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ORIGINAL RESEARCH ARTICLE

Multivariate approach to evaluate the factors controlling the phytoplankton abundance and diversity along the coastal waters of Diu, northeastern Arabian Sea

P. Sathish Kumar[a,b,*], S. Venkatnarayanan[a], Vikas Pandey[a], Krupa Ratnam[a], Dilip Kumar Jha[a], S. Rajaguru[a], G. Dharani[a,*], R. Arthur James[b,*], M.A. Atmanand[a]

[a] *National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences (Govt. of India), Chennai, Tamil Nadu, India*
[b] *Department of Marine Science, Bharathidasan University, Tiruchirappalli, Tamil Nadu, India*

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Abstract The present study investigated the phytoplankton assemblage and diversity with physicochemical parameters of Diu coastal waters in different seasons during 2018—19. During the study period, 61 phytoplankton species comprising diatoms (50 sp.), dinoflagellates (8 sp.), and cyanophyceae (3 sp.) were recorded. Diatom was found to be a major community and contributed 79 to 99% of total phytoplankton abundance. Reduction in dinoflagellate and dominance of pennate-diatoms were observed during the monsoon. Chlorophyll-*a* concentration also showed a similar trend and decreased during the monsoon. However, the phytoplankton abundance was low particularly during the monsoon which might be due to the elevated total suspended solids (TSS) load. Canonical correspondence analysis revealed that diatoms were able to survive in high TSS with the support of high nutrients; while dinoflagellates were limited due to those conditions. Overall, the reduction in phytoplankton abundance, diversity, and biomass was recorded due to the elevated TSS input along the coastal waters of Diu.

* Corresponding authors at: National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, Govt. of India, Pallikaranai, Chennai, India; Department of Marine Science, Bharathidasan University, Tiruchirappalli, Tamilnadu, India.
E-mail addresses: marinesathis@gmail.com (P.S. Kumar), dhara@niot.res.in (G. Dharani), james.msbdu@gmail.com (R.A. James).

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1. Introduction

Phytoplankton dynamics are mainly controlled by a wide range of environmental variables like nutrients, temperature, salinity, light availability, current circulation, water turbidity, and grazing pressure by other trophic level organisms (Gao and Wang, 2008; Levy et al., 2007; Margalef, 1978; Verlencar and Parulekar, 2006; Zarauz et al., 2008). Studies related to the controlling factors of phytoplankton community composition and its fate in the northern Arabian Sea are limited (Geeta and Kondalarao, 2004; Nair et al., 2005; Naqvi et al., 2006). Identification of the main factors controlling phytoplankton in a particular water body is crucial for choosing an appropriate management strategy for the maintenance of the desired state of ecosystem (Peretyatko et al., 2007). Phytoplankton species have different traits and based on their size, shape, growth rate, and motility are together determine their ecological niche and favorable environmental conditions (Litchman and Klausmeier, 2008; Spilling et al., 2018). In recent decades, rapid growth in industrialization, urbanization in coastal zones, tourism, and harbor activities have exerted enormous anthropogenic pressure on nearshore ecology (Bhavya et al., 2016; Seitzinger et al., 2010). The aquatic environment like estuaries and coastal waters is affected by both riverine nutrient input and water properties like turbidity (Wang et al., 2019).

The total suspended solids (TSS) is one of the important environmental factors which reflect the turbidity characteristic of eroding coastline or the entry of the suspended materials into the coastal seawater through land runoff and determines the plankton composition and abundance (Wu et al., 2011). TSS is a significant variable that impacts the spatio-temporal patterns of phytoplankton and regulates the biogeochemical processes of aquatic ecosystems (Weyhenmeyer et al., 1997). The increase in TSS strongly affects the light attenuation which further influences the chlorophyll-*a* concentration in seawater and consequently affects the zooplankton and higher tropical organisms (Dunton, 1990). The natural process of particular coastal regions has unique characteristics that are controlled by water exchange with nearby areas, the topology of the coastline, rainfall, and river discharge (Ilyash et al., 2015). A combination of these processes with anthropogenic activities results in the formation of a gradient in biotic and abiotic factors which impacts phytoplankton species composition, succession, and abundance (Biswas et al., 2015; Hardikar et al., 2017). Diu Island (20.71°N, and 70.98°E) is located along the northeastern Arabian Sea, Gujarat. The geographical area of Diu is about 40 km^2. The climate is particularly warm and humid, the average annual rainfall ranges between 2300 and 4800 mm, the annual atmospheric temperature ranged from 15°C to 42°C (Jha et al., 2021). In Diu, the TSS load is always high throughout the year which originates from the erosion of farmlands and forests which are discharged through rivers and increases mainly during the monsoon. Disturbance of shore sediments and resuspension in shallow parts of estuarine and coastal regions due to tidal currents also play a major role in higher TSS load in the coastal region (NCCR, 2018; NIO, 2015). Phytoplankton distribution patterns are strongly correlated with environmental factors such as TSS (Lepisto et al., 2004). Studies related to phytoplankton community dynamics concerning environmental drivers are deficient in Diu and the surrounding coast.

In view of this above, the present study was conducted in the coastal waters of Diu, the northeastern Arabian Sea, 1) to investigate the distribution patterns of phytoplankton community composition and diversity during different seasons, 2) to examine the relationship between the phytoplankton groups, and the environmental variables, and 3) addressing the physicochemical factors controlling the abundance of diatoms and dinoflagellates.

2. Material and methods

In the present study, seven sampling locations (Station-1,2,3,4,5,6, and 7) with the depth of 2 to 18 m were selected for the seawater collection and analysis of physicochemical and biological parameters (Figure 1). The seasonal samples were collected in Pre-monsoon (PRM) (February), Monsoon (MON) (September), and Post-monsoon (POM) (November) from the study region during the period 2018 to 2019. Rainfall data were collected from the Indian Meteorological Department (IMD). Sea surface temperature (SST), salinity, and pH were measured using a calibrated portable multi-parameter water quality instrument (HANA-HI 9829). Surface water samples were collected using a Niskin sampler for the estimation of dissolved oxygen (DO), total suspended solids (TSS), nutrients, and chlorophyll-*a* (Chl-*a*). DO was measured using the modified Winkler's method (Carrit and Carpenter, 1966). The TSS was determined by filtering known quality of well-mixed sample through a preweighed standard glass-fiber filter (0.45 μm Millipore GF/C), and the residue retained on the filter was dried at 103–105°C to a constant weight. The increase in the weight of the filter represents the total suspended solids (APHA, 2012). All the nutrients (ammonia, nitrite, nitrate, phosphate, and silicate) were analyzed following standard spectrophotometric procedures (Grasshoff et al., 1999). For chl-*a* analysis, 1 L of seawater sample was filtered by GF/F filter and was wrapped with an aluminum foil and frozen at −20°C until analysis. Chl-*a* was analyzed spectrofluorometrically by following the standard protocol (Parson et al., 1984). For phytoplankton analysis, 5 L of the surface water sample was collected and preserved with Lugol's iodine solution. In the laboratory, samples were kept for 48 h for settling. For the enumeration of phytoplankton, the concentrated sample was examined under the microscope (ZEISS J-902984) and identified to the lowest possible taxonomic level using the identification keys (Subrahmanyan, 1946, 1959; Taylor, 1976; Tomas, 1997).

Diversity indices (viz., Shannon Weiner diversity index (H') and Margalef's species richness (d) and Pielou's evenness (J')) were calculated for all the seasons by using the statistical software package PRIMER 6.0. One-way analysis of variance (ANOVA) was performed on XLSTAT software to evaluate the statistical significance of diversity indices. Pearson correlation and multivariate regression analyses were performed to find out the linear relationship between the biotic and abiotic factors. Canonical Correspondence Analysis (CCA) was performed to examine the rela-

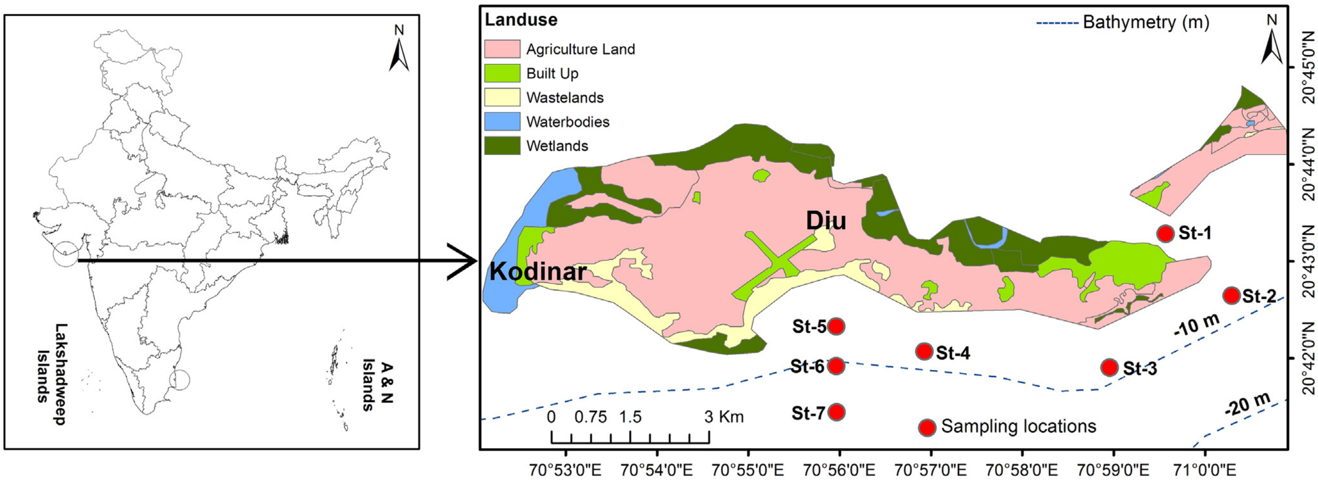

Figure 1 Map showing the study locations along the coastal waters of Diu, northeastern Arabian Sea.

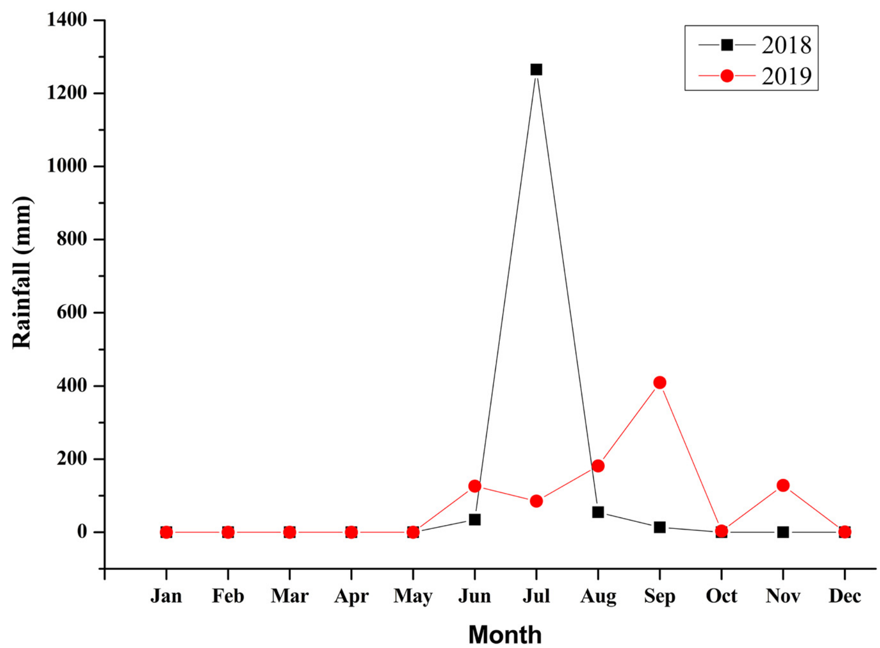

Figure 2 Temporal variation of Rainfall in the coastal region of Diu, northeastern Arabian Sea during 2018—2019.

tionships between the phytoplankton community and environmental variables by using CANOCO statistical software. Prior to statistical analysis, the heterogeneity in the phytoplankton data was removed by converting all the data to log (x+1) transformation.

3. Results and discussion

3.1. Seasonal variation of environmental parameters

During the study period, the monthly total rainfall was higher during July 2018 (Figure 2). In the last six years, the maximum rainfall in Diu was recorded in July 2018 (1265.4 mm). Spatio-temporal variations of physio-chemical parameters are presented in Figure 3. The TSS load in the coastal waters of Diu is moderately high throughout the year which may be due to the erosion of coastal land, farmlands, and forests which are discharged through rivers and increase mainly during heavy rainfall. During the study period, the TSS level ranged from 17.7 to 202.2 mg L^{-1}, the mean concentration was lower during the PRM and 2 to 3 times higher during the MON (Figure 3). Erosion of soil from farmlands and forests may be the major source for TSS load which was brought through the runoff and river discharge mainly during the high rainfall (NCCR, 2018). High TSS level (202.2 mg L^{-1}) at the river mouth station (St-1) during the MON confirmed that the main source for the elevated TSS was through land runoff caused by the high rainfall. Previous studies also reported that siltation caused by the large river run-off was the main reason for the high concentration of TSS along the Gulf of Khambhat (Raghunathan et al., 2004). Disturbance of shore sediments and resuspension in shallow

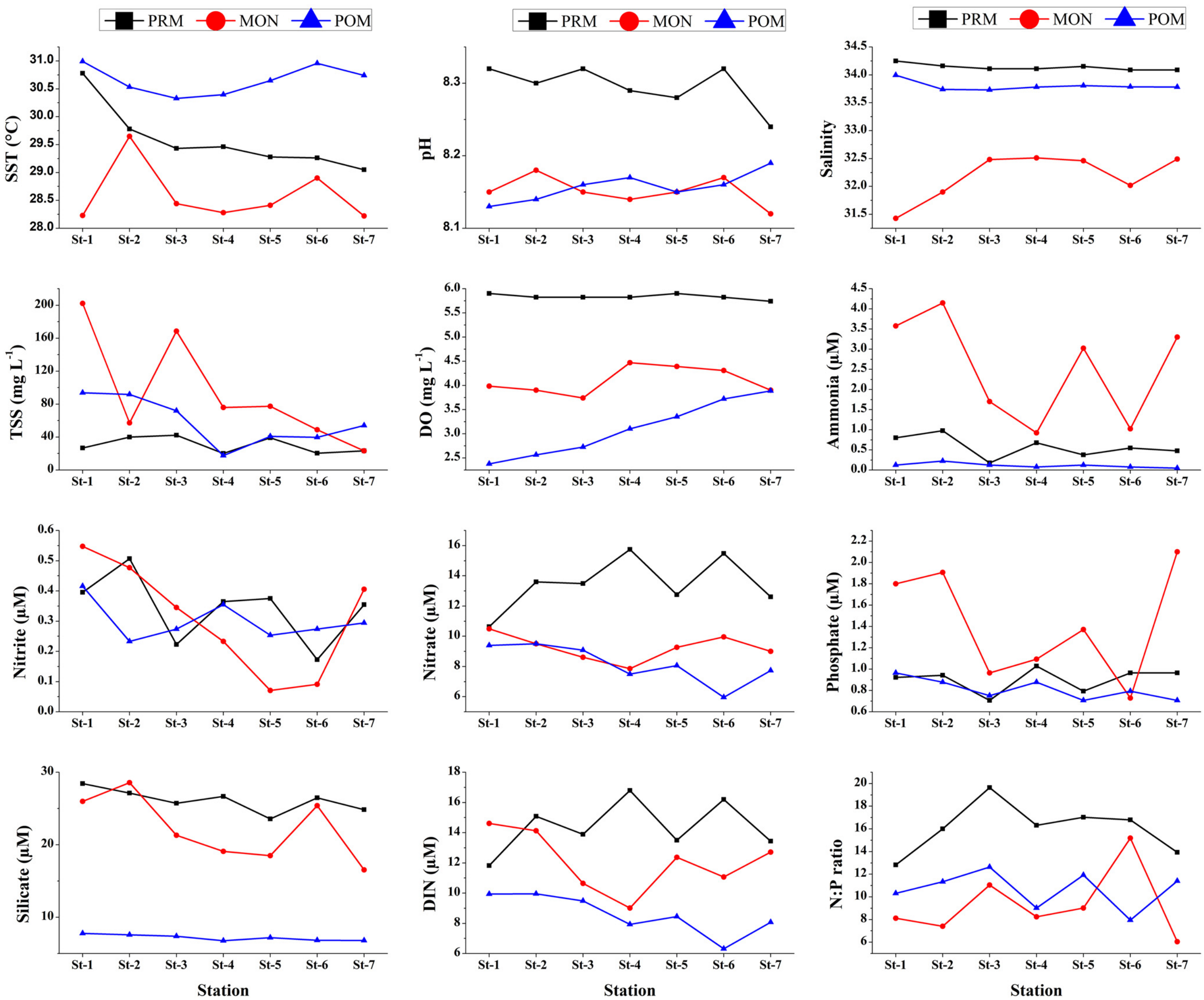

Figure 3 Spatio-temporal variation of physico-chemical variables along the coastal waters of Diu, northeastern Arabian Sea for the different seasons like pre-monsoon (PRM), monsoon (MON), and post-monsoon (POM).

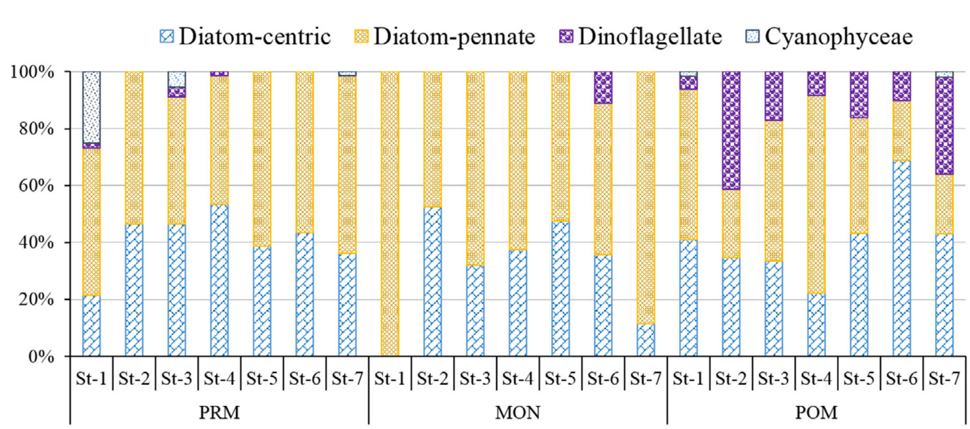

Figure 4 Seasonal changes in the taxonomical composition of phytoplankton abundance in the coastal waters of Diu, northeastern Arabian Sea for the different seasons like pre-monsoon (PRM), monsoon (MON), and post-monsoon (POM).

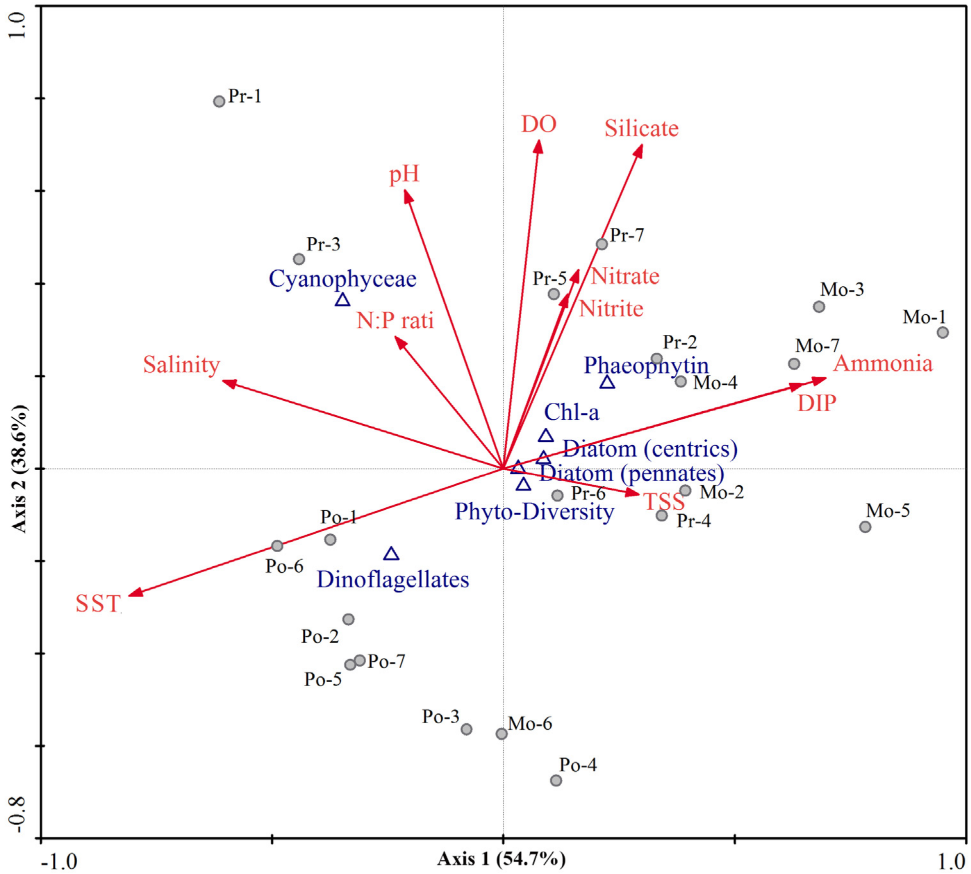

Figure 5 Canonical correspondence analysis (CCA) triplots for phytoplankton abundance, biomass (Chl-*a*), and diversity with associated environmental variables in the coastal waters of Diu, northeastern Arabian Sea. Environmental variables (SST — sea surface temperature, salinity, DO — dissolved oxygen, TSS — total suspended solids, pH, DIP — dissolved inorganic phosphorus, nitrite, nitrate, ammonia, silicate, and N:P ratio) are represented by arrows. Stations represented as Pr-1 to Pr-7 (pre-monsoon stations 1—7), Mo-1 to Mo-7 (monsoon stations 1—7), and Po-1 to Po-7 (post-monsoon stations 1—7).

parts of estuarine and coastal regions due to tidal currents also plays a major contribution to TSS load in the coastal region (NIO, 2015). The SST varied from 28.22 to 30.99°C, the higher and lower SST was found during the POM and MON, respectively. Salinity fluctuated highly among the seasons, higher salinity was recorded during the PRM (34.25) and lower during the MON (31.43). Drop in the SST and salinity might be due to the intense rainfall recorded during the MON. The pH was higher during the PRM and lower during the MON and POM. However, the salinity (r = 0.81, $p < 0.01$) and pH (r = 0.88, $p < 0.01$) showed strong positive correlation with the phytoplankton abundance, whereas the TSS (r = −0.60, $p < 0.01$) was correlated negatively. The DO ranged from 2.38 to 5.9 mg L^{-1}, the higher mean concentration of DO was found during the PRM which might be due to the higher primary production (Kumar et al., 2018).

Inorganic nutrients showed significant variation (n=21, p<0.01) between the stations (Figure 3). The dissolved inorganic nitrogen (DIN) ($NH_4^+ + NO_2^- + NO_3^-$) was high during the PRM and MON, which might be due to the increased concentration of nitrate and ammonia. The increased nitrate concentration could be due to anthropogenic input (Kumar et al., 2018; Zhou et al., 2008). JiyalalRam et al. (2011) also reported that the significant positive correlation between TSS and DIN indicates the erosion of soil and nutrient flux which is carried through river discharge. The mean concentration of ammonia was high during the MON. The phosphate and silicate concentrations were also higher during the MON and lower during the POM. Ammonia and phosphate formed a strong positive correlation (r=0.90, $p < 0.01$), the similar result from the previous study suggested that it could be the indication of sewage disposal and sediment release leading to higher phosphate concentration (Hardikar et al., 2019; Howarth et al., 2011). The mean N:P ratio was higher during the PRM (~16) and lower during the MON (~9) and POM (~10), the optimal N:P ratio during the PRM resulted in higher phytoplankton abundance and biomass.

3.2. Seasonal variation of phytoplankton biomass, abundance, and diversity — relationship with environmental variables

The phytoplankton biomass (chlorophyll-*a*) varied from 0.09 to 0.31 mg m^{-3}, the mean concentration of chl-*a* was higher during the PRM and lower in the MON and POM, respectively (Table 1). Depletion in phytoplankton biomass during the MON might be due to the elevated level of TSS (r = −0.72, $p < 0.01$). The phaeophytin concentration varied from 0.01

Table 1 Seasonal variations of phytoplankton abundance, biomass, and species diversity indices in the coastal waters of Diu, northeastern Arabian Sea. Values in the open and parentheses represent the minimum-maximum and mean values ± standard error respectively. PRM — Pre-monsoon; MON — Monsoon; POM — Post-monsoon.

	PRM	MON	POM
Phytoplankton abundance (x 10^3 cells L^{-1})	13.5—42.0 (23.6±3.5)	1.2—2.8 (1.8±0.2)	2.6—5.3 (4.0±0.4)
Chlorophyll *a* (mg m^{-3})	0.20—0.31 (0.26±0.01)	0.09—0.23 (0.15±0.02)	0.09—0.24 (0.15±0.02)
Phaeophytin (mg m^{-3})	0.29—0.44 (0.36±0.02)	0.18—0.45 (0.29±0.04)	0.01—0.25 (0.07±0.03)
Species diversity (*H'*)	2.06—2.56 (2.30±0.07)	1.10—2.18 (1.71±0.17)	2.14—2.71 (2.40±0.09)
Species richness (*d*)	1.26—1.70 (1.51±0.07)	0.28—1.03 (0.68±0.12)	1.09—1.88 (1.45±0.11)
Species evenness (*J'*)	0.72—0.89 (0.83±0.02)	0.97—1.00 (0.99±0.004)	0.91—0.97 (0.94±0.01)

to 0.45 mg m^{-3}, the higher and lower concentration was observed during the MON and POM, respectively. Phytoplankton diversity indices showed a significant variation (n=21, $p < 0.01$) between the seasons (Table 1). The mean phytoplankton diversity (*H'*) was higher during the POM (2.40 ± 0.24) followed by the PRM (2.30 ± 0.18) and low during the MON (1.71 ± 0.45). The maximum and minimum species richness (*d*) was recorded during the PRM and MON, respectively. The species evenness (*J'*) did not show much variation between the seasons, however, the higher evenness was found during the MON (0.99) despite low diversity and richness, which could be due to the lower abundance of phytoplankton species at all the locations.

The phytoplankton taxa identified during the study period are shown in Table S1 (supplemental material). A total of 61 phytoplankton species (23-centric diatoms, 27-pennate diatoms, 8 dinoflagellates, and 3 cyanophyceae) were recorded along the coastal waters of Diu. Diatoms were the most dominant phytoplankton group during all the seasons, whereas dinoflagellate and cyanophyceae were low. The higher number of phytoplankton taxa was recorded during the POM (38) followed by the PRM (27) and MON (17). The phytoplankton abundance varied from 1.2 to 41.9 × 10^3 cells L^{-1}, the higher abundance was observed during the PRM which could be attributed to a higher N:P ratio. The mean phytoplankton abundance was higher during the PRM (23581 cells L^{-1}) and lower during the MON (1780 cells L^{-1}) followed by the POM (4046 cells L^{-1}). A similar trend was also observed in phytoplankton biomass (chl-*a*) during the present study. During the PRM phytoplankton abundance was high at St-1 and decreased towards St-7. Whereas during the MON and POM the abundance was low at St-1 and increased towards St-7, which might be due to the higher TSS release from the riverside. Many studies along the west coast of India encountered higher phytoplankton abundance and biomass during the MON (Hardikar et al., 2019; Kumar et al., 2018; NIO, 2015). However, the present phytoplankton abundance and biomass were low compare to the previous reports of Diu and surrounding regions (Hardikar et al., 2019; NIO, 2015). Though, very few studies reported low phytoplankton abundance in the Diu coast, the reason was not documented (Raghunathan et al., 2004). However, the present study explored the limiting factors for phytoplankton growth. During the study period, 79 to 99% of the phytoplankton density was contributed by diatoms, the detailed contribution of phytoplankton groups during all the seasons are presented in Figure 4. Diatoms were dominant during the MON (99%) followed by PRM (92%) and POM (79%). Total phytoplankton abundance during the MON was very low and varied from 1189 to 2788 cells L^{-1} and the maximum abundance was contributed by diatoms (pennate diatoms — 68% and centric diatoms — 31%). Dinoflagellate's contribution was higher during the POM (21%) and dropped during the MON (1%) and PRM (1%). Particularly during the MON, only one species of dinoflagellate (*Protoperidinium pallidum*) was observed and contributed 1% to the total phytoplankton community. The drop in the dinoflagellate abundance and diversity during the MON and PRM might be due to the higher TSS (r = −0.23). During the MON, resulting 100% pennate diatoms at the riverine station (St-1, Figure 4) indicate that mixing of bottom waters due to the high rainfall and runoff could be the reason for the higher TSS and dominance of pennate diatoms.

Canonical correspondence analysis (CCA) was performed to determine the environmental factors controlling the phytoplankton groups (Figure 5). Eigenvalues of axes 1 (λ_1=0.104) and 2 (λ_2=0.074) explained 93.3% of the relationship between the phytoplankton community and environmental variables. The axis-1 was associated with the MON and PRM stations, where the diatoms (pennate and centric) and phytoplankton biomass (Chl-*a*) were positively correlated with TSS, nutrients, and negatively correlated with SST and salinity (Figure 5). Whereas, for dinoflagellates, the reverse trend was observed and associated with the POM stations. CCA result suggests that diatoms could survive in high TSS and favored to low SST, salinity, and high nutrients; while the dinoflagellates were restricted due to those elevated TSS, nutrients and favored to high SST and salinity. Ke et al. (2012) also observed a similar trend that diatoms favor the high silicate, phosphorus with low temperature, and the dinoflagellate favors the low silicate, phosphorus

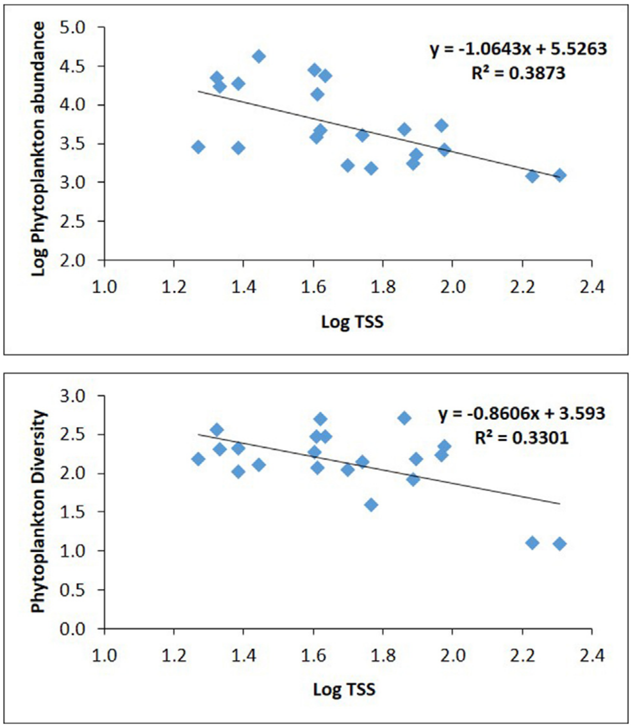

Figure 6 Relationship between TSS with phytoplankton abundance, and diversity in the coastal waters of Diu, northeastern Arabian Sea.

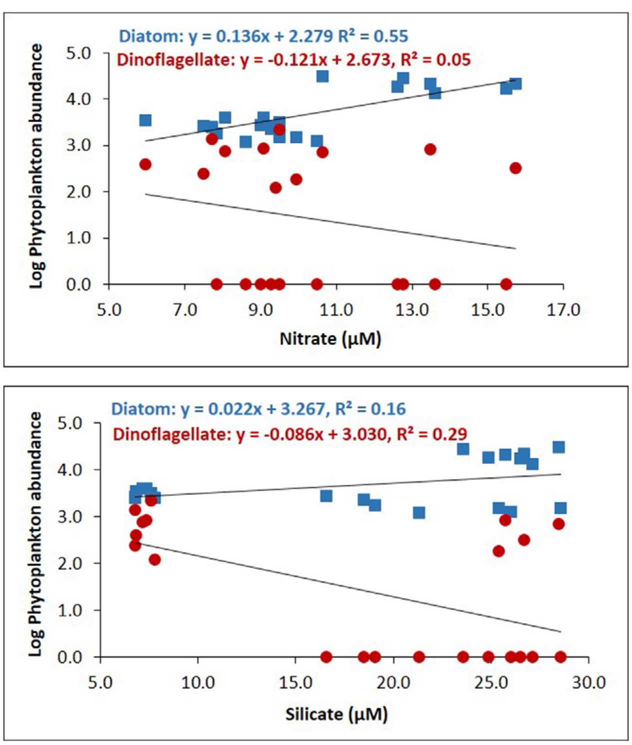

Figure 7 Relationship between diatom and dinoflagellate abundance with nitrate, and silicate, respectively, in the coastal waters of Diu, northeastern Arabian Sea.

with high SST. In addition to that, the regression analysis conformed that, overall the decline in phytoplankton abundance, and diversity due to the elevated level of TSS (Figure 6). The previous study at Veraval also encountered a reduction in phytoplankton growth due to the elevated level of turbidity (Hardikar et al., 2019). The regression analysis illustrated that the nitrate and silicate were the main factors influencing the abundance of diatoms, whereas the dinoflagellates were reducing with those factors (Figure 7). Further studies need to be carried out for the better understaning about the fluctuation among the phytoplankton groups with varying nutrients.

Several studies have reported the increased phytoplankton abundance or harmful algal blooms due to the elevated nutrients in the coastal environmment by land runoff and upwelling phenomenon (Hardikar et al., 2019; Kumar et al., 2020; Levy et al., 2007). In the present study, the reduction in phytoplankton abundance was observed due to the elevated level of TSS which could be attributed to natural erosion patterns as well as anthropogenic activities. Continuous reduction in phytoplankton abundance could also affect the zooplankton and higher tropical levels which may impact the fish stock in the future. Further studies need to be carried out in the future for a better understanding of the TSS, nutrients load, and their effect on plankton and higher tropical level. Thus, the present study suggests that to control erosion through plantation and shore protection measures and managing the anthropogenic discharge in the coastal waters of Diu. Though the TSS load is due to natural erosion, there is a need for shore protection measures which will ultimately conserve the coastal environment and enhance biological productivity.

4. Conclusion

Though light is the primary limiting factor for the phytoplankton growth, the high TSS recorded in the present study could have reduced the light and result in the lower phytoplankton abundance. Hence, the TSS played a key role in affecting the phytoplankton abundance, diversity, and biomass in the coastal waters of Diu. Possibly the coastal erosion and land runoff could be attributed to higher TSS load which might affect the growth of phytoplankton and higher trophic level. Thus, the present study suggests to develop the plantation in the coast and nutrient management strategy for the coastal waters of Diu. Reduction in phytoplankton abundance and biomass could reflect in fish stock, hence, more attention and continuous monitoring are required for developing better conservation and management plan in the coastal regions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.oceano.2021.11.005.

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