50	31.00	35.54	6.27	0.12	1.48	1.11	0.67	2.85
Monsoon									
M1	27.68 (±1.08)	61.84 (±4.35)	35.23 (±0.18)	6.5 (±0.91)	0.13 (±0.02)	1.08 (±0.28)	1.31 (±0.28)	0.81 (±0.09)	5.55 (±2.39)
M2	26.63 (±0.21)	92.22 (±13.45)	34.77 (±0.17)	5.52 (±0.88)	0.13 (±0.02)	1.42 (±0.29)	1.35 (±0.37)	1.51 (±0.33)	17.98 (±6.27)
M3	26.85 (±0.26)	98.81 (±16.62)	35.13 (±0.18)	5.52 (±0.88)	0.18 (±0.06)	1.57 (±0.17)	1.00 (±0.15)	1.71 (±0.28)	16.95 (±4.36)
M4	27.18 (±0.17)	86.81 (±9.23)	35.09 (±0.24)	5.84 (±0.71)	0.16 (±0.03)	1.85 (±0.13)	1.15 (±0.28)	1.48 (±0.32)	15.07 (±3.72)
M5	28.10	81.00	35.18	6.40	0.08	1.13	0.74	0.40	4.20
M6	27.80	82.00	34.81	6.40	0.05	1.39	0.75	1.00	10.40
Post-monsoon									
M1	27.97 (±1.34)	22.84 (±13.06)	35.06 (±0.11)	7.08 (±0.48)	0.15 (±0.00)	1.06 (±0.15)	0.82 (±0.26)	0.50 (±0.03)	3.48 (±2.20)
M2	27.8 (±0.93)	20.67 (±1.29)	35.09 (±0.11)	6.26 (±0.16)	0.13 (±0.04)	1.73 (±0.32)	0.76 (±0.11)	0.39 (±0.05)	4.73 (±0.48)
M3	27.83 (±0.78)	18.96 (±0.77)	35.27 (±0.11)	5.94 (±0.30)	0.24 (±0.06)	2.25 (±0.25)	0.89 (±0.13)	0.41 (±0.05)	5.66 (±0.38)
M4	27.48 (±0.28)	17.88 (±1.19)	35.18 (±0.15)	6.42 (±0.30)	0.35 (±0.10)	2.25 (±0.36)	1.50 (±0.29)	0.49 (±0.07)	5.83 (±0.55)
M5	29.50	22.00	35.00	7.29	0.21	2.31	1.16	0.62	5.69
M6	29.60	23.00	35.18	6.97	0.16	1.10	1.45	0.41	4.66

(<0.8 µM). Silicate was relatively high during monsoon (>11 µM) but ranged between 3 and 6 µM in pre-monsoon and post-monsoon. Exceptionally, low silicate was observed at M1 during pre-monsoon (0.86 µM). During monsoon both phosphate and silicate, at stations M1 and M5, showed exceptionally low values compared to other stations (Fig. 4a–e).

Phytoplankton biomass, abundance, and community structure

Phytoplankton biomass distinctly varied spatially and temporally with the highest average biomass in post-monsoon (av. 4.95 mg m⁻³) followed by pre-monsoon (av. 4.17 mg m⁻³) and monsoon (av. 3.59 mg m⁻³). Bay and near shore stations (M1,

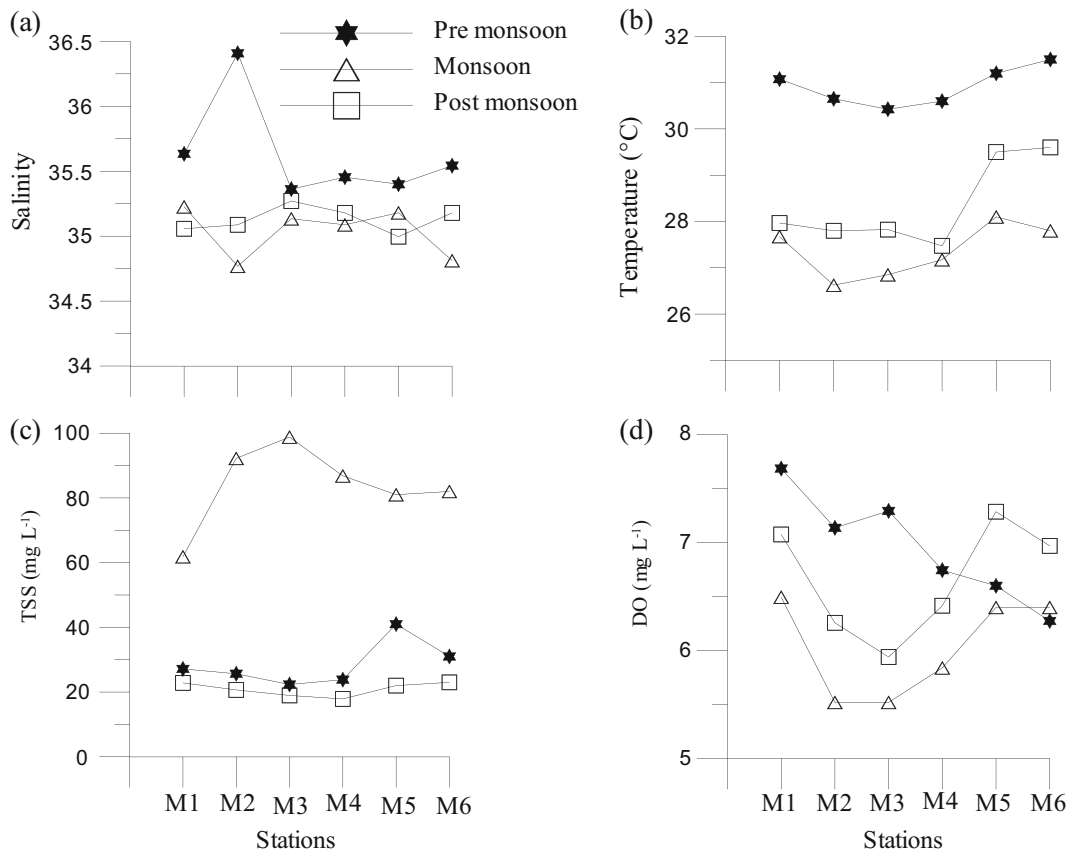


Fig. 3 Seasonal variations of different physico-chemical parameters. **a** Salinity. **b** Temperature. **c** TSS total suspended solids. **d** DO dissolved oxygen

M2, M5, and M6 sustained comparatively higher biomass than the outer stations (M3 and M4) with the highest biomass at station M2 (16.52 mg m^{-3}) during pre-monsoon. High biomass at station M2 was contributed by *Skeletonema costatum* (*S. costatum*) which eventually decreased during monsoon and post-monsoon. Phytoplankton density followed the similar trend as that of phytoplankton biomass (Fig. 5a, b).

Bacillariophyceae (diatoms) was the dominant class at all the stations with 90 to 97% contribution to the total phytoplankton density followed by dinophyceae (dinoflagellates) with contribution of just 2 to 7%, chlorophyceae (0 to 0.2%), cyanophyceae (0 to 0.2%), and dictyochophyceae (0 to 0.2%); last three classes together contributing under 1% to the total abundance (Fig. 6a–c). A total of 57 species falling under five classes namely diatoms (40 sp.), dinoflagellates (9 sp.), chlorophyceae (5

sp.), cyanophyceae (2 sp.), and dictyochophyceae (1 sp.) prevailed off Malvan. Among diatoms, *S. costatum*, *Chaetoceros* sp., *Pseudo-nitzschia* sp., *Thalassiosira* sp., *Guinardia striata* (*G. striata*), *Streptotheca thamensis* (*S. thamensis*), *Thalassionema nitzschioides* (*T. nitzschioides*), *Thalassiothrix* sp., *Eucampia zodiacs* (*E. zodiacus*), *Odontella mobiliensis* (*O. mobiliensis*), *Lithodesmium undulatum* (*L. undulatum*), *Navicula* sp., and *Navicula delicatula* (*N. delicatula*) were the major species in the study region. Among them *S. costatum* and *Chaetoceros* sp. during pre-monsoon whereas *Pseudo-nitzschia* sp., *S. thamensis*, *E. zodiacus* and *L. undulatum* during post-monsoon were in high abundance ($>1 \times 10^5 \text{ Cells L}^{-1}$). Even though diatom was the major class during all the seasons, the species number, and abundance of dinoflagellates proliferated during monsoon due to increased populations of *Protoperidinium* sp.,

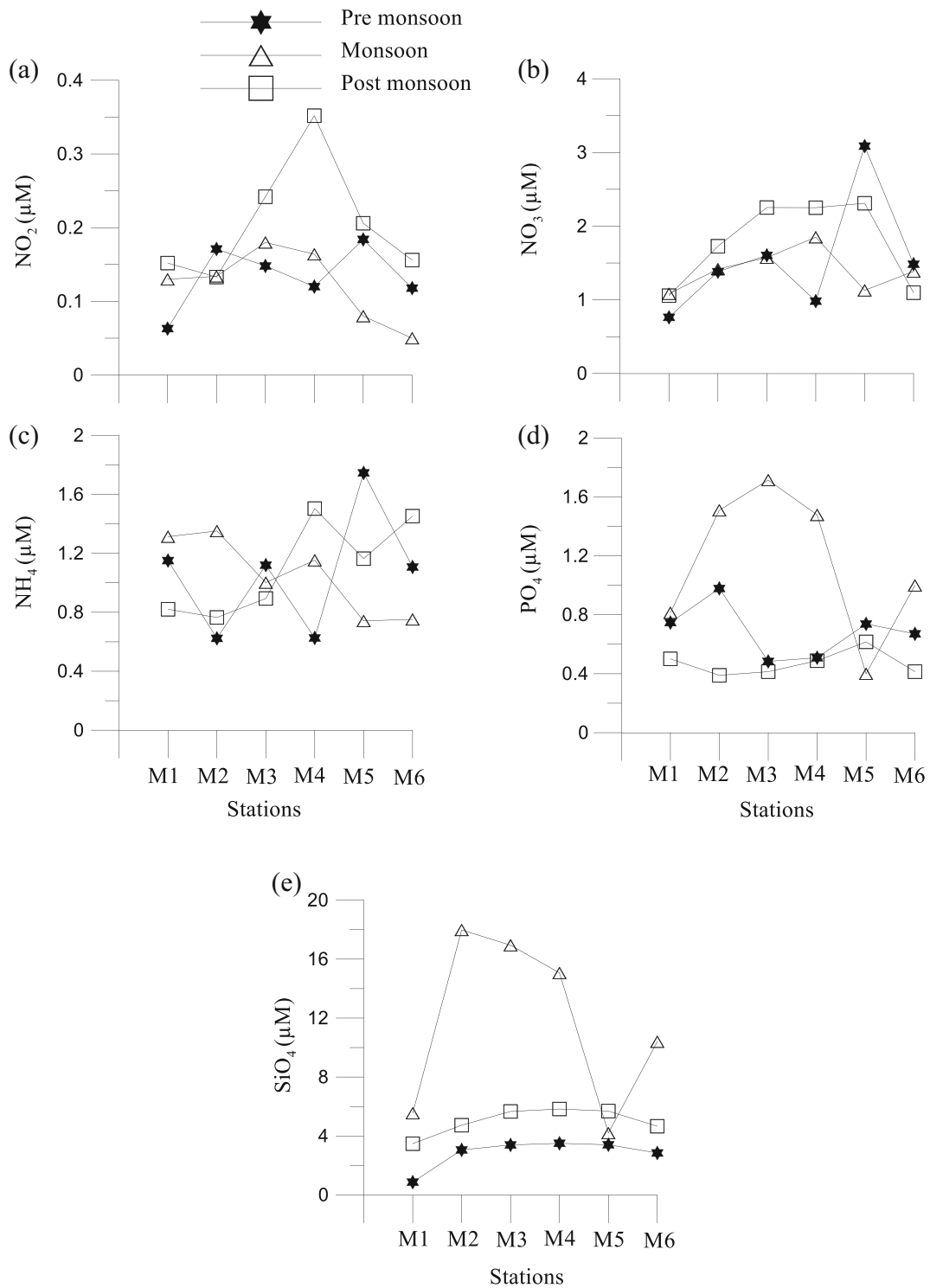
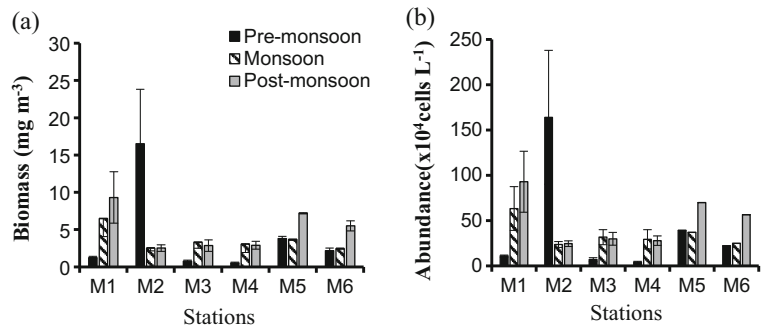


Fig. 4 Seasonal variation of dissolved nutrient concentration. **a** NO₂. **b** NO₃. **c** NH₄. **d** PO₄. **e** SiO₄

Prorocentrum sp., and *Peridinium* sp. whereas chlorophyceae, cyanophyceae, and

dictyochophyceae did not show much variation and recorded low abundance throughout the study period.

Fig. 5 Seasonal variation of **a** phytoplankton biomass and **b** abundance at different stations of Malvan coast



Statistical analysis

Phytoplankton species diversity and evenness

Shannon-Weiner diversity index (H' at \log_2) varied from 1.84 to 4.06 and evenness (J') from 0.36 to 0.80 in the study region with the highest diversity index at station M4 ($H' = 4.0$) during monsoon and the lowest at station M2 ($H' = 1.8$) during pre-monsoon. Marked seasonal as well as spatial variation in phytoplankton diversity were absent; however, the average diversity index was high (av. 3.23 ± 0.62) throughout the year. Evenness followed the similar trend as that of diversity and low values of evenness coincided with the stations of low diversity index (Fig. 7a, b).

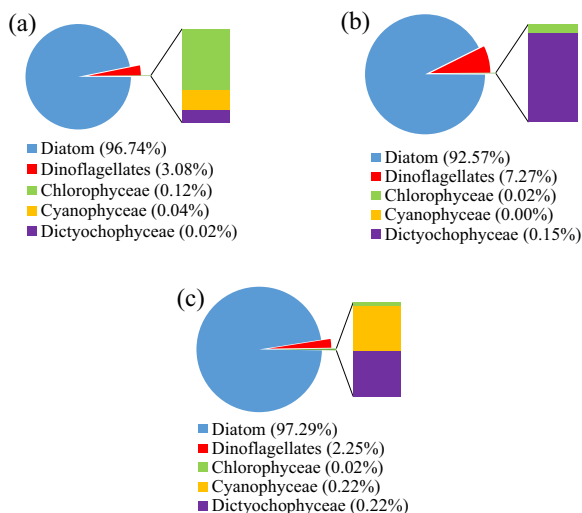
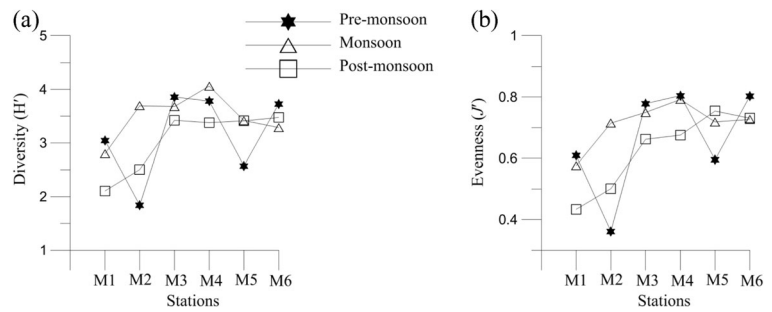


Fig. 6 Percentage composition of different phytoplankton classes during **a** pre-monsoon, **b** monsoon, and **c** post-monsoon

Canonical correspondence analysis

To find out the environmental drivers of major phytoplankton species from near shore to coastal region, stations M1 to M4 were selected for Canonical Correspondence Analysis (CCA). Four axes of CCA biplot together explain 94.2% variation in species–environment relationship. Out of the four axes, only the first two axes showing 78.9% of variance were selected for plotting CCA biplot. Axis 1 display 52.4% of variance in species–environment relationship and is strongly influenced by temperature, salinity, TSS, SiO₄, and NH₄. The second axis explains 37.6% of data set variability, and PO₄, NO₂, and NO₃ were the strongest contributors to this axis. The first axis of CCA which showed high percentage of variability divided the phytoplankton species into two groups according to their growth requirement. *T. nitzschioides*, *P. lima*, *Fragillaria* sp., *Peridinium* sp., *G. striata*, *Thalassiosira* sp., *Thalassiothrix* sp., *E. zodiacus*, *Protoperdinium* sp., and *O. mobiliensis* were in the first group and revealed adaptability to high TSS and requirement of relatively high nutrient concentrations such as SiO₄ and PO₄ for their growth. Other group included *S. costatum*, *Chaetoceros* sp., and *L. undulatum* which required relatively high temperature and salinity and preferred low TSS. *Pseudo-nitzschiasp.*, *S. thamensis.*, *N. delicatula*, and *Navicula* sp. which were significant to second axis showed preference to elevated NO₃ and NO₂ where as *L. undulatum* revealed preference to PO₄ (Fig. 8, Table 3).

Fig. 7 Seasonal variation of **a** diversity and **b** evenness at different stations of Malvan coast



Discussion

Spatio-temporal variation in physicochemical parameters

The physico-chemical parameters like rainfall, temperature, salinity, DO, and nutrients immensely influence the distribution and abundance of phytoplankton and the survival of aquatic organisms (Godhe et al. 2015). MPA of Malvan coast maintained relatively high salinity throughout the year. This could be probably due to high evaporation and inadequate freshwater influx from upstream waters (Integrated Coastal and Marine Area Management, ICMAM, 2001; Thillai et al., 2010). As expected for tropical shallow coastal areas, the surface water temperature varied in

accordance with the air temperature with relatively low values during monsoon due to heavy precipitation and cloud cover and high values during pre-monsoon because of intense solar radiation (Govindasamy et al. 2000; Prabu et al. 2008). Among the above mentioned physico-chemical parameters, TSS also played a role in controlling the phytoplankton distribution in the water column. Increased TSS during monsoon was perhaps due to re-suspension of fine-grained bottom sediment in the water column due to increased turbulence caused by tidal and wind induced currents as compared to other seasons (Panigrahi et al. 2009; Lim et al. 2012). MPA of Malvan coast remained well oxygenated ($> 5.5 \text{ mg L}^{-1}$) throughout the study period. Low concentration of nutrients like nitrate, nitrite, and ammonia, and absence of seasonal variation could be due to low land runoff in the study region and dominance of neritic water (Govindasamy et al. 2000). However, nutrients phosphate and silicate showed temporal variation with relatively high values during monsoon (Fig. 4d, e). Further phosphate ($r = 0.96, p < 0.0001$) and silicate ($r = 0.91, p < 0.0001$) showed significant positive correlation with TSS (Table 2) which was further confirmed by CCA as evident in Fig. 8 wherein phosphate, silicate, and TSS co-varied together (Table 3). Allochthonous origin of phosphate and silicate are negligible in MPA of Malvan coast due to inadequate freshwater influx through adjoining river or creek. Therefore, the observed high monsoonal phosphate and silicate content might be due to the regeneration and release of these nutrients from bed sediments into the water column by increased turbulence and mixing (Saravanakumar et al. 2008; Thillai et al. 2010). Although phosphate and silicate values were high during monsoon, their uptake by phytoplankton was found to be low due to

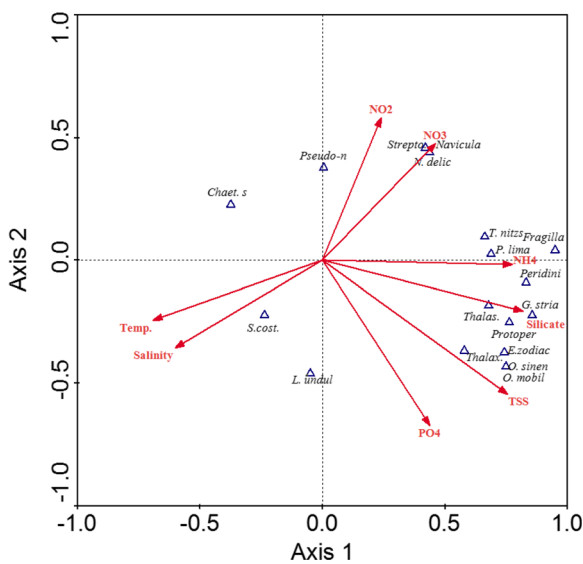


Fig. 8 CCA bi-plot of species environmental relationship

Table 2 Summary of the results of Pearson's correlation analysis. Values marked in italic are significant

Variables	Temp.	TSS	Salinity	DO	NO ₂	NO ₃	NH ₄	PO ₄	Silicate	Biomass	Diatom	Dino.	Diversity	Evenness
Temp.	<i>1</i>													
TSS	-0.59*	<i>1</i>												
Salinity	0.76**	-0.43	<i>1</i>											
DO	0.86***	-0.69***	0.61*	<i>1</i>										
NO ₂	-0.40	-0.17	-0.10	-0.33	<i>1</i>									
NO ₃	-0.49	-0.02	-0.24	-0.54	0.82***	<i>1</i>								
NH ₄	-0.44	0.37	-0.48	-0.24	0.31	0.24	<i>1</i>							
PO ₄	-0.42	0.94***	-0.16	-0.57	-0.15	-0.04	0.25	<i>1</i>						
Silicate	-0.74**	0.92***	-0.55	-0.86***	0.10	0.28	0.36	0.87***	<i>1</i>					
Biomass	0.12	-0.10	0.61*	0.23	0.06	-0.14	-0.36	0.08	-0.19	<i>1</i>				
Diatom	0.12	-0.12	0.62*	0.23	0.07	-0.14	-0.38	0.06	-0.20	1.00	<i>1</i>			
Dino.	-0.44	0.88***	-0.33	-0.56	-0.17	-0.01	0.41	0.76***	0.73***	-0.16	-0.19	<i>1</i>		
Diversity	-0.20	0.43	-0.47	-0.44	0.11	0.30	0.42	0.32	0.52	-0.79**	-0.80**	0.53	<i>1</i>	
Evenness	-0.14	0.40	-0.45	-0.39	0.07	0.22	0.37	0.28	0.47	-0.80**	-0.81**	0.51	0.99***	<i>1</i>
Richness	-0.30	0.21	-0.03	-0.37	0.24	0.55	0.25	0.30	0.37	0.11	0.11	0.07	0.08	-0.05

* $p \leq 0.05$; ** $p \leq 0.001$; *** $p \leq 0.0001$

Table 3 CCA results of environmental variables against phytoplankton community

Environmental variables	Axis 1	Axis 2	Axis 3	Axis 4
Salinity	-0.60	-0.36	-0.06	0.14
Temperature	-0.69	-0.24	0.10	0.32
TSS	0.75	-0.54	0.11	-0.27
NO ₂	0.24	0.58	-0.45	-0.03
NO ₃	0.46	0.47	-0.27	-0.06
NH ₄	0.77	-0.02	-0.33	0.21
PO ₄	0.44	-0.67	0.19	-0.35
Silicate	0.82	-0.21	0.16	-0.37
Eigenvalues	0.29	0.15	0.05	0.03
Species-environment correlations	1.00	1.00	0.91	0.99
Cumulative percentage variance				
Of species data	49.10	74.00	82.60	88.30
Of species-environment relation	52.40	78.90	88.10	94.20

reduction in light penetration as a consequence of high TSS. On the other hand, low phosphate and silicate concentration in pre-monsoon and post-monsoon can be attributed towards the utilization of these nutrients by phytoplankton for their growth (Prabu et al. 2008; Saravanakumar et al. 2008).

Phytoplankton biomass, abundance, and community structure

Seasonal variation in physical, chemical, and biological process is the determining factor for the phytoplankton succession and abundance (Thillai et al. 2010). High phytoplankton biomass and abundance during pre-monsoon and post-monsoon could be attributed to optimum temperature and increased light penetration due to reduction in TSS. Conversely, increase in TSS and short residence time of nutrients during monsoon might have resulted in low phytoplankton biomass (Achary et al. 2014). Phytoplankton community was dominated by diatoms which contributed more to the total phytoplankton biomass throughout the study period (Table 4). The dominance of diatoms in the coastal waters is very common phenomenon and has been reported by many researchers (Sahu et al. 2012; Rai and Rajashekhar 2014). Stowe (1996) reported that

the large sized diatoms as compared to other phytoplankton reduce their floating efficiency and make them more susceptible to sinking. Thus to overcome this problem, diatoms always prefer to inhabit and dominate the phytoplankton community in shallow, turbulent, coastal waters. Dinoflagellates which were less abundant than diatoms marginally increased in their percentage contribution during monsoon probably due to increased phosphate and silicate content as supported by their significant positive relation with phosphate ($r = 0.76, p = 0.004$) and silicate ($r = 0.73, p = 0.007$). Increase in abundance of dinoflagellates in phosphate enriched water due to sediment re-suspension during monsoon has been reported by Pednekar et al. (2014) in the Mandovi estuary. Low species count of chlorophyceae, cyanophyceae, and dictyochophyceae might be due to their preference to low salinity and high nutrient (Marshall et al. 2009; Liu et al. 2011) which is unavailable in Malvan coast.

Phytoplankton species composition and environmental gradient

Phytoplankton species composition is mostly influenced by nutrient fluxes and environmental factors (Achary et al. 2014). The CCA biplot of phytoplankton species composition and environmental variables suggested that species mainly responded to seasonal changes in environmental variables. High abundance of *S. costatum* (10.24×10^5 Cells L⁻¹) and *Chaetoceros* sp. (2.42×10^5 Cells L⁻¹) could be due to favorable pre-monsoonal conditions with optimum temperature and low TSS. Tian et al. (2002) and Li et al. (2009) also showed that even though *S. costatum* is a euryhaline and eurythermal species, to form bloom, it requires prolong exposure to high salinity and temperature. Further, *S. costatum* and *Chaetoceros* sp. are known to form resting spore under reduced water transparency and low temperature (Shikata et al. 2008). According to Patil and Anil (2011), reduction in TSS and high temperature during pre-monsoon elicit the conversion of resting spore into vegetative cells in coastal waters of Goa. Similar kind of environmental conditions has also been observed in Malvan coast during pre-monsoon. Thus, the conversion of resting spore into vegetative cells could be one of the reasons for high abundance of *S. costatum* and *Chaetoceros* sp.

Table 4 Check list of Phytoplankton species encountered during the present investigation

Phytoplankton species	Stations and seasons																	
	Pre-monsoon						Monsoon						Post-monsoon					
	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
Diatoms																		
<i>Achnanthes brevips</i>	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
<i>Amphiprora alata</i>	+	-	-	-	+	-	-	-	-	-	-	-	-	+	+	+	-	-
<i>Amphora</i> sp.	+	+	+	+	+	+	+	+	-	+	+	-	-	+	+	+	+	+
<i>Asterionella glacialis</i>	+	++	-	-	-	+	+	+	+	+	-	-	+	+	+	-	-	-
<i>Bacillaria</i> sp.	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Bacteriastrium delicatula</i>	+	+	+	+	-	+	+	+	+	+	-	+	+	+	+	+	+	+
<i>Chaetoceros</i> sp.	++	+++	++	+	+	++	+	+	+	+	++	-	+++	++	++	+	+	++
<i>Corethron</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	-	-
<i>Coscinodiscus</i> sp.	+	-	-	+	+	+	+	+	+	+	+	+	-	-	-	-	+	+
<i>Cyclotella</i> sp.	+	+	-	-	-	-	+	+	+	+	+	+	+	+	+	++	+	+
<i>Diploneis</i> sp.	-	+	+	-	-	-	-	-	-	-	-	-	+	+	+	+	-	-
<i>Ditylum brightwellii</i>	-	-	+	+	-	-	+	+	-	-	-	-	+	-	-	-	-	-
<i>Eucampia zodiacus</i>	-	-	-	-	-	+	+	+	-	+	+	-	+	+	-	-	+++	++
<i>Fragillaria</i> sp.	+	+	+	+	++	+	+	+	+	+	-	+	-	-	+	+	++	++
<i>Grammatophora</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
<i>Guinardia striata</i>	+	+	+	+	+	++	++	++	++	++	++	++	+	+	+	+	++	++
<i>Gyrosigma</i> sp.	+	+	+	+	+	-	+	+	-	+	-	+	+	-	+	+	-	-
<i>Hemiaulus hauckii</i>	-	+	+	-	-	+	+	+	+	+	+	-	-	-	-	-	-	++
<i>Leptocylindrus danicus</i>	+	-	+	+	+	+	-	-	-	-	-	-	+	+	+	-	-	-
<i>Licmophora juergensii</i>	+	+	-	-	+	-	-	-	-	-	-	-	+	-	-	-	-	-
<i>Lithodesmium undulatum</i>	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+++	++
<i>Melosira</i> sp.	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Meuniera</i> sp.	-	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	-	-
<i>Navicula delicatula</i>	+	++	+	+	++	++	+	+	+	++	+	+	+	+	++	++	++	++
<i>Navicula</i> sp.	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	++	+
<i>Odontella mobiliensis</i>	+	+	+	-	++	+	+	+	+	+	+	+	-	-	+	-	+	+
<i>Odontella sinensis</i>	+	+	+	-	++	+	+	+	+	+	+	+	-	-	+	-	+	+
<i>Planktoniella sol</i>	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-	-	-
<i>Pleurosigma angulatum</i>	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	++	-	-
<i>Pseudo-nitzschia</i> sp.	++	+++	+	+	++	++	++	++	++	++	++	+	+++	++	+++	+++	+++	++
<i>Rhizosolenia hebetata</i>	+	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Rhizosolenia imbricata</i>	+	++	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Skeletonema costatum</i>	++	+++	+	+	+	++	+++	++	++	++	+++	++	+++	++	++	+	-	++
<i>Skeletonema tropicum</i>	-	+	+	-	-	+	-	-	-	-	+	-	-	-	+	+	+	+
<i>Streptothecha thamensis</i>	+	+	-	+	++	-	-	+	+	+	-	-	+	+	+	+	++	+++
<i>Surirella</i> sp.	-	+	+	+	-	-	-	+	+	+	-	-	-	+	+	+	+	+
<i>Synedra ulna</i>	-	+	-	-	+	+	++	+	+	++	-	+	-	-	-	+	-	-
<i>Thalassionema nitzschioides</i>	+	+	+	+	+	++	++	++	++	+	++	+	+	+	++	++	-	+
<i>Thalassiosira</i> sp.	+	++	+	+	+	+	++	++	++	++	++	++	++	+	++	++	++	+
<i>Thalassiothrix</i> sp.	+	++	+	+	-	++	++	++	+	++	++	++	+	+	+	+	-	+

Table 4 (continued)

Phytoplankton species	Stations and seasons																	
	Pre-monsoon						Monsoon						Post-monsoon					
	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
Dinoflagellates																		
<i>Ceratium furca</i>	+	-	+	+	-	-	-	+	+	+	-	+	-	+	+	-	-	-
<i>Dinophysis miles</i>	-	-	-	-	-	-	-	+	+	+	+	-	-	-	+	-	-	-
<i>Noctiluca</i> sp.	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Ornithoceros magnificus</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
<i>Peridinium</i> sp.	+	-	+	+	++	+	+	+	+	+	+	+	+	+	+	+	++	+
<i>Prorocentrum lima</i>	+	+	+	+	-	-	+	+	+	+	+	+	+	+	+	+	++	+
<i>Prorocentrum micans</i>	+	+	+	+	-	-	+	+	+	+	+	+	+	+	+	+	+	+
<i>Proto-peridinium</i> sp.	+	+	+	+	-	+	++	+	+	+	++	++	+	+	+	+	+	-
<i>Pyrophacus holorigicum</i>	-	-	-	-	-	-	+	+	+	+	+	-	+	+	+	+	-	-
Chlorophytes																		
<i>Actinastrum</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
<i>Cosmarium botrytis</i>	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
<i>Pediastrum duplex</i>	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Scenedesmus dimorphus</i>	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Staurastrum</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
Cyanophytes																		
<i>Anabaena</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+
<i>Oscillatoria</i> sp.	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Dictyochophytes																		
<i>Dictyocha</i> sp.	+	+	+	-	-	-	-	+	-	+	+	-	+	+	+	+	-	-

+ = 1–10,000, ++ = 10,001–100,000, +++ = >100,000, and - = absent

during pre-monsoon. Maximum phytoplankton biomass during post-monsoon was contributed by *Pseudo-nitzschia* sp., *L. undulatum*, *E. zodiacus*, and *Streptotheca thamensis* when temperature was comparatively low and NO₃ and NO₂ were relatively high. According to CCA analysis, relatively high NO₃ and NO₂ supported the growth of *Pseudo-nitzschia* sp. and *L. undulatum* whereas high salinity, temperature, and TSS had negative impact on their growth. The present results are well supported by the findings of Fehling et al. (2006) and Trainer et al. (2012) who explained that the bloom of *Pseudo-nitzschia* sp. was related to the availability of nitrate and relatively low irradiance. Pednekar et al. (2014) also reported the dominance of *Streptotheca thamensis* during the non monsoon period (Fig. 8).

Phytoplankton species diversity and evenness

Shannon-Wiener diversity index (*H'*) is one of the most widely used indices for measuring diversity. It can change with key ecological factors such as competition, predation, and succession altering the diversity through changes in evenness without any change in species richness (Stirling and Wilsey 2001). Present study showed positive correlation (*r* = 0.98, *p* < 0.0001) between diversity and evenness, but the relation with species richness was unclear.

Shannon-Wiener diversity index can be used as a proxy for ecosystem modification under eutrophication or pollution stress. Balloch et al. (1976) found that Shannon-Wiener index to be a suitable indicator for water quality. Hendley (1977) used the Shannon-Wiener index as a pollution index in diatom

communities and suggested the following scale: 0–1 for high pollution, 1–2 for moderate pollution, 2–3 for marginal pollution, and 3–4 for incipient pollution. From India Xivanand et al., 2006 and Thakur et al., 2013 also used the diversity index for the assessment of water quality. In Malvan, the seasonal distribution of species diversity H' ranged from 1.8 to 4.0 with the bay stations (M1 and M2) having diversity in the range of 2 to 3 and near shore as well as outer stations (M3, M4, M5, and M6) it was 3 to 4. Hence it appeared that the stations located in the bay were marginally polluted due to anthropogenic activities like fishing boat operations, tourism, and non point domestic waste disposal which might have brought down the diversity. Whereas, the stations like M3, M4, M5, and M6 were incipiently polluted with relatively high diversity due to lower human interventions. In the present study, the high diversity was mainly due to equal distribution of total abundance among all species. Species diversity can decrease to minimal level when one or few species dominate (Gao and Song 2005). Station M1 during post-monsoon and station M2 during pre-monsoon sustained high abundance of *S.costatum* and *Pseudonitzschia* sp. contributing almost 80% to the total population thereby resulted in low diversity index at these stations.

Conclusion

The study revealed that the variations in phytoplankton species abundance were strongly related to temporal and spatial variability in TSS and water temperature. Nutrients (NO_2 , NO_3 , NH_4 , PO_4 , and SiO_4) had a lesser control on phytoplankton abundance. Bacillariophyceae were overwhelmingly abundant throughout the study period. Diversity change in the Malvan coast was related to species evenness rather than richness. High abundance of *S.costatum*, *Chaetoceros* sp., and *Pseudonitzschia* sp. brought down the phytoplankton diversity at bay stations. In spite of high abundance of these species, other species were also observed in lower density indicating the ecosystem was not under stress wherein only single species can dominate. In general, study region showed slight to incipient polluted condition and sustained relatively high phytoplankton diversity. From the above discussion, it is concluded that the MPA of Malvan coastal waters is more fertile with rich phytoplankton diversity. Since phytoplankton

distribution and diversity studies are limited in Malvan coast, it is advised to have year round study in this stations.

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