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RESEARCH

Dynamics of environmental variables during the incidence of algal bloom in the coastal waters of Gujarat along the northeastern Arabian Sea

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Abstract The dynamics of physico-chemical, nutrient, and chlorophyll-*a* variables were studied in the bloom and non-bloom locations along the off-Gujarat coastal waters to understand the variability in biogeochemistry using multivariate analytical tests. The dissolved oxygen was significantly lower in the bloom stations (3.89 ± 0.44 mgL^{-1}) than in the non-bloom stations (5.50 ± 0.70 mg L^{-1}), due to the biological degradation of organic matter in addition to anaerobic microbial respiration. Nutrients (PO_4 and NO_3) and Chl-*a* concentrations were recorded higher in the bloom locations at 0.83 ± 0.21 µmol L^{-1}, 4.47 ± 0.69 µmol L^{-1}, 4.14 ± 1.49 mg m^{-3}, respectively. PO_4 and NO_3 have shown a significantly higher positive correlation of $r = 0.73$ and $r = 0.69$ with Chl-*a* for bloom data than the non-bloom data. The percentage variance contributed by PC1 and PC2 for both bloom and non-bloom locations were estimated at 52.33%. The variable PO_4 explains the highest 24.19% variability in PC1, followed by Chl-*a* (19.89%). The PO_4 triggers the bloom formation and also correlates to the higher concentrations of Chl-*a* in the bloom locations. The bloom concentration ranges from 9553 to 12,235 trichomes L^{-1}. The bloom intensity has shown a significant positive correlation with Chl-*a* ($r = 0.77$), NO_3 ($r = 0.56$), and PO_4 ($r = 0.30$), but a negative correlation was noticed

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with DO ($r = -0.63$) and pH ($r = -0.49$). The study also initiates a way forward research investigation on ocean-color technologies to identify and monitor blooms and climate change–driven factors for bloom formation. The occurrence of bloom and its influence on fishery resources and other marine biotas will open many research windows in marine fisheries, oceanography, remote sensing, marine biology, and trophodynamics.

Keywords *Trichodesmium* · Northeastern Arabian Sea, NEAS · Multivariate analysis · Nutrients · Chl-*a*

Introduction

The structure of the phytoplankton community has a significant role in basic biogeochemical processes (nutrient cycling, energy transfer through the marine food web, deep ocean carbon export, etc.) and evidently on marine fishery resources (Bracher et al., 2017; Harrison et al., 2017). The identification of phytoplankton composition and the intensity at global and regional scales will evaluate the relevance of ocean biodiversity for marine ecosystem services as well as the connections between the climate and ecosystem. However, for many socioeconomic applications, including fisheries, aquaculture, and coastal control, precise data on phytoplankton diversity is required (IOCCG, 2000). The formation of a phytoplankton bloom indicates a fundamental imbalance between the phytoplankton growth and removal. In general, bloom can influence the structure of the food chain and the transport of carbon in marine ecosystems positively or negatively. Fast-growing species like diatoms, which have a significant impact on the biogeochemical cycles around the world, typically dominate blooms (Smetacek, 1998). Others, such as raphidophytes and dinoflagellates, may generate hazardous algal blooms that have a negative impact on the production of shellfish and fish (Hallegraeff, 1993; Glibert et al., 2005). The intensity of phytoplankton beyond the optimum levels causes bloom formation, which may cause either a positive or negative impact on the biota depending on the causative species.

The marine cyanobacteria are an important nitrogen-fixer in the sea, and the *Trichodesmium* species are known to cause a massive bloom in many areas of the world's oceans (Ramamurthy & Krishnamurthy, 1968; Capone et al., 1997; Zingone & Enevoldsen, 2000; Chang et al., 2000; Gomes do Rosario et al., 2008; McKinna, 2015; Hu et al., 2010; Spatharis et al., 2012; Yu et al., 2016; Harrison et al., 2017). *Trichodesmium* is typically found in tropical and subtropical oceans and is responsible for more than 30% of global algal blooms (Padmakumar et al., 2010; Westberry & Siegel, 2006). There have been numerous reports of *Trichodesmium* blooms in the Arabian Sea, primarily in the eastern Arabian Sea (Qasim, 1970; Devassy et al., 1978; Chaturvedi et al., 1986; De Sousa et al., 1996; Koya & Kaladharan, 1997; Krishnan et al., 2007, Padmakumar et al., 2010; Basu et al., 2011; Roy et al., 2011; Parab & Matondkar, 2012; Martin et al., 2013; Tholkapiyan et al., 2014; Jyothibabu et al., 2017; Ahmed et al., 2017). The threshold cell concentration varies with different algal bloom-forming species. Some species of *Pyrodimum* and *Alexandrium* are capable of exhibiting toxic effects even at lower cell concentrations of 10^2–10^3 per liter (Zingone & Enevoldsen, 2000). The higher cell concentrations of 10^5–10^6 cells/L were found to be associated with *Pseudo-nitzschia*-associated HABs from the north-west pacific (Stone et al., 2022).

Remote sensing methods and ocean color sensors have aided in the detection and monitoring of algal blooms caused by various species in diverse ecosystems (Capone et al., 1998; Subramaniam et al., 1999; Tang et al., 2002; Prabhu et al., 2004; Sarangi et al., 2005; Desa et al., 2005; Raghavan et al., 2006; Hu et al., 2010; Sarangi, 2012; McKinna, 2015; Yu et al., 2016; Dias et al., 2020). Sarangi et al. (2004) used IRS-P4 OCM data for the identification of *Trichodesmium* bloom off the Gujarat coast of the Arabian Sea. For example, at high Chl-*a* concentrations (>1 mg m^{-3}), the model developed by Gokul et al. (2019) paves ways to accurately detect the *Trichodesmium erythraeum* in the Arabian Sea. A machine-learning method was developed by Ghatkar et al. (2019) based on spectral reflectance data and information from several ocean-color sensors to identify different types of algal blooms. Based on the bio-optical algorithm, mapping and identification of algal blooms in optically complex waters were achieved by implementing reliable estimates of chlorophyll-*a* (Shanmugam, 2011). The present investigation used ocean-color techniques to monitor the dynamics and impact of the bloom while taking into consideration the influence of nutrients and Chl-*a* during the bloom incidence.

Algal bloom occurrences at diverse marine ecosystems in the Arabian Sea were reported earlier, additionally, the remote sensing techniques were employed to explain variations in Chl-*a*, absorption spectra differences, species reasoning for bloom occurrence and quantitative analysis, implications in nitrogen fixation, and bloom characterization methods were also studied (Al Shehhi et al., 2014; Bracher et al., 2009; Dupouy et al., 1988; Dwivedi et al., 2015; Gokul et al., 2019; Hu et al., 2010; Pettersson & Pozdnyakov, 2013; Shanmugam, 2011; Simon & Shanmugam, 2012; Subramaniam et al., 2001). The literature review on bloom incidence along the Indian coast carried out for this research revealed an upward trend in bloom occurrences caused by a wide range of causative species, which opens the way to link climate variables to subsequent repercussions on the region's marine habitats. We attempt to find out how physical and chemical variables (SST, pH, salinity, and DO), nutrients (nitrates, phosphates, and silicates), and Chl-*a* differ in bloom and non-bloom locations in the current research. The aforementioned variables' influence will define the biogeochemical understanding throughout the bloom period and its consequences for the environment and biota in the food web. With this investigation, we intend to fill in the knowledge gaps regarding how nutrients and productivity variables relate to bloom intensity.

Material and methods

The north-eastern Arabian Sea is one of the highly productive zones of the global oceans (Chauhan et al., 2001; De Sousa et al., 1996). The current study location is situated in the productive and ecologically significant northeastern Arabian Sea on the Indian coast; however, there has been relatively little research on the physical, chemical, and nutritional dynamics particular to bloom conditions (Temkar et al., 2015; Vase et al., 2018). From 2016 to 2018, fishing boats off the Gujarat coast carried out in situ sampling (Fig. 1). Temperature, salinity, pH, dissolved oxygen, nutrients (silicates, phosphates, and nitrates), chlorophyll-*a*, the N–P ratio, and cell counts of bloom species were among the parameters assessed in the current study.

Various methods and approaches were employed in the current study to compute the physical, chemical, and nutrient parameters (APHA, 2005; Grasshoff et al., 1983; Strickland & Parsons, 1972; Trivedi & Goel, 1986). The mercury thermometer and CTD probe were used to measure sea-surface temperature simultaneously. A pH meter was used to measure the pH, a refractometer was employed to compute the salinity, and Winkler's analytical method was applied to determine the dissolved oxygen concentration (Grasshoff et al., 1983). The total orthophosphate (also referred to as available phosphate) in the water was measured using the ascorbic acid method, and the estimation of silicon was performed using the molybdosilicate method. The nitrate-nitrogen was determined using the ultraviolet spectrophotometric screening method (APHA, 2005; Vase et al., 2018). The Chl-*a* concentration was determined using a

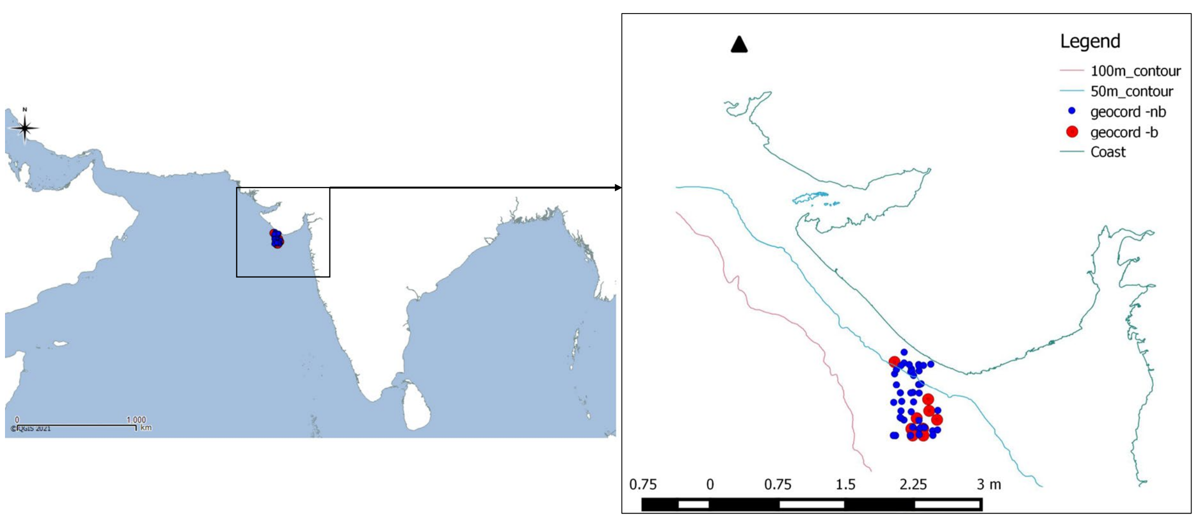

Fig. 1 Study area, i.e., north-eastern Arabian Sea showing sampling sites (blue and red circles represent non-bloom and bloom sites, respectively)

spectrophotometric method in the current investigation. Following onboard collection from the various sampling stations, the samples were filtered through 47-mm GF/F filter paper for chlorophyll-*a* estimation. The filter paper was placed in a 90% acetone solution and left in the dark in a refrigerator for 24 h. A centrifuge was used to separate the extracted material (R-24 Research Centrifuge, REMI, India). Using a spectrophotometer, the absorbance concentration for an extracted solution was calculated at various wavelengths (750 nm, 665 nm, 645 nm, and 630 nm) using a spectrophotometer (EPOCH2TC microplate reader, Biotech, USA) (Vase et al., 2018).

Diverse methods are used to identify HAB species (microscopy) and quantifications of toxins by enzyme-linked immunosorbent assays (ELISA) and high-pressure liquid chromatography (HPLC) (King et al., 2018; Trainer et al., 2007). Employing microscopic techniques, the bloom species have been identified and quantified, and counted using a Sedgwick-Rafter plankton counting chamber in the current study. The phytoplankton species were identified from the standard literature key (Gopinathan et al., 2007). The cells were enumerated and expressed as cells L^{-1}. The diversity of major plankton species was computed qualitatively using a microscope (Olympus Corp. CX31RTSF) with the power of 10 and 40× lenses.

A multivariate analysis was done for statistical analysis to demonstrate the correlations between environmental variables in the bloom and non-bloom stations (Vase et al., 2018). In an attempt to visualize, organize, and define principal components from multivariate data, principal component analysis (PCA) was used in the study (Kim et al., 2019). Major principal components (PCs), that are obtained by the PCA, minimize the dimensionality with the least amount of information loss. The analysis was done separately for the bloom and non-bloom datasets to obtain major PCs. The correlation analysis was done for the concentration of algal bloom against the physico-chemical, nutrient, and chl-*a* variables estimated. The PCA and correlation analysis (CA) were done using R statistical computing version 4.0.3 with command *prcomp* (Venables & Ripley, 2002) and pcaPP package with command *cor* (https://github.com/valentint/pcaPP).

Results

Literature on algal bloom events in the coastal waters of India

A total of 127 bloom occurrence events were collected from both the west and east coasts of India from 1916 to 2019 (Supplementary material). The decadal frequency trend of algal bloom incidence along the Indian coast has shown a significant positive trend ($R^2 = 0.671$) during the observed period (Fig. 2). Out of 127 bloom incidences observed during the study period, the highest of 75 bloom occurrences were observed on the west coast and 52 incidences on the east coast of India. The second quarter

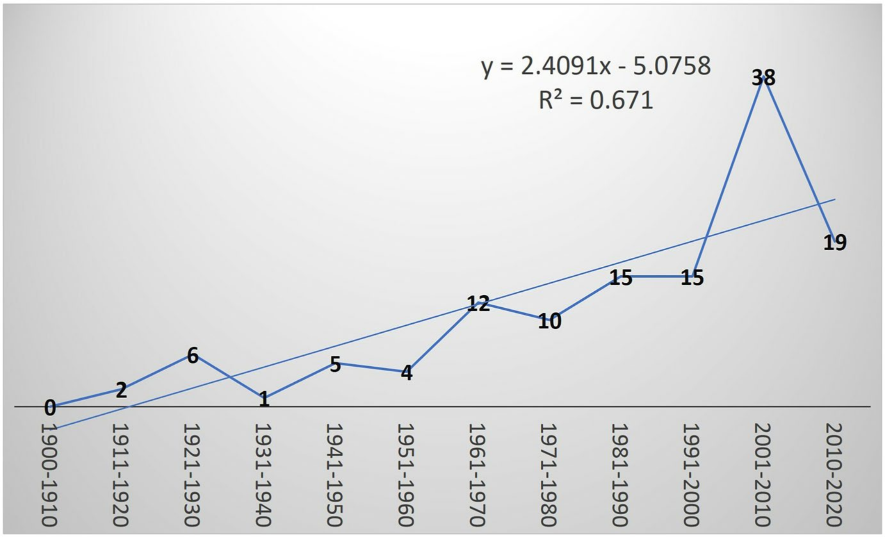

Fig. 2 The decadal trend of bloom incidences along the Indian coast

recorded the highest number of bloom occurrences along the west and east coasts of India, followed by quarter 1 (on the east coast) and quarter 3 (on the west coast) (Fig. 3). Dinoflagellate (52) was the dominant bloom-causing group in the marine waters of India, followed by diatoms (29), cyanobacteria (24), rhodophytes (4), and haptophytes (1). Frequently reported bloom species in the coastal waters of India are the *Trichodesmium erythraeum* (23), followed by *Noctiluca scintillans* (19), *Noctiluca miliaris* (15), *Asterionella glacialis* (11), *Cochlodinium polykrikoides* (5), *Karenia mikimotoi* (3), etc. (Fig. 4).

Variations in water quality variables

The physical, chemical, and nutrient variables were estimated for both the bloom and non-bloom locations (Table 1). The euphotic depth was observed at 9.16 ± 1.47 m and 11.67 ± 1.43 m for the B and NB locations, respectively. Dissolved oxygen indicated a significant difference between B and NB locations and recorded lower DO for bloom locations (3.89 ± 0.44 mg L^{-1}) and higher DO for non-bloom locations (5.50 ± 0.70 mg L^{-1}). The other variables, i.e., temperature, pH, and salinity, have not shown many differences between the B and NB sites. D-ortho phosphate and nitrates showed higher concentrations of 0.08 ± 0.02 μmol L^{-1} and 4.47 ± 0.69 μmol L^{-1} for the bloom locations than in the non-bloom locations (0.04 ± 0.02 μmol L^{-1} and 3.98 ± 0.76 μmol L^{-1} for B and NB locations, respectively). The higher chlorophyll-*a* was recorded at bloom locations (4.14 ± 1.49 mg m^{-3}) than the non-bloom locations (1.12 ± 0.44 mg m^{-3}).

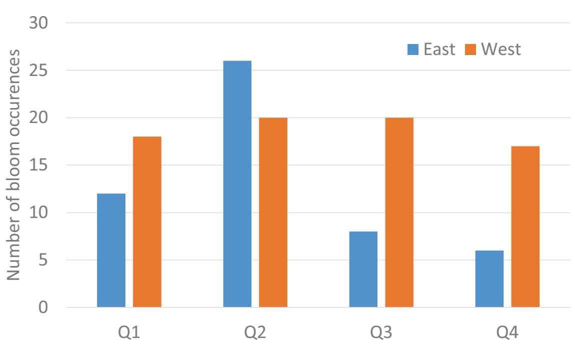

Fig. 3 Quarter-wise bloom occurrences in the east and west coast of India

The correlation analysis was attempted across the estimated variables for the bloom and non-bloom locations (Fig. 5). The temperature is shown a negative correlation with euphotic depth ($r = -0.55$, $p < 0.05$) for the bloom dataset, but in the case of the non-bloom dataset, no significant correlation was observed ($r = 0.14$, $p > 0.05$). A significant negative correlation was observed between pH and d-ortho phosphate for bloom data ($r = -0.80$, $p < 0.05$), but a significant positive correlation was noticed for non-bloom data ($r = 0.58$, $p < 0.05$). The nutrients d-ortho phosphate and nitrates shown significant higher positive correlations ($r = 0.73$, $p < 0.05$ and $r = 0.69$, $p < 0.05$) for bloom data than the non-bloom data ($r = 0.53$, $p < 0.05$ and $r = 0.50$, $p < 0.05$).

Principal component analysis

The PCA preserves most of the information in the initial few components with the largest eigenvalues, and each of the variables reflects several relationships among variables. The concentration ellipses depict that the variables showed distinct grouping for both bloom and non-bloom sampling locations (Fig. 6). The contribution of PC1 and PC2 for both bloom and non-bloom locations was estimated at 52.33%. The variable d-ortho phosphate explains 24.19% variability in the PC1, followed by Chl-*a* (19.89%), N–P ratio (17.36%), and DO (10.88%), but temperature explains a maximum percentage of 28.22 variabilities in case of PC2.

Variability in non-bloom sites

Principal component analysis (PCA) of physico-chemical, nutrients, and Chl-*a* variables were done for the non-bloom sites (Table 2 and Figs. 7a and 8a). The PC1 showed a high amount of variation (eigenvalue) of 3.193, indicating the maximum variation in the data set. The proportion of variance explained by PC1 was 31.93 for the non-bloom data, followed by PC2 (18.36), PC3 (13.40), PC4 (10.92), etc. The eigenvalues of the first three PCs together explain 63.70% of the variation in the data set (Table 3). The PCA was done for the bloom sites, the PC1 explained the highest percentage of variance 30.34, followed by PC2 (27.50%), PC3 (22.55%), etc. The initial three PCs explained a cumulative variance of 80.40% of the bloom data set.

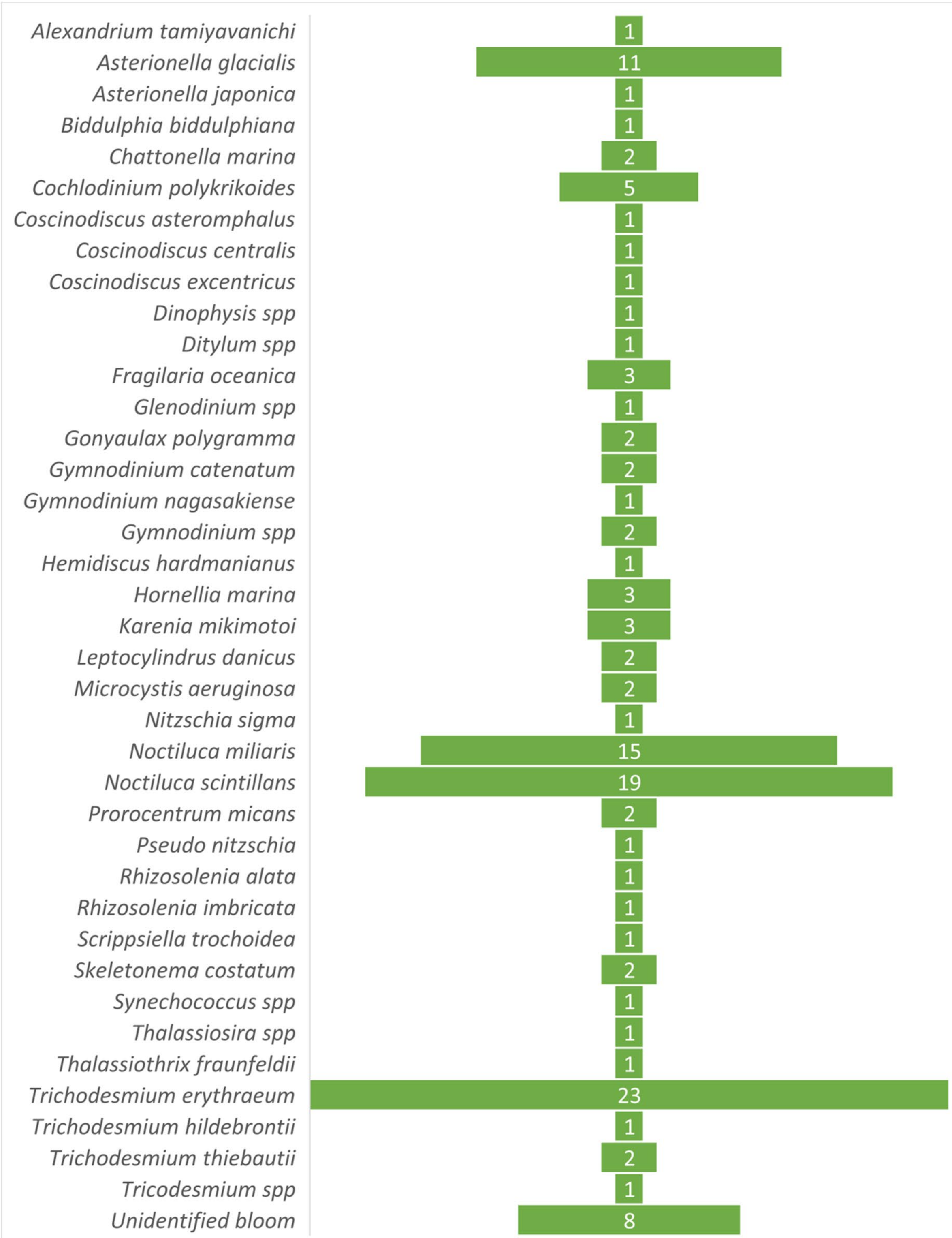

Fig. 4 Occurrence frequency of bloom causative species along the Indian coast from 1916 to 2019

Table 1 Estimation of physico-chemical and biological variables at bloom and non-bloom sites

Variables	Units	Bloom sites			Non-bloom sites		
		Mean ± SD	CV	IQR	Mean ± SD	CV	IQR
Euphotic depth	M	9.16 ± 1.47	16.13	2.54	11.67 ± 1.43	12.32	2.50
Temperature	°C	24.28 ± 0.55	2.28	0.53	24.41 ± 1.43	5.88	2.37
pH		8.77 ± 0.10	1.09	0.18	8.76 ± 0.13	1.54	0.16
Salinity	PPT	36.95 ± 0.51	1.40	0.66	36.90 ± 0.57	1.56	0.57
Dissolved oxygen	mg L^{-1}	3.89 ± 0.44	11.44	0.65	5.50 ± 0.70	12.77	0.90
Reactive silicates	µmol L^{-1}	0.54 ± 0.17	31.94	0.27	0.52 ± 0.14	26.66	0.16
D-ortho phosphate	µmol L^{-1}	0.83 ± 0.21	25.31	0.32	0.44 ± 0.18	41.82	0.14
Nitrates	µmol L^{-1}	4.47 ± 0.69	15.24	1.32	3.98 ± 0.76	19.25	1.25
Chlorophyll-*a*	mg m^{-3}	4.14 ± 1.49	36.07	1.79	1.12 ± 0.44	39.74	0.34
N–P ratio		54.51 ± 16.41	28.85	25.44	98.93 ± 27.13	27.42	40.31

SD standard deviation, *CV* coefficient of variation, *IQR* inter-quartile range

Variability in bloom sites

The contribution of variables in accounting for the variability of respective PCs are expressed in percentage, the variables that are correlated with PC1 and PC2 are critical while explaining the variability in the bloom sites (Table 2 and Figs. 7b and 8b). The variable pH explains 28.84% variability in the PC1, but in the case of PC2, DO explains the maximum percentage of 28.57 variability, followed by N–P ratio (22.30), (Table 3). In the non-bloom dataset, variable d-ortho phosphate explains the highest variance of 23.68% in the PC1 followed by Chl-*a* (16.49%), nitrate (16.44), and pH (15.67%). In the case of PC2, DO explains the highest variance of 25.88% followed by temperature (24.82%), silicates (17.27%), N-P ratio (11.02%), etc.

In-situ observation of Trichodesmium bloom

In the present study, *Trichodesmium* species blooms were encountered nine times predominantly during the winter months (Fig. 9). The blooms were very dense, brownish-yellow color, and range of nearly 5–15-m long and 3–6-m width patches, and it was spread over several kilometers. The bloom concentration ranges from 9553 to 12,235 trichomes L^{-1} (mean of 10,612 trichomes L^{-1}). A significant positive correlation was observed for the variables chlorophyll-*a* ($r=0.769$), nitrate ($r=0.565$), and PO_4 (0.298), but a negative correlation was noticed with variables DO ($r=-0.626$), pH ($r=-0.487$), and silicates ($r=-0.352$). The bloom density does not show a significant correlation recorded for the other physico-chemical variables like euphotic depth, temperature, and salinity. Moreover, the phytoplankton species recorded were *Skeletonema* sp., *Risosolenia* sp., *Pleurosigma* sp., *Protoperidinium* sp., *Peridinium* sp., *Ceratinium* sp., *Biddulphia* sp., and *Chaetoceros* sp. by using a microscope (Olympus Corp. CX31RTSF) with the power of 10 and 40 × lens.

Discussion

The microscopic algae play a key role in CO_2 sequestration from the atmosphere and also transport to deeper waters in the ocean, sometimes excess production will cause dynamics in biomass and the production of endogenous toxins that can harm the ecosystem (Glibert et al., 2005). The global coastal waters experienced frequent incidences of algal blooms predominantly HABs, because of anthropogenic activities and oceanic processes (Ahn & Shanmugam, 2006; Hallegraeff, 1993). Although HABs usually develop in a small region, the dynamic regional circulation can move water masses hundreds of kilometers from the source (Zhan et al., 2014). D'Silva et al. (2012) documented the 101 times that an algal bloom occurred in Indian waters from 1908 to 2009 and noted that dinoflagellates predominated along the west coast and diatoms along the east coast. A total of 39 bloom-causative species were recorded, of which *Noctiluca scintillans* and *Trichodesmium erythraeum* are the most common. The literature survey attempted in the present study revealed 110 bloom occurrences along the Indian coast with dinoflagellates emerging as the leading species, followed by diatoms.

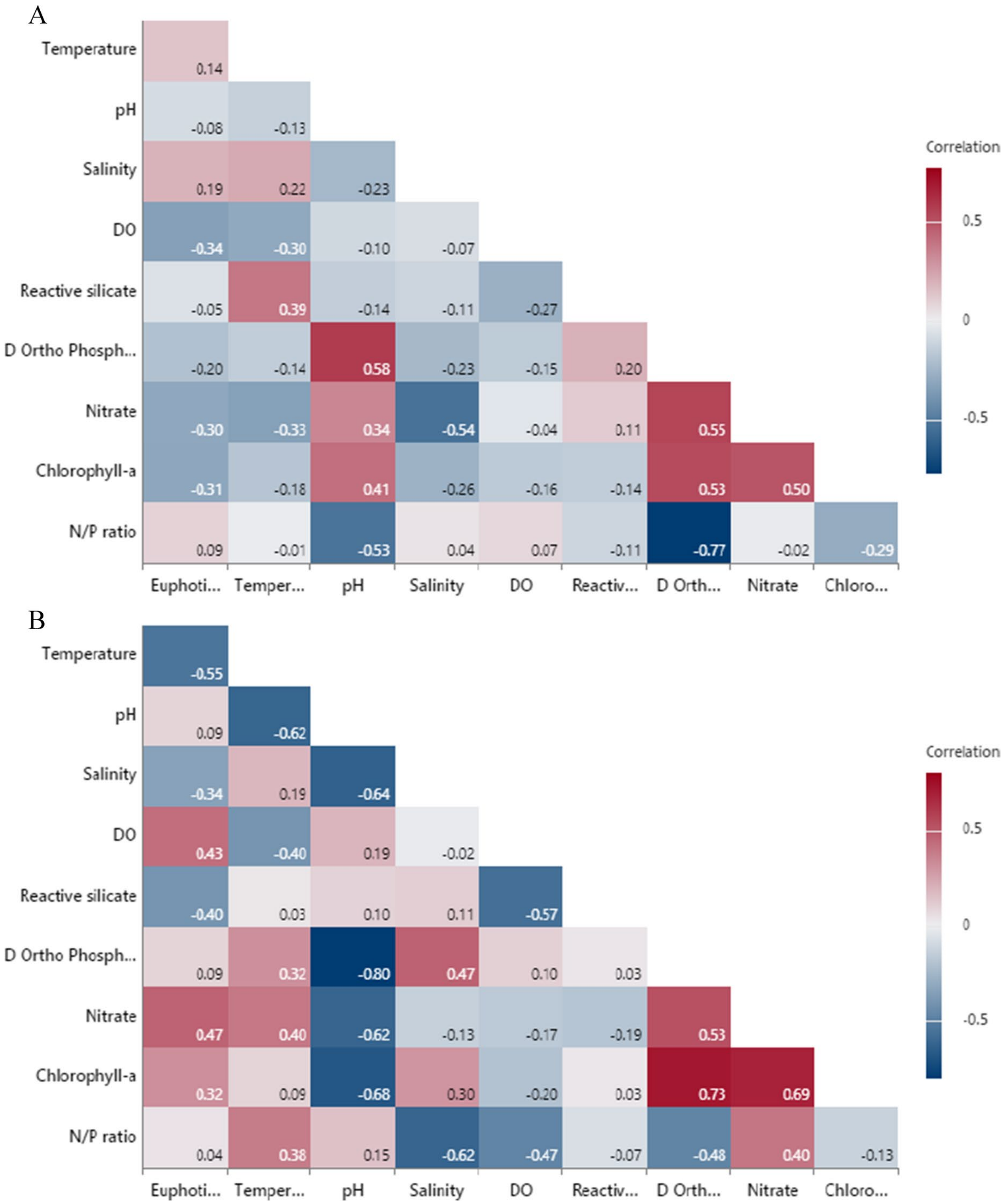

Fig. 5 Correlation analysis of physical, chemical, and nutrient variables **A** non-bloom and **B** bloom sites

Table 2 Principal component loadings of physico-chemical, nutrient, and Chl-*a* variables for non-bloom and bloom sites

Site	PC	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10
NB	Eigenvalue	3.19	1.84	1.34	1.09	0.81	0.62	0.43	0.37	0.25	0.05
	Variance percent	31.9	18.4	13.4	10.9	8.1	6.2	4.3	3.7	2.5	0.50
	Cumulative variance percent	31.9	50.3	63.7	74.6	82.7	88.9	93.2	96.9	99.5	100.0
B	Eigenvalue	3.03	2.75	2.25	1.12	0.51	0.24	0.05	0.03		
	Variance percent	30.3	27.5	22.5	11.2	5.1	2.45	0.5	0.30		
	Cumulative variance percent	30.3	57.8	80.4	91.6	96.7	99.2	99.7	100.0		

The incidences of algal blooms are more frequent in recent along the Arabian Sea with strong seasonal dynamics in the type of bloom-causative species predominantly in the coastal waters of the eastern Arabian Sea (Basu et al., 2011; Padmakumar et al., 2012). *Trichodesmium* blooms were encountered with varied intensity in 3 years of the present study predominantly during the winter and post-winter months in the coastal waters of Gujarat. The dominance of blooms occurred during the withdrawal of the southwest monsoon and pre-monsoon periods in the coastal waters of India (D'Silva et al., 2012; McCabe et al., 2016). Most often, *Noctiluca* and *Trichodesmium* are the bloom-causative species in the region; during the present investigations, we observed both *Noctiluca* and *Trichodesmium* bloom in the coastal waters of Gujarat (Ahmed et al., 2017; Naqvi et al., 1998; Roy et al., 2011; Smitha et al., 2022). The patches of blooms were encountered during the winter and post-summer months in the region, which is in agreement with the earlier investigations in the Arabian Sea (Capone et al., 1998; Prabhu Matondkar et al., 2004; Desa et al., 2005; Hegde et al., 2008; Padmakumar et al., 2012; Parab & Matondkar, 2012; Parab et al., 2012; Tholkapiyan et al., 2014; Dias et al., 2020). The *Noctiluca scintillans* bloom-formation starts in early winter and reaches a maximum during the spring period along the Gulf of Oman. The changes in hydrographic and biological factors and their spatial distribution because of the wind intensity and direction are the major driving factors for bloom formation (Al-Azri et al., 2007; Dwivedi et al., 2006). The decline of *Trichodesmium* bloom was observed in the coastal waters of Goa (Arabian Sea) during April and May, and a mixed diatom bloom formed with the dominance of *Chaetoceros* sp. (Devassy et al., 1978).

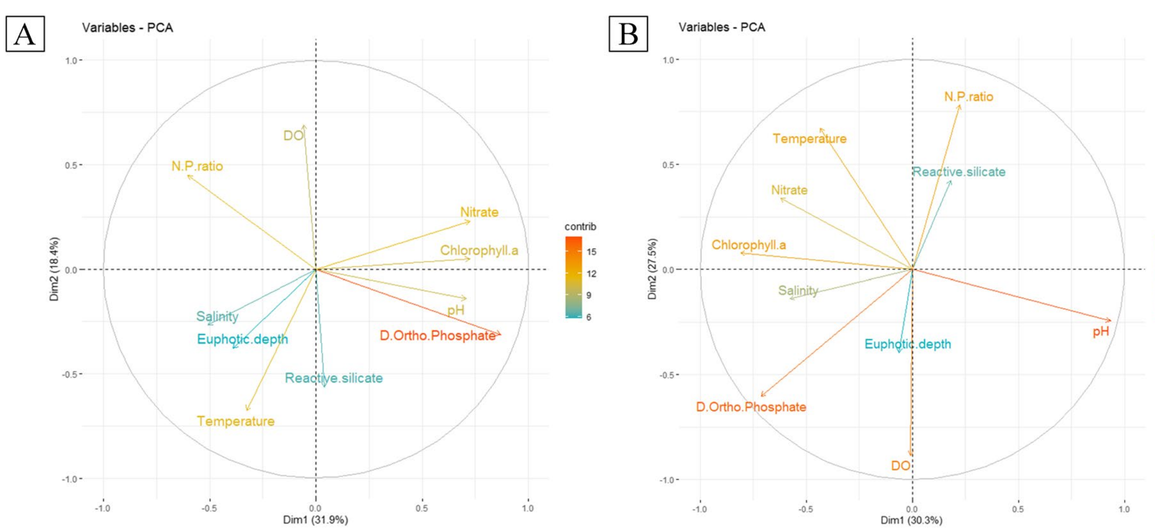

Fig. 6 PCA analysis of physic-chemical, nutrient, and Chl-*a* parameters for **A** non-bloom and **B** bloom datasets

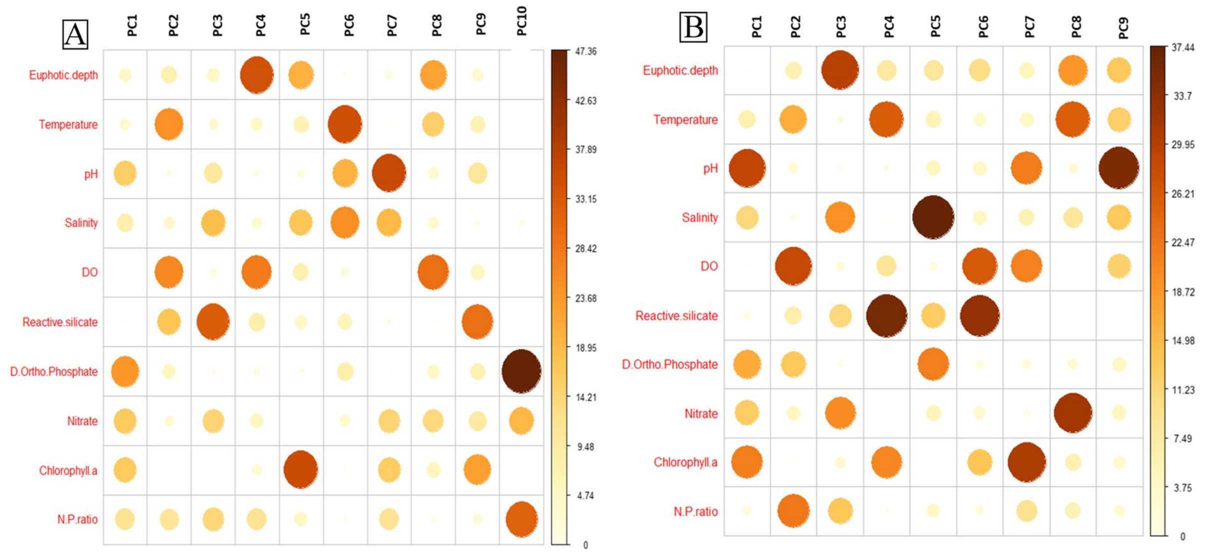

Fig. 7 Variable contribution plots for the **A** non-bloom and **B** bloom datasets

The variables euphotic depth and dissolved oxygen have shown a significant difference between bloom and non-bloom sites ($p < 0.05$), but other variables like temperature, pH, and salinity do not show any significant differences ($p > 0.05$) (Martin et al., 2013). Nayak and Karunasagar (2000) observed consistent pH and temperature levels during the bloom period along the southwest coast of India, with similar dynamics in the variables observed during the current study. The SST observed around the bloom

Table 3 Percentage of contribution by different variables to principal components for both non-bloom (NB) and bloom (B) datasets

Variables		PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10
Euphotic depth (m)	NB	4.73	7.73	4.84	34.44	20.17	0.23	1.76	22.33	3.62	0.13
	B	0.13	5.69	29.92	7.95	8.36	10.02	4.79	18.83		
Temperature (°C)	NB	3.34	24.82	3.13	4.26	6.98	34.71	0.24	15.50	6.97	0.00
	B	6.22	16.40	1.22	25.65	5.41	3.18	3.95	25.57		
pH	NB	15.67	1.09	10.15	0.96	1.68	19.96	35.88	3.56	10.86	0.14
	B	28.84	2.18	0.46	0.78	4.61	3.93	21.77	1.94		
Salinity (PPT)	NB	8.07	3.85	18.36	3.03	17.22	24.86	19.04	3.75	0.74	1.05
	B	10.98	0.68	19.47	0.14	37.44	4.04	5.58	8.35		
DO (mg L^{-1})	NB	0.10	25.88	1.48	27.78	7.47	1.87	0.01	29.65	5.70	0.02
	B	0.01	28.57	1.54	8.61	1.29	26.23	21.23	0.03		
Reactive silicate (μmol L^{-1})	NB	0.05	17.27	32.50	8.09	4.66	6.37	0.86	0.18	29.83	0.16
	B	1.07	6.53	10.70	35.71	12.55	33.21	0.05	0.04		
D-ortho phosphate (μmol L^{-1})	NB	23.68	5.30	0.78	1.48	1.17	8.06	0.07	4.87	7.19	47.36
	B	16.74	13.24	0.54	0.04	21.58	1.27	1.68	2.18		
Nitrate (μmol L^{-1})	NB	16.44	2.87	14.54	5.30	0.01	3.36	14.62	13.58	9.86	19.38
	B	12.71	4.14	20.21	0.12	5.03	3.01	0.94	31.71		
Chlorophyll-*a* (mg m^{-3})	NB	16.49	0.13	0.09	3.10	35.40	0.23	15.93	5.70	22.73	0.16
	B	21.61	0.21	2.45	20.62	0.07	13.57	30.76	5.79		
N–P ratio	NB	11.39	11.02	14.10	11.50	5.19	0.30	11.57	0.83	2.47	31.58
	B	1.66	22.30	13.45	0.34	3.63	1.50	9.22	5.53		

Fig. 8 PCA bi-plot indicating variables contributed for the bloom and non-bloom sites

patches was > 24 °C (Sarangi, 2012), 28.0 °C (Parab & Matondkar, 2012), 29.0 °C (Koya & Kaladharan, 1997), and 30.61 °C (Raghavan et al., 2010). The sea surface temperature in the bloom waters was recorded at 24.28 ± 0.55 °C, which is similar to the previous results during the *Trichodesmium* bloom along the north-western Bay of Bengal (Sahu et al., 2017) and eastern Arabian Sea (Ahmed et al., 2017). The distributional pattern of *Trichodesmium* bloom was not shown any impact on the temperature in the southern East China Sea (Chang et al., 2000), which supports the narrow range of temperature difference between the bloom and non-bloom stations in the current investigation. The average salinity during the bloom

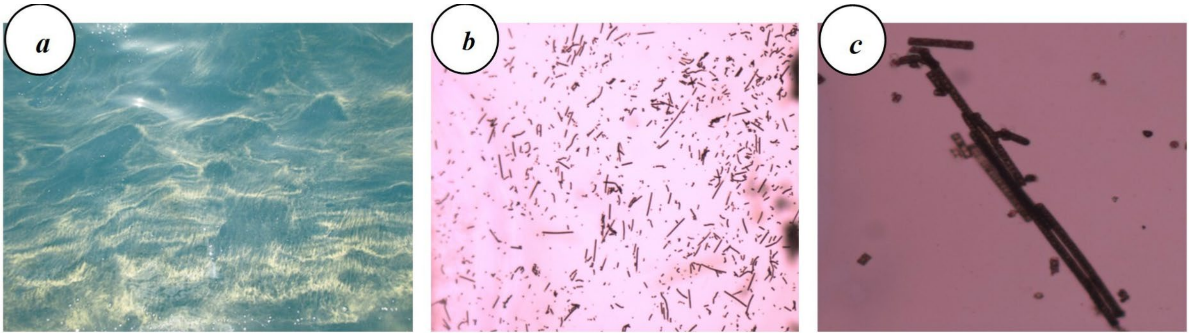

Fig. 9 **a** Bloom of *Trichodesmium* species, **b** filaments, and **c** *Trichodesmium* species

period in the region is 36.95 ± 0.51 ppt, the results are coinciding with previous reports of 34.4 ppt in the Lakshadweep Sea (Koya & Kaladharan, 1997), 35.2 ppt along the off Karnataka-Goa coast (Raghavan et al., 2006), and 35.86 ppt along the off Karwar coast (Raghavan et al., 2010).

The hydrographical and meteorological parameters supported the bloom formation along the southwest coast of India (Krishnan et al., 2007). Euphotic depth recorded at bloom sites was lower (9.16 ± 1.47 m) than at the non-bloom sites (11.67 ± 1.43 m), which could be due to the enhancement of primary productivity (Jyothibabu et al., 2003), pigments, epiphytes, and bloom-associated zooplankton (Padmakumar et al., 2010). Significantly lower DO concentrations were recorded at bloom sites (3.89 ± 0.44 mg L^{-1}), but higher values were observed at non-bloom sites (5.50 ± 0.70 mg L^{-1}). The levels of dissolved oxygen during the bloom incidence were measured at 1.90 mg L^{-1} (Koya & Kaladharan, 1997), 1.25 mg L^{-1} (Naqvi et al., 1998), 1.2 mg L^{-1} (Satpathy & Nair, 1996), and 6.85 mg L^{-1} (Padmakumar et al., 2010). The DO concentrations recorded in the bloom sites are within the limits reported by earlier researchers in the region. The bloom locations in the region are characterized by lower DO due to the biological degradation of organic matter associated with algal blooms and microbial respiration (Breitburg et al., 2018; Diaz & Rosenberg, 2008; Gilbert et al., 2010).

Nutrient enrichment stimulates and increases the growth and biomass of HABs in addition to altering the ecosystem dynamics and food web (Allen et al., 2006; Sarkar, 2018). The phytoplankton growth in the ecosystem is majorly governed by the types of phosphates and nitrates available in the system (Sarkar, 2018). D-ortho phosphate has shown a significant difference between the bloom and non-bloom locations ($p < 0.05$), the values recorded at 0.83 ± 0.21 μmol L^{-1} and 0.44 ± 0.18 μmol L^{-1} in the bloom and non-bloom locations, respectively. Phosphate concentrations were estimated during the bloom period by Koya and Kaladharan (1997) (1–2.3 μM in the Lakshadweep Sea); Nayak and Karunasagar (2000) (2.4 μg L^{-1} in the eastern Arabian Sea); Padmakumar et al., 2010 (0.108 μmol L^{-1} in the southeastern Arabian Sea); and Santhanam et al., 2013 (0.52 μmol L^{-1} in the southeast coast of India). The concentration of phosphates estimated during the bloom period in the region is lower than the previous estimates due to patchy bloom formations, but a two-fold increase in levels was observed when compared with non-bloom sites (Mohanty et al., 2010; Raghavan et al., 2006; Satpathy & Nair, 1996).

Algal blooms are potentially stimulated by nutrients generated from an agricultural source, land runoff, sewage, and atmospheric deposition. Mostly, the total nitrogen showed a strong correlation with phytoplankton production in the estuarine and marine waters (Anderson et al., 2002; Kudela et al., 2010). The nitrogen fixation rate ranged from 0.1 to 59 μmol N m^{-2} d^{-1} and the investigations depict that *Trichodesmium* is one of the major contributors to new production in Kuroshio waters (Chang et al., 2000). The levels of nitrates were moderately higher in the bloom zones (4.47 ± 0.69 μmol L^{-1}) than in the non-bloom zones (3.98 ± 0.76 μmol L^{-1}). The wider range of nitrate concentrates was estimated at 1.3–2.9 μM in the southwest coast of India (Madhu et al., 2011), 9.4 μg L^{-1} in the eastern Arabian Sea (Nayak & Karunasagar, 2000), 0.34 μM in the Arabian Sea (Parab & Matondkar, 2012), 8.0 μM in the west coast of India (Martin et al., 2013), 0.32 μmol L^{-1} in the southeast coast of India (Santhanam et al., 2013). The key characteristics during the bloom were a spare population of other phytoplankton and zooplankton and a lower concentration of nitrates, but the *Trichodesmium* bloom species fix molecular nitrogen which enriches the nitrogen sources in the tropical seas to maintain the equilibrium (Qasim, 1970; Subramaniam et al., 1999). The reactive silicates have shown no significant difference between the bloom (0.54 ± 0.17 μmol L^{-1}) and non-bloom (0.52 ± 0.14 μmol L^{-1}) sites. The previous studies reported the range of silicates from 1.29 to 39.9 μmol L^{-1} during the bloom (Madhu et al., 2011; Padmakumar et al., 2010; Santhanam et al., 2013), but the lower silicates were recorded in the present study.

Ocean-color monitoring technologies are using to detect algal blooms in recent years based on the high-spectrophotometric surface chlorophyll-*a* values (Minu et al., 2015; Raghavan et al., 2010; Sarangi, 2012). The MODIS spectra reported on the bloom intensity as a proxy of chlorophyll-*a* concentration: less dense bloom (< 2 mg m^{-3}), a surface scum bloom (> 2 to < 10 mg m^{-3}), and floating blooms (> 10 mg m^{-3}) (Gokul & Shanmugam, 2016; Gokul et al., 2019). A significantly higher average of chlorophyll-*a* was estimated in bloom zones (4.14 ± 1.49 mg m^{-3}) than in the non-bloom zones

(1.12 ± 0.44 mg m^{-3}) in the current study. The interquartile range of chlorophyll-*a* in the bloom waters was 1.79 mg m^{-3}, but a lower range was observed in non-bloom waters at 0.34 mg m^{-3}, depicting the wide range of chlorophyll-*a* in the bloom waters. Unusually high chl-*a* concentrations were observed during the bloom incidences by Dwivedi et al. (2012) (0.4–2.0 mg m^{-3}), Madhu et al. (2011) (56.8 ± 23.7 mg m^{-3}), Mohanty et al. (2010) (42.15 mg m^{-3}), Sarangi (2012) (20 mg m^{-3}), Raghavan et al. (2010) (32–39 mg m^{-3}), Parab et al. (2012) (2–5.90 mu gl sup^{-1}), Thomas et al. (2013) (22.7 mg m^{-3}), and Santhanam et al. (2013) (22.04 mg m^{-3}). The chlorophyll-*a* estimated in the bloom waters in the present study agrees with previous results (Dwivedi et al., 2012; Parab et al., 2012) and is lower than the other investigations.

The *Trichodesmium* colonies often signify a large fraction of the plankton biomass in tropical, oligotrophic waters and contribute significantly to primary production and the N_2 fixation is a major input to the marine and global nitrogen cycle (Capone et al., 1997). The *Trichodesmium erythraeum* species were reported along the east coast of India (Kannan & Vasantha, 1992) and Mohanty et al. (2010) and Kumar et al. (2015) reported approximately 7000 filaments L^{-1} in the Andaman Sea. The *Trichodesmium thiebautii* was reported along the coastal waters of Port Blair and Kalpakam, Tamil Nadu (Sahu et al., 2014, 2016). The population densities of *Trichodesmium* range from 0 to 600 trichomes L^{-1} mostly in surface water between 0 and 50 m depth in the southern East China Sea (Chang et al., 2000). The population density of *Trichodesmium erythraeum* was recorded at an average of 10,612 trichomes L^{-1} (9553 to 12,235 trichomes L^{-1}) in the present study. The intensity of *Trichodesmium* bloom was reported with a wider range by various researchers along the east coast of India and was provided in the supplementary materials.

The blooms of toxic or noxious species of phytoplankton can disrupt the energy transfer in planktonic food webs and result in illness or death of mammals, birds, and commercially important fish and shellfish. The trophodynamic studies will reveal the negative impacts caused by a bloom on different resources with a special focus on marine fishery resources (Ahn & Shanmugam, 2006; Harrison et al., 2017; Koya & Kaladharan, 1997). The detrimental impact of toxic algal blooms negatively impacts the biological integrity of the ecosystem, the decline of fishery resources, and alters the biogeochemistry of the habitat. The reasons for the frequent occurrence of blooms and their impact on plankton diversity and the food web need to be investigated. Climate change is a major driving factor for bloom formation majorly due to the thermal stratification and acidification which needs elaborate research investigation in the region in support of satellite-derived ocean-color monitoring techniques.

Summary and conclusions

The diversity and quantum of phytoplankton in the marine ecosystem are influenced by physical forces, biogeochemistry, human-induced, and climate-driven factors. The current study area is known for better productivity, rich marine biota, and ecologically significant ecosystems, but the region witnessed frequent algal blooms in recent years. The bloom-causative bloom species were dominated by *Trichodesmium*, *Noctiluca*, and *Gymnodinium*, but *Trichodesmium* plays a vital role in marine biogeochemistry by new production. The nutrients (PO_4 and NO_3) and Chl-*a* have shown a significant positive correlation during the *Trichodesmium* bloom incidence, but the variables like DO and pH have shown a negative correlation with the intensity of trichomes. The variable PO_4 explains the highest variability in PC1, followed by Chl-*a*, N–P ratio, and DO. The identification and intensity of *Trichodesmium* bloom in-relation to physical, chemical, nutrient, and Chl-*a* revealed insights of biogeochemistry during the bloom incidence. The quantum of nutrients (PO_4 and NO_3) was recorded at higher levels in the bloom locations which indicate key factors to induce bloom formation. The variables like DO and pH are negatively related to bloom intensity which is a major concern with slow-swimming and bottom-dwelling biota due to acidification and deoxygenation. The upcoming ocean-color sensors help to provide synoptic understanding to identify and monitor the blooms at the species level with various spectral absorption information. Research investigations need to undertake on the shifts in other phytoplankton species during the bloom incidence and also quantify the cumulative impact on the trophic web interactions. The fisher's perception was that the incidences of bloom patches in the coastal waters give poor catch rates and are signs to close fishing activities. More biological investigations on important fishery resources (stock status, diet composition, biochemical analysis, etc.), bloom characterization, and mapping of blooms using remote-sensing techniques at spatial and temporal scales will reveal many scientific facts.

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Author contribution VKV: conceptualization, data curation and analysis, and writing the manuscript. MR: data curation, project administration, and supervision. AS: investigation and review and editing. SR: data curation, writing original draft, and literature retrieval. RK: formal analysis, review and editing. SKR: investigation, project administration, and methodology. GRD: investigation and project administration. JJ: methodology, supervision, and review and editing. PR: supervision, review, and editing. RK: investigation, resources, and review and editing.

Data availability The supporting data is available with the corresponding author.

Declarations

Ethics approval and consent to participate In no case, human participants whose consent to participate was needed to be involved.

Consent for publication Consent for publication was taken from the competent authority and all co-authors.

Competing interests The authors declare no competing interests.

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