Indian Journal of Geo Marine Sciences
Vol. 54 (09), September 2025, pp. 465-477
DOI: 10.56042/ijms.v54i09.18991

Research Article

Mixed bloom of diatoms (*Skeletonema costatum* (Greville) Cleve, 1873 and *Lauderia annulata* Cleve, 1873) in coastal waters at Kalpakkam, southeast India, during the northeast monsoon

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Received 22 April 2025; revised 09 September 2025

The present study reports a dual-species bloom of marine diatoms *Skeletonema costatum* (Greville) Cleve, 1873 and *Lauderia annulata* Cleve, 1873, observed during the northeast monsoon of 2019 in the Kalpakkam coastal waters, southeast coast of India. Phytoplankton density during the bloom event ranged from 1.01 – 1.90×10^6 cells L^{-1}, with an average of 1.39×10^6 cells L^{-1}. *Skeletonema costatum* and *L. annulata* contributed approximately 53.7 % (7.4×10^5 cells L^{-1}) and 16.65 % (2.8×10^5 cells L^{-1}) of the average population density. High fluctuations in chlorophyll-*a* (chl-*a*) concentrations (0.49 – 6.44 mg m^{-3}) and physico-chemical parameters, *viz*., turbidity (0.25 – 2.5 NTU), Suspended Particulate Matter (SPM) (7.32 to 39.84 mg L^{-1}), and ammonium (10.29 – 31.59 µM) were observed during the bloom. Statistical analysis revealed that temperature, salinity, and turbidity were crucial in the bloom formation. The results indicated phosphate might be a limiting factor rather than nitrate and silicate. The available reports indicate that the co-bloom of *S. costatum* and *L. annulata* is the first of its kind and a rare occurrence in the Bay of Bengal coastal waters.

[Keywords: Bay of Bengal, Chlorophyll, Coastal water, Multispecies phytoplankton bloom, Physico-chemical parameters]

Introduction

Phytoplankton plays an essential role in the marine environment; approximately 30 – 60 % of primary productivity is contributed by phytoplankton, and it maintains the structure and functioning of marine and coastal water ecosystems[1]. They are essential components of the marine food web[2] and directly affect biogeochemical cycles and climate[3,4]. Around 5000 phytoplankton species exist globally. Of these, roughly ~7 % of species, including diatoms, dinoflagellates, raphidophytes, prymnesiophytes, and silicoflagellates, are responsible for bloom formation[5]. Only ~2 % of the bloom forming species are considered to be harmful or toxic, and predominantly (~75 %) contributed by dinoflagellates[6]. In a natural environment, blooms are spontaneous and inevitable; however, their growth and persistence are determined by the interplay of various physical, chemical, and biological factors that are often sudden and unpredictable[7]. Algal blooms that result in the discolouration of seawater are commonly referred to as "red tide" and mainly occur in the coastal and inland seas when the hydrobiological conditions are optimal[8,9].

In general, bloom formation in the marine environment is beneficial to food web processes[6]; however, some bloom species exhibit harmful effects by either releasing toxins or creating anoxic conditions, which are called Harmful Algal Blooms (HABs). These HABs can damage the entire ecosystem and result in economic loss through various processes such as toxin production, fish mortality, and shellfish poisoning[10]. Broadly, bloom species are categorised into three groups: (1) blooms that produce harmless water discolouration with high density, upon decomposition, produce anoxia and result in indiscriminate mortality of marine life; (2) potent toxin-producing bloom species that cause various illnesses (gastrointestinal and neurological) to humans, and (3) Non-toxic bloom species that cause no harm to humans but harmful to fish and invertebrates (damage or clog fish gills).

In Indian coastal waters, *Trichodesmium erythraeum* blooms are reported to be more common, followed by 'Red tide' blooms caused by dinoflagellates. However, reports on diatom blooms are scarce from the Bay of Bengal (BOB) and the Arabian Sea. The first-ever report on a diatom bloom formed by *Rhizosolenia* sp. in BOB was from the coastal waters of Mandapam, Palk Bay[11], followed by an *Asterionella japonica* bloom from Visakhapatnam coast[12]. Subsequently, reports on diatom blooms in BOB were made from the Vellar estuary[13], off Kalpakkam, Tamil Nadu[14] and along the coast of Orissa[15-17]. On most occasions, monospecific blooms occur, and occasionally mixed diatom blooms have been reported[18]. Nevertheless, reports on diatom blooms are still meagre as they constitute only about 20 % of total blooms reported from Indian waters[19]. Despite the recent increase in diatom blooms in Indian waters[9,20-25], the phenomenon still requires further study to understand the mechanisms behind it. The present study reports the co-bloom of two diatom species, *Skeletonema costatum* (Greville) Cleve, 1873 and *Lauderia annulata* Cleve, 1873, in Kalpakkam coastal waters, and the causative factors responsible for the mixed bloom.

Skeletonema costatum and *L. annulata* are common micro-phytoplankton encountered in the coastal waters[26-30]. These species have been reported from various coastal habitats of India, such as mangrove ecosystems of West Bengal[31,32], estuarine and coastal waters of Odisha[16,17], Vellar estuary of Tamil Nadu[28], backwaters of Kerala[26], Goa coast[33], Mumbai coast of Maharastra[34], etc. Though there are a few reports of *S. costatum* bloom from world oceans[35-37], reports on bloom of *S. costatum* from Indian coasts are very rare[28]. Interestingly, the population explosion of *L. annulata*, contributing significantly to the phytoplankton standing stock, has never been reported.

Materials and Methods

The bloom was observed in the coastal waters off Kalpakkam (Lat. 12°33′27″N and Long. 80°10′31″E), situated on the southeast coast of India, during a regular seasonal sampling. A detailed description of the study area is given in an earlier report[38]. Sampling was conducted during the northeast (NE) monsoon in December 2019 at 12 locations in the nearshore waters. The sampling stations were in two transects parallel to the shoreline (at 1.6 and 5 km) inside the sea (Fig. 1). Physical parameters such as temperature, pH, salinity, Dissolved Oxygen (DO), and turbidity were measured in situ using a portable multiparameter probe (HANNA instruments). The accuracy of measurement of the above parameters was: temperature: ±0.05 °C, pH: ±0.02, salinity: ±0.05 PSU, dissolve oxygen: ±0.05 mg/l, and turbidity: ±0.1 NTU. The surface water samples were collected using pre-cleaned polypropylene containers and were preserved at -20 °C until analysis. Filtered samples were analysed for nutrients such as nitrate, phosphate, silicate, ammonium, Total Nitrogen (TN), and Total Phosphorus (TP) using the SKALAR SAN++ continuous flow analyser. The Suspended Particulate Matter (SPM) content was estimated using the method described by Manuri *et al.*[39]. All nutrient methods were based on ISO and ASTM procedures based on colourimetric analysis. Sensitivity of these methods followed for nutrient analyses were: nitrate: 0.1 µM, phosphate: 0.01 µM, and silicate 0.5 µM. The spectrophotometric method by Strickland & Parson[40] was used to estimate chlorophyll-*a* (chl-*a*), where filter papers were stored in the dark and at -20 °C with 90 % acetone for 24 h. The extract was then centrifuged, and absorbance was measured at various wavelengths for chl-*a* calculations. The phytoplankton samples were collected in 1 L bottles and were preserved in Lugol's iodine solution (1 %). A detailed procedure from preservation to counting was followed, as given by Sahu *et al.*[41]. The phytoplankters were identified by following standard taxonomic monographs[42-44], and the quantitative analysis was performed using the Sedgwick–Rafter counting chamber and an inverted microscope (Zeiss Axio observer).

Results and Discussion

Indian coastal waters are significantly influenced by monsoon rainfall, which causes heavy river discharge. Especially in eastern India, there are heavy downpours, and a large amount of freshwater is received through monsoon-fed rivers, reducing salinity and temperature[45]. On the day of regular monitoring program (23 December 2019), the surface water of the study area was observed to be light brown, indicating the presence of the bloom. Approximately 100 km^2 of coastal water stretch was covered during the study, and the bloom was present in almost all the study regions. After microscopic observation, the dense bloom caused by two diatom species *viz.*, *S. costatum* and *L. annulata* (Fig. 2a – e) was identified. So far, a few studies pertaining to *S. costatum* bloom occurrence from Indian coastal waters have been reported[26-28]. However, to date, no reports has been published on the co-bloom occurrence of *S. costatum* and *L. annulata* from the coastal waters of India. Hence, the available literature suggests that this would be the first report on the mixed bloom occurrence of the

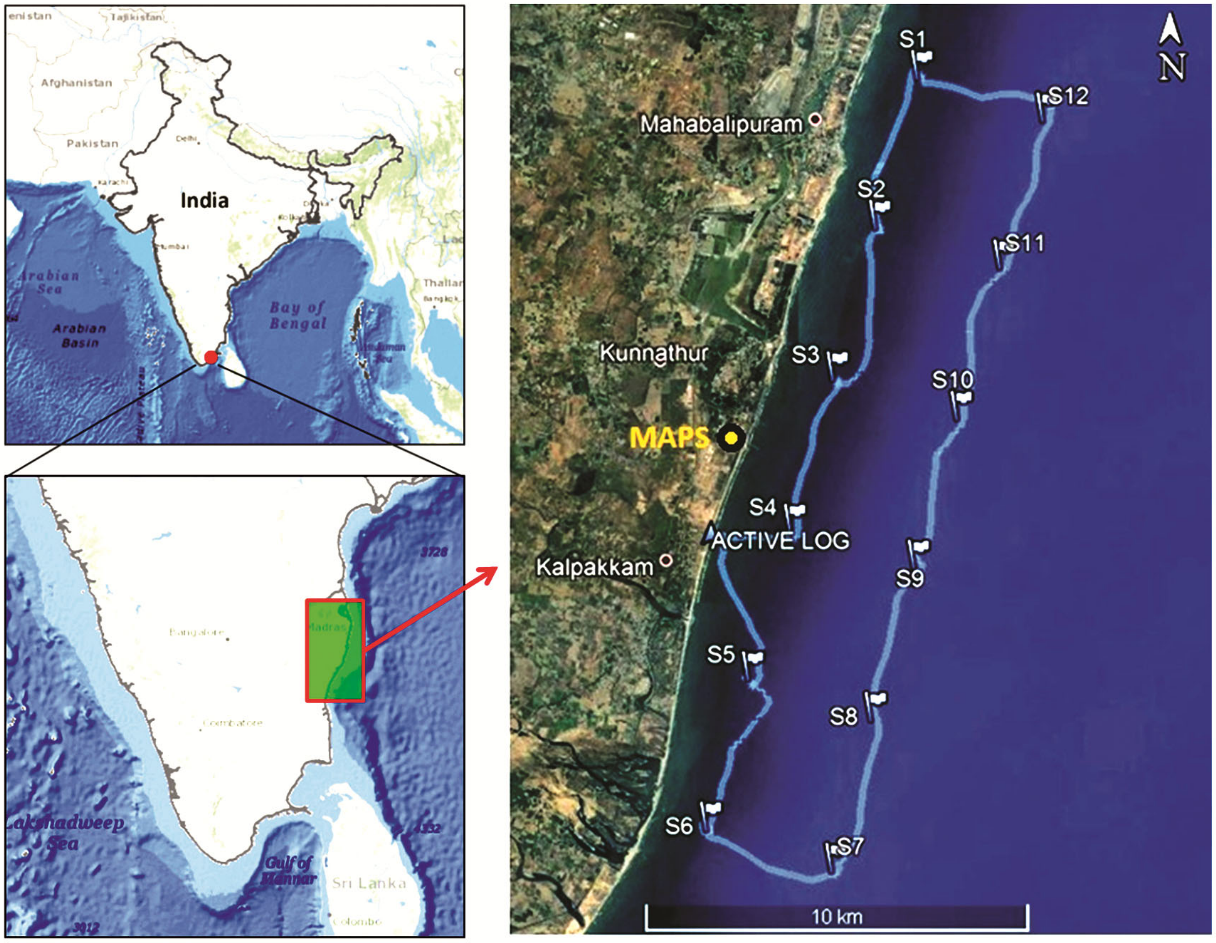

Fig. 1 — Map showing the study area and sampling locations along with GPS tracking; stations 1 to 6 represent transect 1 (situated 1.2 km inside the sea), and stations 7 to 12 represent transect 2 (situated 5 km inside the sea)

above species. Moreover, the bloom of *L. annulata* has never been reported from Indian waters, and the present observation is perhaps the first of its kind.

During bloom, the total phytoplankton population density varied from 1.01 – 1.90×10^6 cells/L with an average of 1.39×10^6 cells/L (Fig. 3a) across the 12 stations observed. Of the total population density, *S. costatum* and *L. annulata* alone registered 4.4 – 14.0×10^5 and 1.9 – 2.8×10^5 cells/L, respectively, and were found to be predominant among the phytoplankton community (Fig. 3b). *Skeletonema costatum* and *L. annulata* contributed approximately 53.7 % (7.4×10^5 cells/L) and 16.65 % (2.8×10^5 cells/L) of the average population. Though there is no report of a mixed diatom bloom at this location, several studies on other diatom, dinoflagellate, and cyanobacterial blooms, such as *Asterionellopsis glacialis*[8,23], *Noctiluca scintillans*[46], and *Trichod esmium erythraeum*[47,48] have been reported over the last two decades. Comparatively, the population density of the presently reported bloom species (*S. costatum* and *L. annulata*) is lower than the previously reported bloom species cell density in this region[8,23,47-48] (*Asterionellopsis glacialis*: 5.45×10^7 cells/L & 5.63×10^7 cells/L; and *Tricho desmium erythraeum*: 2.88×10^7 cells/L & 4.414×10^6 cells/L). However, the present bloom density was much higher than that of *Noctiluca scintillans* (38000 cells/L) reported from the exact location[46]. The highest *Skeletonema* sp. density (1.4×10^6 cells/L) observed in the present study is comparable with the earlier published densities from the west coast of India (1.9×10^6 cells/L at Kerala coast[26]; and 1.4×10^6 cells/L at Dharamtar creek[27], west coast of India). However, it is significantly higher than the only published value (0.4 – 3×10^5) for *Skeletonema* sp. from Parangipettai coastal waters, the east coast of India[28].

Skeletonema costatum is a cosmopolitan and the most common species in tropical coastal waters, whereas

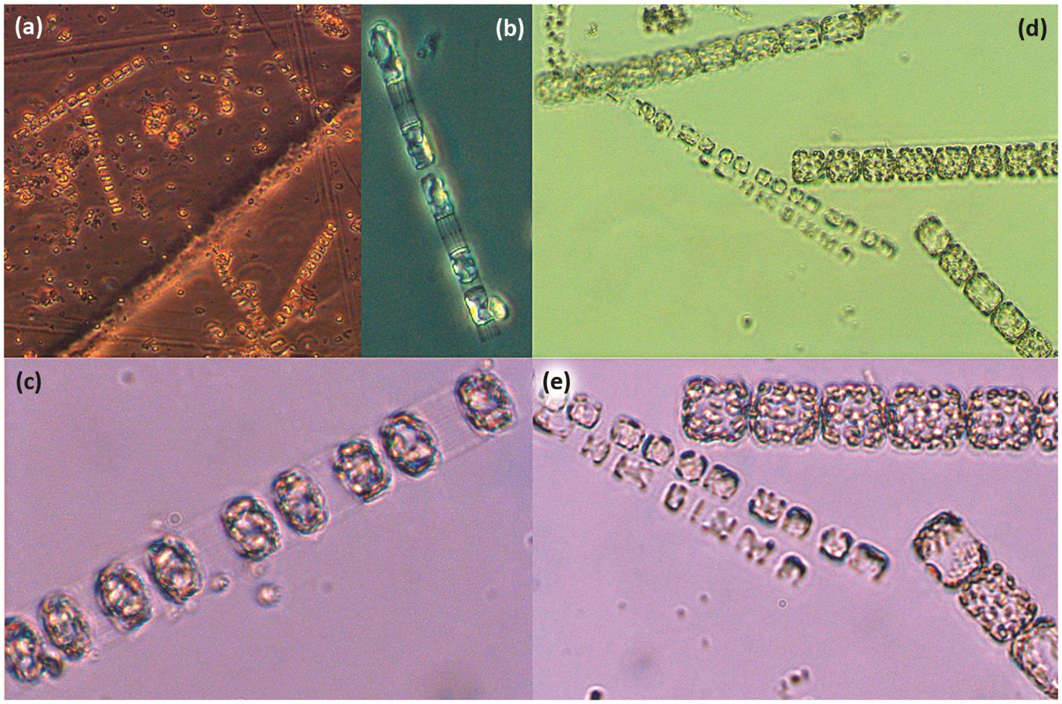

Fig. 2 — Microscopic view of bloom species in the surface water samples at Kalpakkam coast: a – c) *Skeletonema costatum*; and d – e) *Lauderia annulata*. Magnification: a, d: 100x; b: 400x; and c, e: 200x

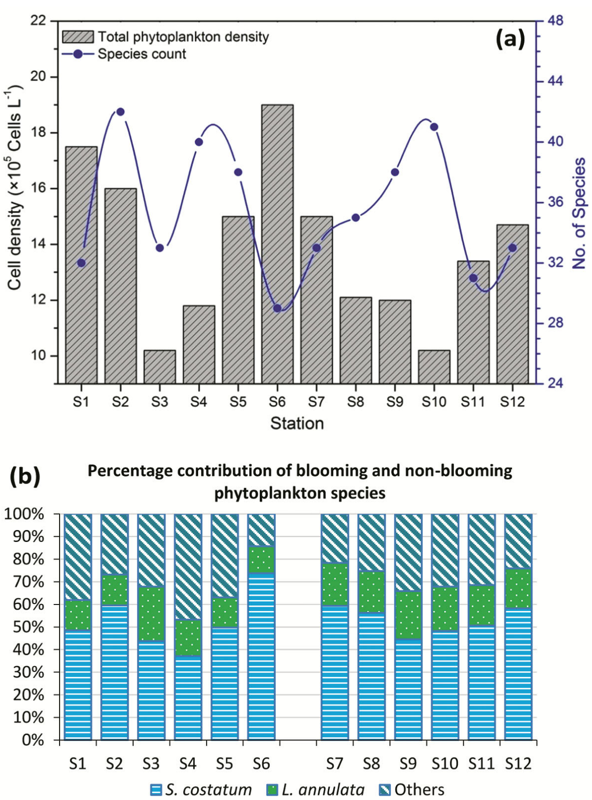

Fig. 3 — a) Phytoplankton total abundance and species distribution; and b) Relative abundance of bloom forming species and other associated phytoplankters, during post northeast monsoon (2019) along the Kalpakkam coastal waters

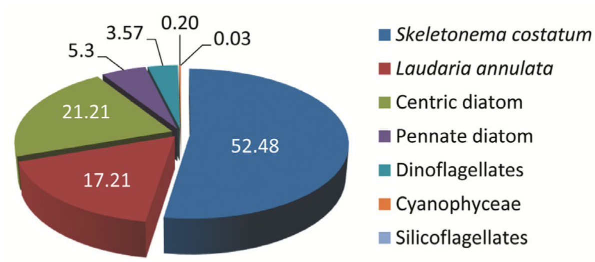

Fig. 4 — Pie chart showing the cumulative percentage contribution of different phytoplankton species/groups during the bloom event (December 2019)

L. annulata is relatively less common and distributed in temperate and tropical waters[26-30]. These species are placed in the group Centrales (now called the Biddulphiales) and are chain-forming species. The abundance of *S. costatum* and *L. annulata* preceded other phytoplankton species in all 12 stations. *Skeletonema costatum* cell counts were significantly high (except at station 4), and *L. annulata* registered as the following dominant species (Fig. 3b). Similarly, the cumulative percentage contribution to the entire phytoplankton community revealed a significant contribution (~ 70 %) by *S. costatum* and *L. annulata* as compared to other diatoms and phytoplankton groups (centrales: 5.3 %; pennates: 3.6 %; cyanophyceae: 0.2 %; and silicoflagellates: 0.03 %) (Fig. 4). Aside from the bloom species, a few other species, such as

Chaetoceros curvisetus, *Dactyliosolen fragilissimus*, *Guinardia striata*, *Leptocylindrus danicus*, *Leptocylindrus minimus*, and *Protoperidinium* spp., were also found at all stations and contributed more than 1 % to the total phytoplankton community abundance.

One hundred eighteen species of phytoplankton were identified during the bloom event. From the microscopic enumeration, it was observed that diatoms dominated the phytoplankton species composition in the study region (56 centrales + 34 pennates = 90 species), followed by dinoflagellates (25 species), cyanophyceae (2 species), and silicoflagellate (one species) (Table 1). The present study reports a relatively high species composition, suggesting that, despite bloom formation, the diversity of the phytoplankton community was not affected. The present observation sufficiently corroborates other diatomic bloom events reported on the east coast of India[21,23,49].

Table 1 — Species list and relative abundance (%) of various phytoplankton species in different stations during northeast monsoon period at Kalpakkam coastal waters

Sampling locations	**Transect-1**						**Transect-2**					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Centric diatoms												
Asteromphalus elegans	0.1											
Bacteriastrum comosum				0.2				0.4			1.1	0.2
Bacteriastrum furcatum		0.1					0.7	0.2	0.6			
Bacteriastrum hyalinum				0.2		0.2		0.2				
Biddulphia mobiliensis						0.1				0.2		
Cerataulina pelagica	0.1					0.1						
Cerataulina pelagica							0.3	0.7		0.2	0.2	
Ceratium furca					0.2				0.2	0.4		
Chaetoceros atlanticus		0.7										
Chaetoceros coarctatus				0.2								
Chaetoceros curvisetus	1.3	3.1	0.9	1.6			2.0	0.7	4.0	3.7	1.5	
Chaetoceros decipiens	0.6				1.7				1.7	0.4	0.4	
Chaetoceros denticulatus							0.3					
Chaetoceros eibenii	0.4	0.1		0.2		0.2	0.4	0.2	1.3	0.2	0.2	
Chaetoceros lauderi		0.4	0.4									
Chaetoceros lorenzianus		0.3	1.1	1.6	0.3			2.5			1.5	0.9
Chaetoceros peruvianus		0.1										
Chaetoceros socialis				4.5						2.2		
Chaetoceros sp.	0.8					0.2	2.7		0.8			
Chaetoceros weighamii				2.4	0.5	1.0		1.6		0.7	0.7	
Corethron hystrix			0.2	0.2	0.2	0.1	0.3	0.2	0.2			
Coscinodiscus sp.		0.3					0.1		0.2			
Cyclotella sp.	1.6	0.1			0.2			0.2	0.9	0.4		
Dactyliosolen fragilissimus	0.4			0.8	0.6		0.6			0.4		
Ditylum sol		0.1							0.2			
Eucampia cornuta	0.6	0.3	0.2		0.3				1.1	0.2		
Eucampia zodiacus	1.2	1.3							0.9		0.5	
Guinardia cylindrus		0.1	0.2					0.2				
Guinardia delicatula				0.8	2.0	0.7		1.3		0.2	2.0	2.1
Guinardia flaccida	0.4	1.6	0.2				0.1		1.5	0.4		
Guinardia striata	4.0	4.1	5.9	4.5	4.7	2.4	2.9	4.4	3.0	2.8	2.6	3.1
Hemiaulus cuneiformis										0.4		
Hemiaulus hauckii	1.3	0.7	0.2	0.4	0.2	0.2	0.4	0.7	0.6	0.7		0.2
Hemiaulus membranacea								0.2				

(*Contd.*)

Table 1 — Species list and relative abundance (%) of various phytoplankton species in different stations during northeast monsoon period at Kalpakkam coastal waters (*Contd.*)

Sampling locations	**Transect-1**						**Transect-2**					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Hemiaulus sinensis	0.5	0.3	0.7		0.5		0.3	0.4		0.4	0.5	0.7
Lauderia annulata†	13.3	13.6	24.1	16.1	13.3	11.9	18.9	18.5	21.4	19.6	17.9	17.7
Leptocylindrus danicus	1.4	0.8	1.1	1.6	2.0	0.8	0.7	0.7	1.1	1.5	1.3	0.9
Leptocylindrus minimus	10.4	3.4	6.5	6.3	6.1	2.0	2.4	3.3	4.2	5.4	5.1	2.1
Odontella mobiliensis	0.4	0.3										
Podosira sp.			0.2		0.5		0.1		0.2	0.2		
Proboscia alata	0.1		0.9			0.2					0.2	
Rhizosolenia castracanei	0.1											
Rhizosolenia crassispina				0.6			0.1		0.2	0.2		
Rhizosolenia hebetata				0.2				0.4				
Rhizosolenia hyalina		0.4						0.2				
Rhizosolenia imbricata	0.4	0.9		0.6	0.2	0.2	0.6	0.2	1.3	0.9	0.5	0.2
Rhizosolenia setigera		0.1					0.1				0.2	
Skeletonema costatum†	48.5	59.6	43.7	37.1	49.8	73.8	59.4	56.3	44.5	48.2	50.6	58.2
Skeletonema tropicum	1.5	0.3	0.9	2.7	1.9			1.1	1.9	2.1	2.9	0.7
Streptotheca membranacea												0.7
Streptotheca tamensis		0.5	0.4				0.3		0.2			
Thalassiosira convexa	0.2											
Thalassiosira decipiens											0.5	0.3
Thalassiosira eccentrica				0.2								
Thalassiosira sp.						0.2					0.7	
Thalassiosira subtilis				2.9		0.3		0.4			0.5	1.4
Pennate diatoms												
Amphiprora paludosa												0.2
Amphora gigantea				0.2								
Amphora laevis				0.2								
Amphora paludosa						0.1		0.2				
Amphora proteus									0.2			
Amphora sp.							0.4					
Asterionellopsis glacialis			0.4	2.0	4.1	1.9	1.9					
Asterionella sp.	2.1	2.5							1.1	0.4	2.2	2.4
Diploneis bombus									0.2			0.2
Diploneis smithii												0.2
Diploneis sp.		0.1			0.2							
Gyrosigma balticum							0.1					
Meuniera membranacea						0.2						
Navicula sp.			0.7	0.2	0.2	0.1	0.3	0.7	0.6	0.2		0.2
Nitzschia closterium								0.2		0.7		
Nitzschia distans		0.1										
Nitzschia longissima		0.3	0.9	0.6	0.8	0.1	0.3			0.6	0.2	0.3
Nitzschia panduriformis				0.2						0.2		
Nitzschia sigma	0.9	0.8	1.7		0.5	0.2	0.7	0.2	1.3		1.5	1.2
Nitzschia sigmoides		0.1	0.7									
Nitzschia sp.	4.0				0.8			0.2	1.7			
Pleurosigma aestuarii						0.1					0.2	
Pleurosigma angulatum		0.1	0.2									

(*Contd.*)

Table 1 — Species list and relative abundance (%) of various phytoplankton species in different stations during northeast monsoon period at Kalpakkam coastal waters (*Contd.*)

Sampling locations	**Transect-1**						**Transect-2**					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Pleurosigma elongatum	0.1		0.2				0.1	0.2				
Pleurosigma formosum		0.1	0.2				0.1					0.2
Pleurosigma normanii			0.2									
Pseudonitzschia australis		0.3	0.7						0.6			
Pseudonitzschia delicatissima	0.9			1.8	1.3			1.6		0.4		0.3
Pseudonitzschia pungens	0.7	0.3	0.9		0.3					0.4		
Pseudonitzschia sp.			0.4									
Thalassionema bacillare							0.1					
Thalassionema nitzschioides					0.2					0.4		0.3
Thalassiothrix longissima									0.2			
Dinoflagellates												
Dinoflagellate cyst						0.3						
Dinoflagellate spores				1.0								
Dinophysis dens										0.2		
Gymnodinium sanguineum				0.2								
Gyrodinium sp.			0.7	0.4	0.6		0.3		0.2			
Peridinium bulla					0.2							
Peridinium remotum		0.1										
Peridinium sp.					0.3							
Polykrikos schwartzii												0.3
Prorocentrum compressum		0.1		0.6				0.2			0.2	0.3
Prorocentrum gracile				0.2								
Prorocentrum micans	0.2	0.1		1.2	0.3				0.2	0.2	0.2	0.3
Prorocentrum sp.											0.2	
Protoperidinium ampulliforme												0.3
Protoperidinium bulla												0.2
Protoperidinium cerassus						0.2				0.2		
Protoperidinium depressum									0.6			
Protoperidinium globulus					0.2							
Protoperidinium niponicum					0.5							
Protoperidinium remotum										0.2		
Protoperidinium senaicum				1.0	0.5					0.4		0.9
Protoperidinium spp.	1.5	1.3	3.9	3.1	3.4	1.8	1.6	1.3	0.6	1.9	2.4	1.9
Protoperidinium steinii					0.6							
Pyrophacus steinii										0.2		
Scripciella trochoidea				0.6	0.3						1.3	0.7
Cyanophyceae												
Richelia intracellularis								0.4				
Trichodesmium erythraeum						0.1			0.2	1.7		
Silicoflagellates												
Dictyocha fibula				0.2					0.2			

†Blooming species

The salinity and temperature recorded during the bloom were 26.93 – 27.48 °C and 23.7 – 28.5 PSU, respectively (Table 2). Since the study was conducted during the NE monsoon, freshwater discharge through backwaters and lower solar intensity might have contributed to the observed values. A previous study by Sahu *et al.*[23] at this location during a diatom bloom event reported a similar temperature range. According to earlier reports, the *S. costatum* bloom has been strongly

Table 2 — Concentration of physico-chemical parameters during post northeast monsoon (December 2019) in Kalpakkam coastal waters

Sampling locations	**Transect 1**						**Transect 2**					
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Temperature (°C)	27.28	27.42	27.42	27.48	26.93	27.00	27.09	27.10	27.11	27.14	27.24	27.28
pH	8.20	8.18	8.22	8.18	8.24	8.18	8.20	8.18	8.19	8.20	8.17	8.17
Salinity (psu)	26.10	28.50	25.01	24.99	28.10	23.70	26.02	26.52	25.39	25.89	26.05	26.02
Dissolved oxygen (mg L^{-1})	6.38	6.41	6.44	6.44	6.17	6.52	6.44	6.42	6.43	6.43	6.41	6.32
Turbidity (FNU)	0.90	1.00	2.50	2.10	1.10	0.80	0.45	0.30	0.40	0.25	0.30	0.40
Suspended particulate matter (mg L^{-1})	16.06	24.36	39.84	31.66	18.28	23.30	20.92	7.32	20.60	16.14	18.02	33.28
Ortho phosphate (µM)	0.36	0.45	0.34	0.32	0.58	0.29	0.27	0.29	0.28	0.32	0.40	0.25
Silicate (µM)	2.88	3.63	2.47	2.09	1.70	1.36	2.69	2.52	3.15	2.54	2.04	1.65
Ammonium (µM)	31.59	27.03	21.48	22.26	14.71	19.43	18.20	15.75	17.41	14.32	17.11	10.29
Nitrate (µM)	1.21	1.60	1.46	1.07	1.15	0.90	0.82	0.82	0.79	0.79	0.66	0.36
Total nitrogen (µM)	44.55	48.90	48.55	52.10	47.80	44.15	47.40	42.55	47.30	45.90	48.60	44.85
Total phosphate (µM)	0.87	1.05	0.93	0.77	0.78	0.63	0.88	0.59	0.56	0.58	0.67	0.52
Chlorophyll-*a* (mg m^{-3})	5.99	4.20	3.51	4.31	1.19	6.44	0.49	0.78	0.81	0.62	1.05	1.55

Table 3 — Correlation coefficient analysis of hydrobiological parameters during the bloom occurrence

Variables	**Temp.**	**pH**	**Salinity**	**DO**	**Turbidity**	**SPM**	**IP**	**Silicate**	**NH_4^+**	**Nitrate**	**TN**	**TP**	**Chl-*a***	**P density**	**SC**
Temp.	1														
pH	-0.309	1													
Salinity	0.107	-0.627	1												
DO	0.253	-0.521	0.579	1											
Turbidity	0.541	0.391	-0.244	0.014	1										
SPM	0.599	0.036	-0.135	0.090	0.643	1									
IP	-0.115	0.550	-0.261	-0.678	0.290	-0.142	1								
Silicate	0.367	-0.143	0.408	0.393	-0.073	-0.151	-0.135	1							
NH_4^+	0.479	0.041	0.310	0.270	0.480	0.041	0.182	0.568	1						
Nitrate	0.385	0.453	0.095	0.004	0.728	0.209	0.528	0.439	0.741	1					
TN	0.522	0.112	-0.314	-0.024	0.551	0.520	0.325	0.065	0.195	0.375	1				
TP	0.446	0.356	0.120	-0.023	0.585	0.267	0.452	0.437	0.730	0.860	0.454	1			
Chl-a	0.708	0.027	0.109	0.044	0.661	0.336	0.183	0.320	0.860	0.663	0.269	0.631	1		
P density	-0.275	-0.132	0.508	-0.060	-0.116	-0.147	0.160	-0.108	0.354	0.076	-0.312	0.204	0.228	1	
SC	-0.379	-0.236	0.676	0.136	-0.221	-0.133	-0.016	-0.149	0.132	-0.040	-0.431	0.057	-0.033	0.915	1
LA	-0.084	-0.155	0.110	0.192	-0.379	0.153	-0.498	0.198	-0.123	-0.337	-0.234	-0.020	-0.256	0.133	0.192

Values in bold are significantly different from 0 with a significance level alpha=0.05

SC – *Skeletonema costatum* density, LA – *Lauderia annulata* density, P density – Total phytoplankton density

associated with low temperature and salinity[50]. A strong positive correlation of chl-*a* with temperature during the present bloom further supported the role of temperature (Table 3). Several studies around the world have reported that low-saline conditions associated with rainfall favour the bloom formation of *S. costatum*[34,35,51]. In the present instance, *S. costatum* density showed a significant positive correlation with salinity, underlining the importance of this parameter in bloom formation. Nevertheless, Li *et al.*[36] reported that not only is a less saline environment responsible for the *S. costatum* bloom, but increased nutrient inputs through river discharge due to heavy rainfall may also induce the bloom.

pH values did not differ significantly during the bloom event and ranged from 8.17 to 8.24. Similar to the report of Huo *et al.*[35], this study also observed an increase in pH with respect to chl-*a* concentration. Generally, DO values are controlled by salinity and temperature, as both parameters directly affect the dissolution of oxygen in coastal waters; nonetheless, biological activities, such as photosynthetic activity and microbial decomposition also influence DO availability. In the present study, a relatively high DO concentration was observed, ranging from 6.17 to 6.52 mg L^{-1}. These observed higher values might be due to the low salinity and temperature recorded, in addition to its production by autotrophs. High photosynthetic activity by bloom species must also have enhanced the DO content in this study. Enhanced DO content during phytoplankton blooms is a common phenomenon reported worldwide[9].

A long-term observation of phytoplankton data by Biswas *et al.*[31] from a mangrove-dominated estuarine system of India (NW Bay of Bengal) revealed that *S. costatum* blooms were observed during high turbid monsoonal months. In the present investigation, turbidity (0.25 – 2.5 NTU) showed a strong positive correlation with chl-*a*. During the bloom, turbidity values were higher in transect-1 than in transect-2, located at 5 km inside the sea. Like Biswas *et al.*[31], the current study also observed that *S. costatum* bloom was comparatively higher in transect 1, where the turbidity was higher than in transect 2. However, this study found no significant difference in *L. annulata* bloom abundance, except for a slight increase in transect 2, which showed lower turbidity. SPM exhibited considerable variation and ranged from 7.32 to 39.84 mg L^{-1}. Relatively higher concentrations were observed in transect-1 than in transect-2. This could be due to the high bloom density observed in transect-1 because it is believed that high phytoplankton production or bloom density contributes to high SPM content in the coastal waters[52-53].

Nutrients are vital for primary production, and the growth and development of phytoplankton depend on several inorganic nutrients. In this study, nutrients such as nitrate, ammonium, phosphate, silicate, TN, and TP exhibited moderate spatial variations during the NE monsoon (Table 2). Variations in the nitrogenous nutrient concentration (µM) in the coastal waters were as follows: nitrate: 0.36 – 1.6, ammonium: 10.29 – 31.59, and TN: 42.55 – 52.1. Comparatively higher concentrations of ammonium (at station 1), nitrate (at station 2), and TN (at station 4) were observed in transect-1. The lower concentrations for ammonium, nitrate, and TN were observed at stations 12, 8, and 4, respectively, in transect 2. The increase in ammonium levels in the coastal water could be due to monsoonal discharge from the backwaters, which contains sewage, agricultural drainage, and aquaculture waste. An enormous amount of organic and inorganic substances, including a large amount of ammonium, is released through various discharges[54]. Ammonia, the chief excretory product of marine invertebrates, is well known as a nutrient preferred by the phytoplankton community under certain environmental conditions. The above two factors, *i.e.*, excretory release and utilisation by phytoplankton, significantly affect the concentration of ammonium in the marine environment[55,56]. Moreover, ammonium, which is a highly unstable form of nitrogen, is oxidised to other forms in well-oxygenated water, which significantly affects its concentration[57]. In addition, many studies have also reported an increased ammonium content of ~40 – 284 µM in the seawater during blooms, where they depicted that the bloom remains largely ungrazed and decomposes, resulting in elevated ammonium levels[47,48,58-60]. Nitrate and TN concentrations gradually decreased from coastal to offshore waters. The reduction in nitrate might be due to its utilisation by the phytoplankton community, as it is a common phenomenon during a phytoplankton bloom. In general, recently reported nitrate concentration along the study area varies from 1.0 – 9.9 µM[refs. 61,62], and the observed values in current study are relatively low. Though there was no significant correlation between nitrate and phytoplankton population density during this study (Fig. 5a), a significant positive relationship was observed between chl-*a* and nitrate, which strengthened the observation of low nitrate content during this bloom event. Li *et al.*[36] reported a significant reduction in nitrate and ammonium during the peak bloom of *S. costatum* and indicated that the decrease in nitrogen compounds did not affect the bloom density. Similarly, Huo *et al.*[35] observed a significant reduction in nutrient depletion during the post-bloom period of *S. costatum*.

Inorganic phosphates and total phosphorus concentration ranged from 0.25 to 0.58 µM and 0.58 to 1.05 µM, respectively. There was a slight variation in IP and TP, with maximum values recorded in transect 1 and minimum values in transect 2. This coincides with the relatively high bloom density of transect 1 as compared to transect 2. Hence, it is understood that phosphate availability might impact or act as a limiting factor for the bloom species[36]. However, the correlation between phosphate and chl-*a* was insignificant in the study (Fig. 5b). Present observed phosphate values are comparable to those reported from this coast (0.14 – 0.54 µM) recently[61,62]. Silicate values were low during the bloom event (1.36 – 3.63 µM). In the

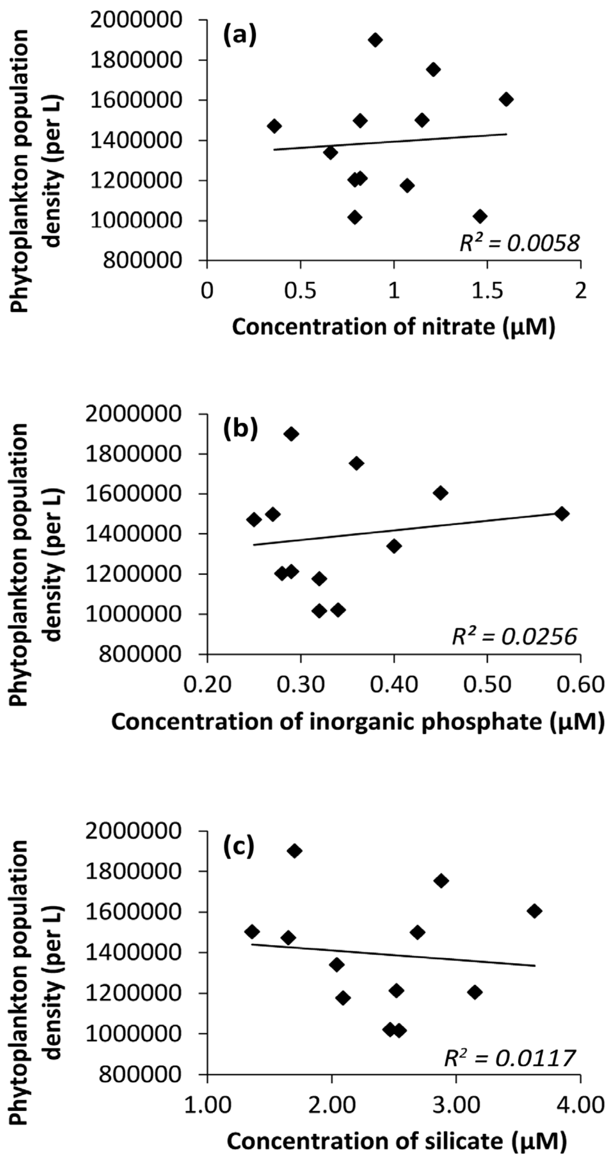

Fig. 5 — Regression analysis showing the correlations between phytoplankton density and a) silicate, b) nitrate, and c) inorganic phosphate, observed during the bloom in the coastal waters of Kalpakkam

marine environment, diatoms directly rely on dissolved silicate concentrations to grow and form frustules[63]. The observed lower silicate values during the bloom were apparently due to utilisation and were corroborated by other reports[36,64]. It has been observed that silicate values above 2 µM do not limit diatom growth[65]. At most stations, silicate concentration did not fall below 2 µM in the present bloom occurrence, which could be supporting the sustenance bloom biomass. Although a direct relation between silicate concentration and cell density was not observed (Fig. 5c), a significant positive correlation between chl-*a* and silicate supported the above hypothesis. The silicate values documented in this study corroborated prior investigations in the same coastal location[41,47,48] and were marginally lower than those reported recently (2.4 – 8.8 µM)[61]. Though phytoplankton consumption could be a plausible reason for the low silicate content observed in this study[66-67], various factors such as adsorption of reactive silicate into suspended sedimentary particles[68], chemical interaction with clay minerals[69], and co-precipitation with humic compounds and iron[70], are also responsible for silicate concentration variations in the marine environment.

Many researchers have used the photosynthetic pigment chl-*a* as an indicator of phytoplankton standing stock for more than 50 years[71]. The highest and lowest chl-*a* values help predict the coastal ecosystem's productivity status. In this study, the highest concentration of chl-*a* (6.44 mg m^{-3}) coincided with the highest diatom cell density, particularly *S. costatum* and *L. annulata* in transect-1. In contrast, the chl-*a* values observed in transect 2 were much lower (Table 2). Similar observations (increased chlorophyll values) during bloom events have been reported earlier from Indian coastal waters[9,20,23,25,72,73].

The primary factors responsible for bloom occurrence in the present study might be physical factors such as temperature and salinity, as these parameters exhibited a strong positive relationship with chl-*a* (Table 3). It is believed that physiological adaptations play a pivotal role in determining which phytoplankton species will bloom under certain conditions[74]. The observed significant reduction in nitrate and silicate during bloom might be due to higher uptake by *S. costatum* and *L. annulata.* It is considered that *S. costatum* has a higher growth rate and nitrate uptake than other diatoms[37]. Similarly, an experimental study by Sommer[75] revealed that *L. annulata* exhibited high bloom density under low-light conditions with a high S:N ratio[75,76]. Based on earlier reports, it is understood that *L. annulata* also requires similar environmental conditions to those of *S. costatum* to proliferate[75,76], which might have resulted in this co-bloom. However, the density of *S. costatum* was much higher than that of *L. annulata* in both transects, indicating the better-competing nature of the former under eutrophic conditions[77]. Further, this study demonstrates that the bloom density of both species (*S. costatum* and *L. annulata*) did not decrease with nitrate and silicate content, indicating that they do not act as limiting factors.

Contrary to other reports, Inorganic Phosphate (IP) concentrations were comparatively higher, suggesting that adequate phosphate availability favoured the bloom density. Even though the current study observed no fish mortality at the bloom site, it is considered that these blooms can potentially harm marine organisms as a tremendous amount of oxygen will be consumed during decomposition, leading to severe ecological impacts on aquatic ecosystems[78]. On the other hand, these species generally serve as favourable food for secondary consumers such as zooplankton and fish larvae, temporarily increasing the region's secondary production. Though the reported bloom event may be non-toxic to the marine ecosystem, continuous monitoring and prolonged analysis of coastal hydrobiological conditions are necessary to determine the triggering mechanisms of such bloom events.

Acknowledgments

This study was sponsored by the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, Tamil Nadu, India (Project Sanction No: KKS/EnSD/2018/). The authors would like to acknowledge the authorities of SRM Institute of Science and Technology, the Associate Director, SQRMG; the Head, EAD; and the Head, RDS, IGCAR, Kalpakkam, for their encouragement and support in carrying out the work.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

AKM: Conceptualisation, formal analysis, software, writing- review & editing; GS: Investigation, formal analysis, writing original draft; RSS: Formal analysis, writing original draft; NPID: Writing - review & editing; KDA: Funding acquisition and supervision; and RV: Supervision, writing - review & editing.

References

1 Otero J, Álvarez-Salgado X A & Bode A, Phytoplankton Diversity Effect on Ecosystem Functioning in a Coastal Upwelling System, *Front Mar Sci*, 7 (2020) p. 592255. https://doi.org/10.3389/fmars.2020.592255

2 Fenchel T, Marine plankton food chains, *Annu Rev Ecol Evil Syst*, 19 (1) (1988) 19–38.

3 Holligan P M, Do marine phytoplankton influence global climate? In: *Primary productivity and biogeochemical cycles in the sea*, (Springer, Boston, MA), 1992, pp. 487–501).

4 Falkowski P G, Physiological responses of phytoplankton to natural light regimes, *Limnol Oceanogr,* 39 (1984) p. 311.

5 Sournia A, Red tide and toxic marine phytoplankton of the world ocean: An inquiry into biodiversity, In: *Harmful Marine Algal Blooms*, Edited by Lassus P G, Arzul E, Erard P, Gentien & Marcaillou C, Proc 6th Int Conf on Toxic Marine Phytoplankton, France, 1993, Lavoisier, 1995, pp. 103–112.

6 Smayda T J, Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea, *Limnol Oceanogr*, 42 (1997) 1137–1153.

7 Glibert P M, Anderson D M, Gentien P, Granéli E & Sellner K G, The global, complex phenomena of harmful algal blooms, *Oceanography,* 18 (2) (2005) 136–147. https://doi.org/10.5670/oceanog.2005.49

8 Sahu G, Mohanty A K, Sarangi R K & Satpathy K K, *Asterionellopsis glacialis* (Family: Fragilariaceae, Class: Bacillariophyceae, Phylum: Ochrophyta) bloom and its impact on plankton dynamics at Kalpakkam (Bay of Bengal, Southeast coast of India), *Oceanologia*, 64 (1) (2022) 145-159. https://doi.org/10.1016/j.oceano.2021.04.005

9 D'Silva M S, Anil A C, Naik R K & D'Costa P M, Algal blooms: a perspective from the coasts of India, *Nat Hazards*, 63 (2) (2012) 1225–1253.

10 Anderson D M, Approaches to monitoring, control and management of harmful algal blooms (HABs), *Ocean Coast Manag*, 52 (7) (2009) 342–347.

11 Raghu Prasad R, Further studies on the plankton of the inshore waters off Mandapam, *Indian J Fish*, 3 (1) (1956) 1–42.

12 Rao S D V, *Asterionella japonica* bloom and discolouration off Waltair, Bay of Bengal, *Limnol Oceanogr*, 14 (1969) 632–634.

13 Mani P, Krishnamurthy K & Palaniappan R, Ecology of phytoplankton blooms in the Vellar estuary, east coast of India, *Indian J Geo-Mar Sci*, 15 (1986) 24–28.

14 Satpathy K K & Nair K V K, Occurrence of phytoplankton bloom and its effect on coastal water quality, *Indian J Geo-Mar Sci*, 25 (1996) 145–147.

15 Choudhury S B & Panigrahy R C, Occurrence of bloom of diatom *Asterionella glacialis* in nearshore waters of Gopalpur, Bay of Bengal, *Indian J Geo-Mar Sci*, 18 (1989) 204–206.

16 Panigrahy R C & Gouda R, Occurrence of bloom of the diatom *Asterionella glacialis* (Castracane) in the Rushikulya estuary, east coast of India, *Mahasagar*, **23** (1990) 179–182.

17 Mishra S & Panigrahy R C, Occurrence of diatom blooms in Bahuda estuary, east coast of India, *Indian J Geo-Mar Sci*, 24 (1995) 99–101.

18 De T K, Ghosh S K, Jana T K & Chowdhury A, Phytoplankton bloom in the Hooghly estuary, *Indian J Geo-Mar Sci*, 20 (1991) 134–137.

19 Oyeku O G & Mandal S K, Historical occurrences of marine microalgal blooms in Indian peninsula: Probable causes and implications, *Oceanologia*, 63 (1) (2021) 51–70. https://doi.org/10.1016/j.oceano.2020.08.008

20 Biswas S N, Godhantaraman N, Sarangi R K, Bhattacharya B D, Sarkar S K, *et al.*, Bloom of *Hemidiscus hardmannianus* (Bacillariophyceae) and its impact on water quality and plankton community structure in a mangrove wetland, *Clean Soil Air Water*, 41 (4) (2013) 333–339. https://doi.org/10.1002/clen.201200012

21 Achary M S, Panigrahi S, Satpathy K K, Sahu G, Mohanty A K, *et al.*, Nutrient dynamics and seasonal variation of phytoplankton assemblages in the coastal waters of southwest Bay of Bengal, *Environ Monit Assess*, 186 (2014) 5681–5695. https://doi.org/10.1007/s10661-014-3812-8

22 Karthik R, Arun Kumar M & Padmavati G, Silicate as the probable causative agent for the periodic blooms in the coastal waters of South Andaman Sea, *Appl Environ Res*, 36 (2) (2014) 37–45. https://doi.org/10.35762/AER.2014.36.2.4

23 Sahu G, Mohanty A K, Sarangi R K, Bramha S N & Satpathy K K, Upwelling-initiated algal bloom event in the coastal waters of Bay of Bengal during post-northeast monsoon period (2015), *Curr Sci*, 110 (6) (2016) 979–981.

24 Sathishkumar R S, Sundaramanickam A, Sahu G, Mohanty A K, Ramesh T, *et al.*, Intense bloom of the diatom *Hemidiscus hardmanianus* (Greville) in relation to water quality and plankton communities in Tuticorin coast, Gulf of Mannar, India, *Mar Pollut Bull*, 163 (2021) 111757. https://doi.org/10.1016/j.marpolbul.2020.111757

25 Karthik R, Robin R S, Anandavelu I, Purvaja R, Singh G, *et al.*, Diatom bloom in the Amba River, west coast of India: A nutrient-enriched tropical river-fed estuary, *Reg Stud Mar Sci*, 36 (2020) p. 101244. https://doi.org/10.1016/j.rsma.2020.101244

26 Devassy V P & Bhattathiri P M A, Phytoplankton ecology of the Cochin backwater, *Indian J Geo-Mar Sci*, 3 (1974) 46–50.

27 Tiwari L R & Nair V R, Ecology of phytoplankton from Dharamtar Creek, west coast of India, *Indian J Geo-Mar Sci*, 27 (1998) 302–309.

28 Vasudevan S, Arulmoorthy M P, Balachandar K, Harikumar S & Ashok V, Extensive bloom of phytoplankton *Skeletonema costatum* in Vellar estuary, Parangipettai, Tamil Nadu, southeast coast of India, *Int J Curr Trends Res*, 3 (2) (2014) 154–157.

29 Ocean Biogeographic Information System (OBIS), *Lauderia annulata*, Ocean Biogeographic Information System, 2011. Accessed online at: https://www.iobis.org/mapper/ ?taxon _id=460503

30 Naik R K, Sarno D, Kooistra W H C F, D'Costa P M & Anil A C, *Skeletonema* (Bacillariophyceae) in Indian waters: A reappraisal, *Indian J Geo-Mar Sci*, 39 (2) (2010) 290–293.

31 Biswas H, Dey M, Ganguly D, De T K, Ghosh S, *et al.*, Comparative analysis of phytoplankton composition and abundance over a two-decade period at the land–ocean boundary of a tropical mangrove ecosystem, *Estuar Coast*, 33 (2010) 384–394. https://doi.org/10.1007/s12237-009-9233-z

32 Roshith C M, Meena D K, Manna R K, Sahoo A K, Swain H S, *et al.*, Phytoplankton community structure of the Gangetic (Hooghly–Matla) estuary: Status and ecological implications in relation to eco-climatic variability, *Flora*, 240 (2018) 133–143. https://doi.org/10.1016/j.flora.2017.06.007

33 Devassy V P & Goes J I, Seasonal patterns of phytoplankton biomass and productivity in a tropical estuarine complex (west coast of India), *Proc Indian Acad Sci (Plant Sci)*, 99 (1989) 485–501. https://doi.org/10.1007/BF03053618

34 D'Costa P M & Anil A C, Diatom community dynamics in a tropical, monsoon-influenced environment: West coast of India, *Cont Shelf Res*, 30 (2010) 1324–1337. https://doi.org/10.1016/j.csr.2010.04.015

35 Huo W Y & Shu J, Outbreak of *Skeletonema costatum* bloom and its relations to environmental factors in Jiaozhou Bay, China, In: *Proc WSEAS Int Conf on Environment, Ecosystems and Development*, Venice, Italy, 2–4 November 2005, pp. 205–210.

36 Li C, Zhu B, Chen H, Liu Z, Cui B, *et al.*, The relationship between the *Skeletonema costatum* red tide and environmental factors in Hongsha Bay of Sanya, South China Sea, *J Coast Res*, 25 (3) (2009) 651–658. https://doi.org/10.2112/07-0996.1

37 Liu D, Sun J, Zou J & Zhang J, Phytoplankton succession during a red tide of *Skeletonema costatum* in Jiaozhou Bay of China, *Mar Pollut Bull*, 50 (1) (2005) 91–94. https://doi.org/10.1016/j.marpolbul.2004.09.029

38 Satpathy K K, Mohanty A K, Sahu G, Sarguru S, Sarkar S K, *et al.*, Spatio-temporal variation in physicochemical properties of coastal waters off Kalpakkam, southeast coast of India, during summer, pre-monsoon and post-monsoon period, *Environ Monit Assess*, 180 (1–4) (2011) 41–62. https://doi.org/10.1007/s10661-010-1761-7

39 Manuri D B, Chandrasekaran M, Perumal M & Mallavarapu R V, Environmental gradients along the tropical coast drive plankton biomass and alter food web interactions, *Environ Sci Pollut Res*, 29 (2022) 36186–36202. https://doi.org/10.1007/s11356-020-09488-4

40 Strickland J D H & Parsons T R, *A practical handbook of seawater analysis*, (Fisheries Research Board of Canada Bulletin 167, Ottawa, Canada), 1972, pp. 310.

41 Sahu G, Satpathy K K, Mohanty A K & Sarkar S K, Variations in community structure of phytoplankton in relation to physicochemical properties of coastal waters, southeast coast of India, *Indian J Geo-Mar Sci*, 41 (3) (2012) 223–241.

42 Desikachary T V, *Atlas of diatoms*, Vol 3, (Madras Science Foundation, Madras, India), 1987.

43 Tomas C R, Hasle G R, Syvertsen E E, Steidinger K A & Tangen K (Eds), *Identifying marine phytoplankton*, (Academic Press, San Diego, USA), 1997, pp. 858.

44 Al-Kandari M, Al-Yamani F & Al-Rifaie K, *Marine phytoplankton atlas of Kuwait's waters*, (Kuwait Institute for Scientific Research, Kuwait), 2009, pp. 351.

45 Behara A & Vinayachandran P N, An OGCM study of the impact of rain and river water forcing on the Bay of Bengal, *J Geophys Res Oceans*, 121 (2016) 2425–2446. https://doi.org/10. 1002/2015JC011325

46 Sargunam C A, Rao V N R & Nair K V K, Occurrence of *Noctiluca* bloom in Kalpakkam coastal waters, east coast of India, *Indian J Geo-Mar Sci*, 18 (1989) 289–290.

47 Satpathy K K, Mohanty A K, Sahu G, Prasad M V R, Venkatesan R, *et al.*, On the occurrence of *Trichodesmium erythraeum* (Ehr.) bloom in the coastal waters of Kalpakkam, east coast of India, *Indian J Sci Technol*, 1 (2) (2008) 1–9.

48 Mohanty A K, Satpathy K K, Sahu G, Hussain K J, Prasad M V R, *et al.*, Bloom of *Trichodesmium erythraeum* (Ehr.) and its impact on water quality and plankton community structure in the coastal waters of southeast coast of India, *Indian J Geo-Mar Sci*, 39 (3) (2010) 323–333.

49 Sasamal S K, Panigrahy R C & Mishra S, *Asterionella* blooms in the northwestern Bay of Bengal during 2004, *Int J Remote Sens*, 26 (17) (2005) 3853–3858. https://doi.org/10.1080/01431160500112377

50 Gilpin L C, Davidson K & Roberts E, The influence of changes in nitrogen:silicon ratios on diatom growth dynamics, *J Sea Res*, 51 (2004) 21–35. https://doi.org/10.1016/j.seares.2003.05.005

51 Lomas M W & Glibert P M, Comparisons of nitrate uptake, storage, and reduction in marine diatoms and flagellates, *J Phycol*, 36 (5) (2000) 903–913. https://doi.org/10.1046/j.1529-8817.2000.99212.x

52 Saravanane N, Nandakumar K, Durairaj G & Nair K V K, Plankton as indicators of coastal water bodies during south-west to north-east monsoon transition at Kalpakkam, *Curr Sci*, 78 (2000) 173–176.

53 Poornima E H, Rajadurai M, Rao T S, Anupkumar B, Rajamohan R, *et al.*, Impact of thermal discharge from a tropical coastal power plant on phytoplankton, *J Therm Biol*, 30 (4) (2005) 307–316. https://doi.org/10.1016/ j.jtherbio.2005.01.003

54 Dey S, Sai Charan S, Pallavi U & Sreenivasulu A, The removal of ammonia from contaminated water by using various solid waste biosorbents, *Energy Nexus*, 7 (2022) 100119. https://doi.org/10.1016/j.nexus.2022.100119

55 Olson R J, Nitrate and ammonium uptake in Antarctic waters, *Limnol Oceanogr*, 26 (1981) 1064–1074. https://doi.org/10.4319/lo.1981.26.6.1064

56 Glibert P M, Biggs D C & McCarthy J J, Utilization of ammonium and nitrate during austral summer in the Scotia Sea, *Deep Sea Res A*, 29 (1982) 837–850. https://doi.org/10.1016/0198-0149(82)90003-7

57 Sankaranarayanan V N & Qasim S Z, Nutrients of the Cochin Backwaters in relation to environmental characteristics, *Mar Biol*, 2 (1969) 236–247. https://doi.org/10.1007/BF00347040

58 Jyothibabu R, Karnan C, Jagadeesan L, Arunpandi N, Pandiarajan R S, *et al.*, *Trichodesmium* blooms and warm-core ocean surface features in the Arabian Sea and the Bay of Bengal, *Mar Pollut Bull*, 121 (1–2) (2017) 201–215. https://doi.org/10.1016/j.marpolbul.2017.05.049

59 Anantharaman P, Thirumaran G, Arumugam R, Kannan R R R, Hemalatha A, *et al.*, Monitoring of *Noctiluca* bloom in Mandapam and Keelakarai coastal waters, southeast coast of India, *Recent Res Sci Technol*, 2 (10) (2010) 51–58.

60 Sahu B K, Baliarsingh S K, Lotliker A A, Parida C, Srichandan S, *et al.*, Winter thermal inversion and *Trichodesmium* dominance in north-western Bay of Bengal, *Ocean Sci J*, 52 (2017) 301–306. https://doi.org/10.1007/s12601-017-0028-1

61 Mohanty A K, Sahu G, Sathishkumar R S, Samantara M K, Arunachalam K D, *et al.*, Seasonal and inter-annual variations in primary productivity proxies (POC and chlorophyll-a): A study from Kalpakkam coast, Bay of Bengal, In: *Dynamics of Planktonic Primary Productivity in the Indian Ocean*, Edited by Tripathy S C & Singh A, (Springer, Cham), 2023, pp. 47–75. https://doi.org/10.1007/978-3-031-34467-1_3

62 Sahu G, Sathishkumar R S, Mohanty A K, Suriyaprakash R, Arunachalam K D, *et al.*, Bloom of *Trichodesmium* species and its impact on coastal water quality and plankton dynamics at Kalpakkam, southeast coast of India, *Indian J Geo-Mar Sci*, 53 (3) (2024) 126–141. https://doi.org/10.56042/ijms.v53i03.17450

63 Sarthou G, Timmermans K R, Blain S & Tréguer P, Growth physiology and fate of diatoms in the ocean: A review, *J Sea Res*, 53 (2005) 25–42. https://doi.org/10.1016/j.seares.2004.01.007

64 Yang D, Gao Z, Sun P, Zhao S & Zhang Y, Silicon limitation on primary production and its destiny in Jiaozhou Bay, China, *Chin J Oceanol Limnol*, 24 (2006) 186–203. https://doi.org/10.1007/BF02842819

65 Justić D, Rabalais N N, Turner R E & Dortch Q, Changes in nutrient structure of river-dominated coastal waters: Stoichiometric nutrient balance and its consequences, *Estuar Coast Shelf Sci*, 40 (1995) 339–356. https://doi.org/10.1016/S0272-7714(05)80014-9

66 Aston S R, Nutrients, dissolved gases and general biochemistry in estuaries, In: *Chemistry and Biogeochemistry of Estuaries*, Edited by Olausson E & Cato I, (John Wiley & Sons, New York), 1980, pp. 233–262.

67 Liss P S & Spencer C P, A biological process in the removal of silicate from seawater, *Geochim Cosmochim Acta*, 34 (1970) 1073–1088. https://doi.org/10.1016/0016-7037(70)90067-7

68 Lal D, Transfer of chemical species through estuaries to oceans, In: *UNESCO/SCOR Workshop on Biogeochemistry of Estuarine Sediments*, (Melle, Belgium), 1978, pp. 166–170.

69 Gouda R & Panigrahy R C, Seasonal distribution and behaviour of silicate in the Rushikulya estuary, east coast of India, *Indian J Geo-Mar Sci*, 21 (1992) 111–115.

70 Stephens C & Oppenheimer C H, Silica contents in the northwestern Florida Gulf Coast, *Contrib Mar Sci*, 16 (1972) 99–108.

71 Ediger D, Polat Beken Ç, Feyzioğlu A M, Şahin F & Tan İ, Establishing boundary classes for the quality classification of Southeastern Black Sea using phytoplankton biomass, *Turk J Fish Aquat Sci*, 15 (3) (2015) 723–731. https://doi.org/10.4194/1303-2712-v15_3_16

72 Padmakumar K B, Sanilkumar M G, Saramma A V & Menon N R, A "red tide" caused by the diatom *Coscinodiscus* on the southwest coast of India, In: *Harmful Algae News*, IOC Newsletter on Toxic Algae and Algal Blooms, 35 (2007) p. 14.

73 Satpathy K K, Sahu G, Mohanty A K, Prasad M V R & Panigrahy R C, Phytoplankton community structure and its variability during southwest to northeast monsoon transition in the coastal waters of Kalpakkam, east coast of India, *Int J Ocean Oceanogr*, 3 (1) (2009) 43–74.

74 Cullen J J & MacIntyre J G, Behavior, physiology and the niche of depth-regulating phytoplankton, In: *The Physiological Ecology of Harmful Algal Blooms*, Edited by Anderson D M, Cembella A D & Hallegraeff G M, (Springer-Verlag, Heidelberg, Germany), 1999, pp. 81–96.

75 Sommer U, Are marine diatoms favoured by high Si:N ratios? *Mar Ecol Prog Ser*, 115 (1994) 309–315. https://doi.org/10.3354/meps115309

76 Riegman R, De Boer M & De Senerpont Domis L, Growth of harmful marine algae in multispecies cultures, *J Plankton Res*, 18 (10) (1996) 1851–1866. https://doi.org/10.1093/plankt/18.10.1851

77 Hodgkiss I J & Ho K C, Are changes in N:P ratios in coastal waters the key to increased red tides? *Hydrobiologia*, 352 (1997) 141–147. https://doi.org/10.1023/A:1003037418480

78 Zhou M J, Zhu M Y & Zhang J, Status of harmful algal blooms and related research activities in China, *Chin Bull Life Sci*, 13 (2001) 54–59.