Journal of Fisheries
Volume 14 Issue 3 December 2026
Open Access

eISSN 2311-3111
pISSN 2311-729X

DOI: https://doi.org/10.17017/j.fish.1368

Original Article

Environmental drivers of dinoflagellate diversity and harmful algal bloom risk in the eastern Arabian Sea

Agalya B. • Raahavishree T. • Sonam Angmo • Annam Pavan Kumar • Asha T. Landge • Abuthagir Iburahim S. • Binaya Bhusan Nayak

Fisheries Resource Management Department, FRHPHM Division, ICAR-Central Institute of Fisheries Education, Mumbai 400061, India

Correspondence
Binaya Bhusan Nayak; Fisheries Resource Management Department, FRHPHM Division, ICAR-Central Institute of Fisheries Education, Mumbai 400061, India
nayakbb@cife.edu.in

Manuscript history
Received 24 June 2026 | Accepted 23 July 2026 | Published online 27 July 2026

Citation
Agalya B, Raahavishree T, Angmo S, Kumar AP, Landge AT, Iburahim S A, Nayak BB (2026) Environmental drivers of dinoflagellate diversity and harmful algal bloom risk in the eastern Arabian Sea. Journal of Fisheries 14(3): 143211. DOI: 10.17017/j.fish.1368

Abstract
Dinoflagellates are ecologically important phytoplankton that contribute to primary production, nutrient cycling, and marine food-web dynamics, while some species are associated with harmful algal blooms (HABs). This study assessed dinoflagellate diversity and environmental drivers across three coastal locations along the Mumbai–Raigad Coast, Maharashtra, India (Versova, Ferry Wharf, and Karanja) from January to June 2025. Physicochemical parameters and dinoflagellate assemblages were analysed using diversity indices, Pearson correlation, Bray–Curtis similarity, and Principal Component Analysis (PCA). A total of 21 dinoflagellate species belonging to 11 genera, nine families, and five orders were recorded. Versova exhibited the highest species richness (16 species), whereas Ferry Wharf showed the lowest diversity. *Tripos furca* was the dominant species across all sites. Dissolved oxygen and temperature emerged as important environmental factors influencing community composition. PCA clearly separated the study sites based on environmental characteristics. Potential HAB-forming taxa, including *Alexandrium catenella* and *Cochlodinium* sp., were detected, indicating possible ecological risks in the region. The results demonstrate that anthropogenic pressure and local environmental conditions strongly influence dinoflagellate distribution and diversity along the Maharashtra Coast. Continuous biodiversity monitoring is recommended to support early HAB detection and sustainable coastal ecosystem management.

Keywords: Arabian Sea; dinoflagellate diversity; harmful algal blooms; physicochemical parameters; sustainable management

1 | INTRODUCTION

Biological diversity (biodiversity) encompasses the variety of life forms, their ecological functions, and genetic variability (FAO 1989). In aquatic ecosystems, phytoplankton form the base of the food web and contribute nearly 40% of global primary productivity (Falkowski 1994; Naselli-Flores and Padisák 2023). According to Guiry (2024), over 40,000 phytoplankton species have been described worldwide. These diverse, photosynthetic microorganisms, belonging to groups such as Bacillariophyceae, Dinophyceae, Cyanophyceae, Chlorophyceae, and Prymnesiophyceae, are highly sensitive to environmental change and serve as reliable indicators of water quality (Baweja and Sahoo 2015). Among them, dinoflagellates (Dinophyceae) are ecologically and biogeochemically significant, especially in tropical marine environments (Calbet 2025). Their ability to function as autotrophs, heterotrophs, or mixotrophs allows them to thrive under variable environmental conditions (Gómez 2020). Dinoflagellates play essential roles in nutrient cycling, primary production, and sulfur cycling through the production of dimethylsulfoniopropionate (DMSP), which influences atmospheric dimethyl sulfide (DMS) and global climate regulation (Lovelock *et al.* 1972; Stefels *et al.* 2007). Some species are also bioluminescent, such as Noctiluca scintillans (Haddock *et al.* 2010). However, dinoflagellates are also well known for forming harmful algal blooms (HABs). Genera such as *Alexandrium* and *Karenia* produce potent neurotoxins responsible for paralytic shellfish poisoning and mass mortality of marine organisms (Hallegraeff 1993). Globally, dinoflagellates account for nearly 75% of HAB-forming taxa (Smayda 1997). Their proliferation is often linked to nutrient enrichment from pollution, runoff, and changing coastal conditions.

India's extensive coastline (11,098 km) hosts diverse and productive marine ecosystems (Ministry of Ports, Shipping and Waterways 2025). Along the Maharashtra coast (877 km), regions such as Versova, Ferry Wharf (Mumbai), and Karanja (Raigad) are ecologically significant yet subject to varying levels of anthropogenic pressure. While Ferry Wharf and Versova experience heavy fishing activity, pollution, urban runoff, and industrial discharge, Karanja represents a comparatively pristine estuarine–mangrove environment. The Jawaharlal Nehru Port Authority, located in the Mumbai harbour region, is one of India's busiest ports, handling a substantial share of the country's maritime cargo traffic. Its intense shipping activity and connectivity to Ferry Wharf increase the risk of species introduction through ballast water discharge. Although phytoplankton studies exist for Mumbai's coastal waters, there is a notable lack of focused research on dinoflagellate diversity and HAB-forming species. Given the recent increase in HAB events in the Arabian Sea (Barathan and Sarangi 2024; Mohan *et al.* 2025), assessing dinoflagellate composition is essential for understanding ecosystem health and for the early detection of toxic or invasive species.

Therefore, the present study aims to: document the occurrence and taxonomic identity of Dinophyceae species along the Mumbai–Raigad coast; compare dinoflagellate species richness, community composition, and diversity among the three selected sites; evaluate the relationships between key physicochemical parameters and dinoflagellate abundance using multivariate statistical approaches; and assess potential HAB risk posed by the recorded toxigenic species.

2 | METHODOLOGY

2.1 Study area

Maharashtra's coastline supports diverse ecosystems and livelihoods but faces rising environmental stress from urbanisation and maritime activities. For the present study, three distinct coastal locations along the Maharashtra coastline were selected to assess and compare dinoflagellate diversity: Versova, Ferry Wharf (Bhaucha Dhakka) in Mumbai, and Karanja in the Raigad district (Figure 1).

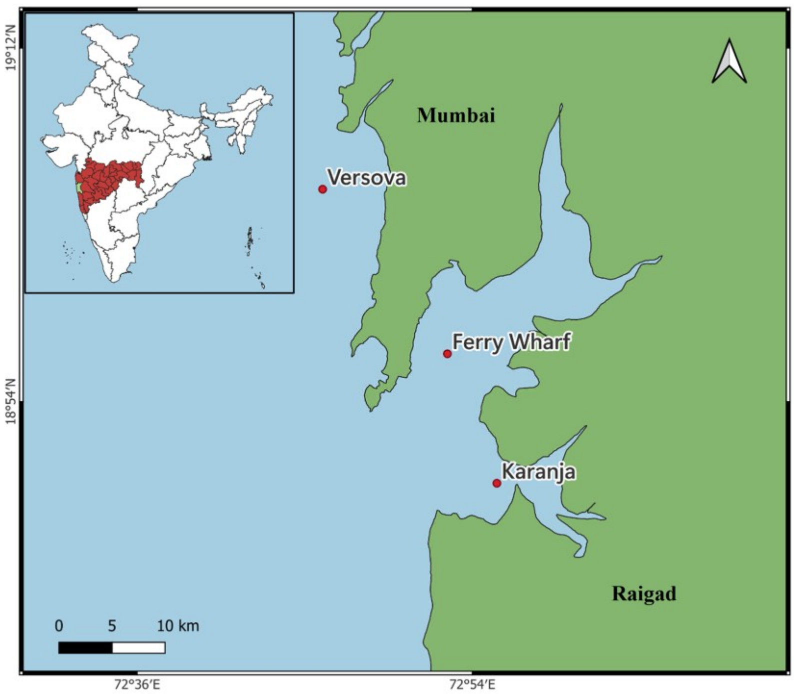

FIGURE 1 Map illustrating the sampling locations at Versova, Ferry Wharf, and Karanja, situated along the coasts of Mumbai and Raigad.

These sites were chosen to represent varying degrees of anthropogenic impact, hydrodynamic conditions, and ecological settings, allowing for a comparative analysis of environmental influences on dinoflagellate community composition. Karanja (18°43′N 72°56′E), an estuarine site in Raigad characterised by variable salinity, sediment influx, low boat traffic, and limited fishing, experiences moderate anthropogenic pollution, making it a distinctive habitat for studying dinoflagellate assemblages (Pawar 2007). Versova (19°08′N 72°48′E), though an active fishing hub with a landing centre and numerous small boats, is less polluted than Ferry Wharf, experiencing mainly localized fishing and settlement impacts with moderate industrial and shipping pressures (personal observation during field sampling). In contrast, Ferry Wharf (18°58′N 72°51′E) is heavily polluted, serving as a major centre for fishing, export, trade and passenger transport, and accommodating large commercial vessels (Gaonkar *et al.* 2010). These three sampling locations thus represent a gradient of environmental stress from moderately impacted to heavily industrialized urban marine regions, which offers valuable insight into how varying environmental and anthropogenic factors influence dinoflagellate diversity and distribution along the Maharashtra coast.

2.2 Sampling approach, estimation of environmental variable estimation

Monthly surface water sampling was conducted over a period from January to June 2025 at three coastal locations along the Maharashtra coastline: Versova and Ferry Wharf in Mumbai, and Karanja in Raigad district. At each site, three replicate surface-water samples were collected during high tide, primarily between 08:00 and 10:00 h, for nutrient analysis and phytoplankton assessment. Geographic coordinates of all sampling stations were recorded using GPS. For each sampling event, the mean values of the triplicate measurements were used for subsequent statistical analyses. During each sampling event, in situ physical parameters such as water temperature and salinity were recorded using a standard mercury thermometer and a handheld refractometer (Erma, Tokyo), respectively. Surface water samples were collected in sterile containers for the analysis of water quality parameters and phytoplankton diversity. Dissolved oxygen (Winkler’s method, samples fixed on-board) and alkalinity was estimated using standard titrimetric methods (APHA 2005). The quantity of available dissolved nutrients, such as ammonia (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), total phosphate (TP) and silicate (SiO_4^{2-}) was analysed using colorimetric methods in accordance with standard procedures (APHA 2005) using a UV-visible spectrophotometer (Nanocolor UV/VIS II).

2.3 Phytoplankton collection and identification

For qualitative analysis, phytoplankton samples were collected by filtering 100 L of surface water through a 5 µm mesh-sized plankton net and subsequently concentrated to 50 mL and preserved with Lugol’s iodine solution. For quantitative analysis, 1 L of surface water was collected in plastic bottles and allowed to settle for 48 h, after which it was concentrated to 50 mL, following Hasle (1978) and Sournia (1978). One mL sub-sample from the concentrated preserved samples was examined under a light microscope using a Sedgwick–Rafter chamber to determine dinoflagellate abundance. Identification was carried out using standard taxonomic keys (Subrahmanyan 1946; Taylor 1987; Tomas 1997; Botes 2001; Carstensen *et al.* 2015; Suthers *et al.* 2019; Guiry 2024).

2.4 Data analysis

Statistical analyses, including descriptive statistics and Species diversity, were quantified using the Shannon-Wiener index (H’), Simpson's index of diversity (1-D), Brillouin index (HB), and Pielou's evenness index (J’). Pearson product-moment correlation coefficients were calculated between physicochemical parameters and dinoflagellate abundance at each site. Community compositional similarity among sites was assessed using the Bray-Curtis similarity index. Principal Component Analysis (PCA) was performed on the standardised physicochemical dataset to identify dominant environmental gradients and their associations with the three study sites. All statistical analyses were performed using R version 4.3.1 (R Core Team 2023).

3 | RESULTS

3.1 Spatial differences in physicochemical parameters

The environmental variables (mean ± standard deviation) for the three coastal ecosystems are presented in Table 1. Water temperature varied across the three sites, with Ferry Wharf recording the highest average 28.90±3.44°C, followed by Versova 26.20±2.39°C and Karanja 21.94±3.72°C. Salinity was relatively stable in all three sites. Dissolved oxygen was highest at Karanja 6.95±1.19 ppm, suggesting better oxygenation, likely reflecting enhanced oxygenation associated with tidal mixing in its estuarine ecosystem. Alkalinity showed spatial variation across the sites, with the highest values recorded at Versova (133.60±15.84 mg/L $CaCO_3$) and the lowest at Ferry Wharf. Total phosphorus was highest at Karanja (0.42±0.11 mg/L). Nitrite and ammonia concentrations were highest at Ferry Wharf, while nitrate levels remained uniform across all three locations (0.02±0.01 mg/L).

3.2 Dinoflagellate species composition and distribution

In total, 21 dinoflagellate species were identified across the three study sites, with Versova exhibiting the highest diversity, accounting for 16 recorded species (Table 2;

Figure 2). Ferry Wharf had 11 species, while Karanja had 12. A total of 21 dinoflagellate species belonging to 11 genera, nine families, and five orders under the class Dinophyceae were recorded across three coastal locations. At Versova, six species were exclusively observed, namely: *Heterocapsa* sp., *Margalefidinium* sp., *Prorocentrum micans*, *Protoperidinium parcum*, *Gymnodinium* sp, and *Tripos macroceros*. Ferry Wharf had three unique species: *Protoperidinium conicum*, *Cochlodinium* sp., and *Protoperidinium oceanicum*. Karanja had two species that were not found at the other sites: *Alexandrium catenella* and *Pyrophacus steinii*. Eight species were common to all sites, while two were shared only between Karanja and Versova (Figure 3).

TABLE 1 Physicochemical parameters across three sampling sites along the Mumbai–Raigad Coast.

Environmental parameters	Sampling sites		
	Versova	Karanja	Ferry Wharf
Temperature (°C)	26.20±2.39	21.94±3.72	28.90±3.44
Salinity (ppt)	33.40±0.55	33.00±2.28	33.00±1.58
DO (ppm)	5.56±2.83	6.95±1.19	5.56±1.02
Alkalinity (mg/L $CaCO_3$)	133.60±15.84	128.50±10.27	126.80±9.34
Total phosphorus (mg/L)	0.35±0.16	0.42±0.11	0.34±0.05
Nitrite (mg/L)	0.90±0.46	0.93±0.30	1.21±0.47
Nitrate (mg/L)	0.02±0.01	0.02±0.01	0.02±0.01
Ammonia (mg/L)	0.19±0.01	0.22±0.05	0.22±0.02

TABLE 2 Checklist of all recorded dinoflagellate species recorded across three sampling sites along the Mumbai–Raigad Coast.

Species name	Study sites		
	Versova	Karanja	Ferry Wharf
Alexandrium catenella (Whedon & Kofoid) Balech 1985	×	√	×
Cochlodinium sp. F. Schütt, 1896	×	×	√
Gymnodinium sp. F. Stein, 1878	√	×	×
Gyrodinium lachryma (Meunier) Kofoid & Swezy 1921	√	√	√
Gyrodinium spirale (Bergh) Kofoid & Swezy 1921	√	√	√
Heterocapsa sp. F. Stein, 1883	√	×	×
Margalefidinium sp. F. Gómez, Richlen & D. M. Anderson, 2017	√	×	×
Prorocentrum micans Ehrenberg 1834	√	×	×
Protoperidinium depressum (Bailey) Balech 1974	√	√	√
Protoperidinium sp. Bergh, 1881	√	√	√
Protoperidinium conicum (Gran) Balech 1974	×	×	√
Protoperidinium oceanicum (Vanhöffen) Balech 1974	×	×	√
Protoperidinium parcum (Balech) Balech 1974	√	×	×
Protoperidinium steinii (Jørgensen) Balech 1974	√	√	√
Pyrophacus steinii (Schiller) Wall & Dale 1971	×	√	×
Scrippsiella trochoidea (F. Stein) A.R. Loeblich 1976	√	√	√
Tripos furca (Ehrenberg) F. Gómez 2013	√	√	√
Tripos fusus (Ehrenberg) F. Gómez 2013	√	√	√
Tripos lineatus (Ehrenberg) F. Gómez 2021	√	√	×
Tripos macroceros (Ehrenberg) Hallegraeff & Huisman 2020	√	×	×
Tripos mulleri Bory 1826	√	√	×

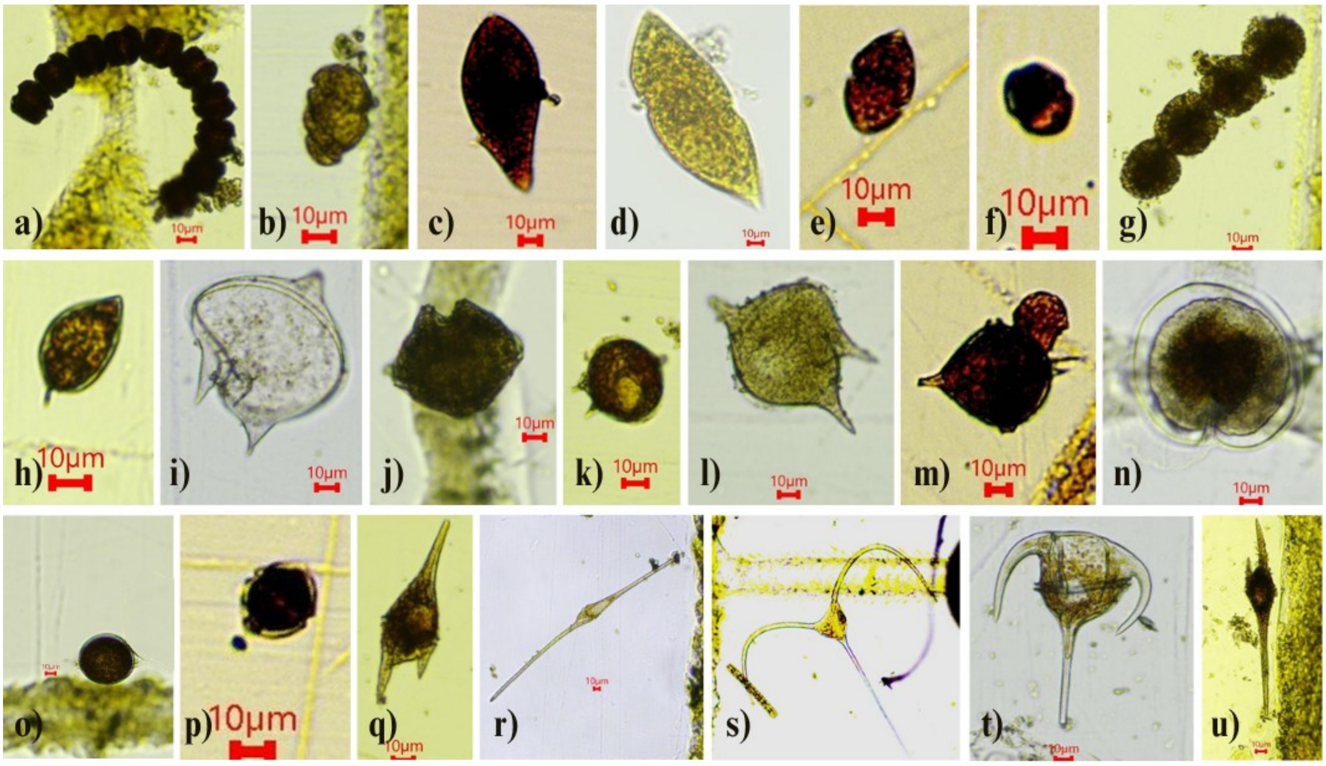

FIGURE 2 Images of Dinoflagellates from three sampling sites along the Mumbai–Raigad Coast. a) *Alexandrium catenella*, b) *Cochlodinium* sp., c) *Gyrodinium lachryma*, d) *Gyrodinium spirale*, e) *Heterocapsa* sp., f) *Gymnodinium* sp., g) *Margalefidinium* sp., h) *Prorocentrum micans*, i) *Protoperidinium depressum*, j) *Protoperidinium conicum*, k) *Protoperidinium* sp., l) *Protoperidinium oceanicum*, m) *Protoperidinium steinii*, n) *Pyrophacus steinii*, o) *Protoperidinium parcum*, p) *Scirpsiella* sp., q) *Tripos furca*, r) *Tripos fusus*, s) *Tripos macroceros*, t) *Tripos mulleri*, and u) *Tripos lineatus*.

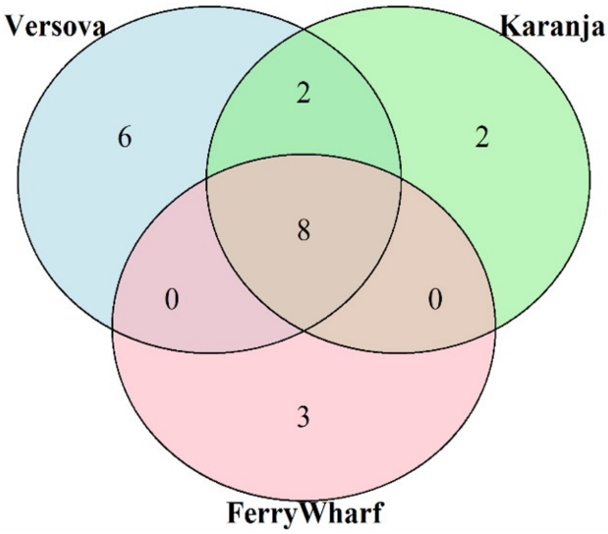

FIGURE 3 Venn diagram showing the number of dinoflagellate species encountered across the study sites along the Mumbai–Raigad Coast.

The highest species richness was observed within the order Gonyaulacales (7 species), especially at Versova. Peridiniales (7 species), mainly represented by the genus *Protoperidinium*, were widely distributed and found across all study sites. Prorocentrales (*Prorocentrum micans*) appeared exclusively at Versova. Whereas Thoracosphaerales (*Scrippsiella* sp.) and several Gymnodiniales were present at all locations (Figure 4 and 5).

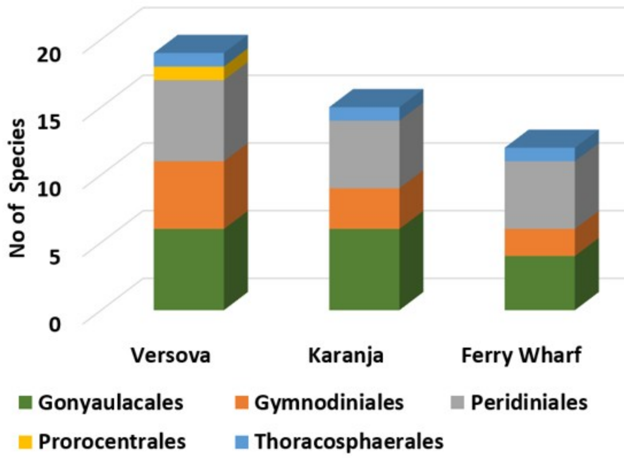

FIGURE 4 Bar chart showing the composition of dinoflagellate species by taxonomic order across the three study sites along the Mumbai–Raigad Coast.

The Bray–Curtis distance analysis revealed that Versova and Karanja exhibit a similarity of 68%, indicating that they share most of the recorded species. In contrast, Versova and Ferry Wharf show a lower similarity of 46%, suggesting a higher proportion of unique species at these sites. Karanja and Ferry Wharf share a similarity of 62%, indicating a moderate level of species overlap and comparatively fewer shared species than the Versova–Karanja (Figure 6). The lower similarity found at Ferry Wharf may be due to greater human disturbances and pollution in this harbor ecosystem. These factors can favour pollution-tolerant dinoflagellate species while limiting the presence of sensitive taxa. This suggests that the polluted ecosystem has a distinct dinoflagellate community structure compared to the other two sites.

FIGURE 5 Sunburst chart depicting the proportion of each dinoflagellate taxon found across all sites along the Mumbai–Raigad Coast.

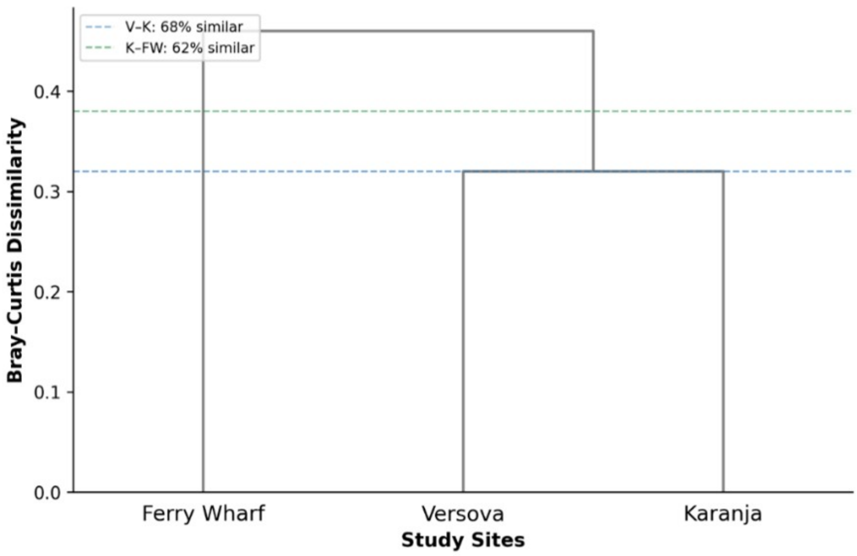

FIGURE 6 Dendrogram based on Bray–Curtis similarity index showing the presence of dinoflagellate species across three sites along the Mumbai–Raigad Coast.

3.3 Physicochemical parameters impact on dinoflagellate abundance

Pearson correlation analysis was employed to examine the relationships between various physicochemical parameters and dinoflagellate abundance across the study sites (Figure 7). At Versova, ammonia correlated strongly with temperature (r = 0.882; p = 0.048), while nitrite and nitrate were also strongly correlated (r = 0.906; p = 0.034), indicating close nutrient interactions. At Karanja, phytoplankton abundance was positively correlated to total phosphorus (r = 0.839; p = 0.037) and also showed a positive correlation with temperature (r = 0.652). In contrast, DO exhibited a strong negative correlation with temperature (r = −0.935; p = 0.006). At Ferry Wharf, a positive correlation was found between DO and phytoplankton abundance (r = 0.927; p = 0.023), indicating that higher oxygen supports dinoflagellate growth.

3.4 Principal component analysis

PCA of the standardised physicochemical dataset across all three sites revealed that PC1 and PC2 together explained the majority of environmental variance. PC1 was predominantly driven by temperature and DO (opposing loadings), reflecting the inverse thermal–oxygen relationship characteristic of coastal marine systems. PC2 was primarily associated with nutrient axes (total phosphorus, nitrite, ammonia). The triplot clearly discriminated the three sites: Ferry Wharf samples clustered in the positive PC1 (high-temperature, elevated nutrient) quadrant, Karanja samples in the high-DO region, and Versova samples occupying an intermediate position with higher alkalinity loadings (Figure 8).

FIGURE 7 Pearson correlation analysis between physicochemical parameters and dinoflagellate abundance across sites a) Versova b) Karanja c) Ferry wharf along the Mumbai–Raigad Coast.

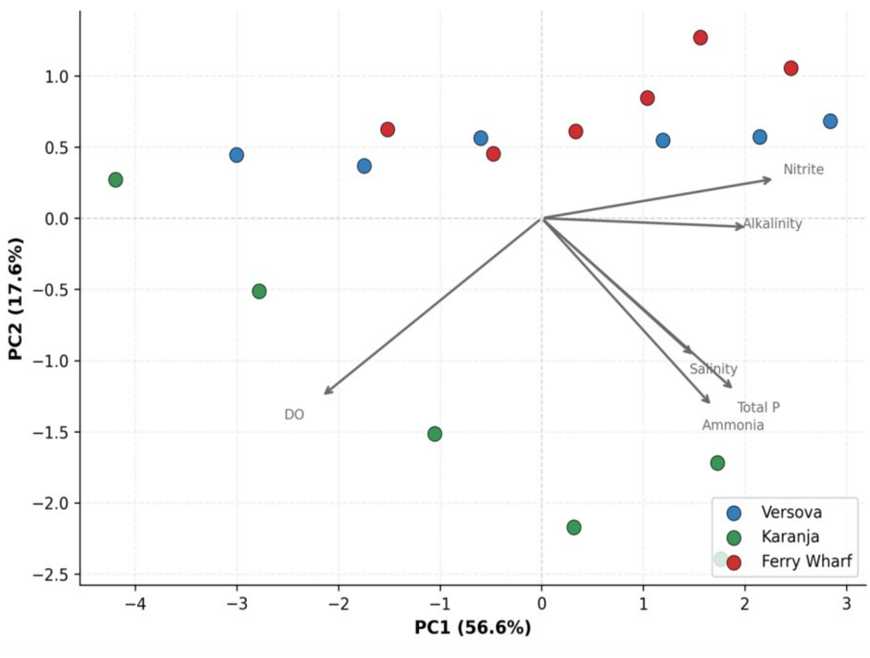

FIGURE 8 Dendrogram based on Bray–Curtis similarity index showing the presence of dinoflagellate species across three sites along the Mumbai–Raigad Coast.

3.5 Dinoflagellate biodiversity indices

The Shannon, Simpson, Brillouin, and Pielou's evenness indices of dinoflagellate diversity were computed for each study location (Table 3). The Shannon index provides an overall measure of diversity by reflecting species richness and evenness. The Simpson index similarly considers both evenness and richness while highlighting the predominance of common species. Because of the comparatively low species richness in the present study, the Brillouin index, which is sensitive to species number was used.

Shannon Wiener index was highest at Versova and lowest at Ferry Wharf. The Simpson's Index of Diversity (1–D) Versova showed the highest diversity followed by Karanja and Ferry Wharf. The Brillouin Index (HB) is high at Karanja 0.51 and Versova 0.49, indicating both sites support relatively balanced dinoflagellate communities. In contrast, Ferry Wharf recorded a much lower value 0.24, suggesting reduced diversity and possible dominance by a few species. Pielou's Evenness Index (J'), the highest species evenness was at Karanja, 0.95, followed by Versova, 0.87, while Ferry Wharf shows the lowest, 0.73. This suggests a more balanced distribution of dinoflagellate species at Karanja, whereas Ferry Wharf may be dominated by a few species and Versova has a greater species richness and diversity.

TABLE 3 Dinoflagellate biodiversity indices across three sites along the Mumbai–Raigad Coast.

Indices	Sampling sites		
	Versova	Karanja	Ferry Wharf
Shannon Wiener (H')	1.426	1.147	0.928
Simpson (1–D)	0.699	0.628	0.510
Brillouin (HB)	0.488	0.510	0.245
Pielou's evenness (J')	0.866	0.948	0.725

4 | DISCUSSION

The Mumbai–Raigad coastline, a major maritime zone comprising estuaries, creeks, ports, and fishing grounds, is increasingly subjected to environmental stress. The region hosts major ports such as Mumbai Port and Jawaharlal Nehru Port, which handle exceptionally high cargo volumes, reflecting intense maritime activity that can contribute to coastal environmental degradation and influence plankton dynamics. In this context, the present study examined three ecologically distinct sites to assess how dinoflagellate diversity varies spatially and temporally in relation to changing water quality parameters.

4.1 Impact of physicochemical parameters on dinoflagellate abundance

Environmental factors such as temperature, salinity, nutrients, and dissolved oxygen play a crucial role in shaping dinoflagellate abundance, as supported by earlier studies (Karati *et al.* 2017; Vase *et al.* 2018; Saravanakumar *et al.* 2021). Temperature a key driver of metabolic processes and nutrient cycling (Wetzel 2001; Van Aken 2008), exhibited a wider range at Karanja (23–33°C), consistent with observations from other estuarine systems such as the Tapi and Gosthani estuaries (22–33.2°C; George *et al.* 2012; 22.9–33.9°C; Sobha Rani 2016). These fluctuations are characteristic of tidal mixing and freshwater influence in estuarine environments. Dissolved oxygen (DO), an important indicator of water quality (Best *et al.* 2007), was highest and relatively stable at Karanja (6.95±1.19 ppm), indicating well-oxygenated conditions associated with moderate hydrodynamic mixing. These align with Akter *et al.* (2024a). Nutrients, particularly nitrogen and phosphorus, are essential drivers of phytoplankton diversity and ecosystem health (Dugdale 1967; Ryther and Dunstan 1971). At Versova, dinoflagellate abundance showed a strong positive association with dissolved oxygen, suggesting favourable conditions for dinoflagellate growth under moderate nutrient enrichment, consistent with findings by Vajravelu *et al.* (2018) and Akter *et al.* (2024a). Temperature exhibited a weaker positive influence, indicating its secondary role compared to oxygen availability. At Karanja, total phosphorus emerged as a key driver of dinoflagellate abundance, highlighting the role of nutrient inputs and estuarine mixing in shaping community dynamics, supporting observations by Sathish Kumar *et al.* (2023). In contrast, at Ferry Wharf, the positive relationship between dissolved oxygen, temperature, and dinoflagellate abundance may reflect nutrient-rich conditions associated with anthropogenic inputs, supporting opportunistic species despite environmental stress, consistent with many others (e.g. Sridhar *et al.* 2006; Sharma and Singh 2018; and Sathish *et al.* 2022). Overall, these results highlight the varying and site-specific impacts of physicochemical parameters on dinoflagellate abundance along the Mumbai–Raigad Coast.

4.2 Dinoflagellate composition and diversity analysis

In the present study, a total of 21 dinoflagellate species belonging to 11 genera, nine families, and five orders under the class Dinophyceae were recorded across three coastal locations - Karanja, Ferry Wharf, and Versova. Species richness varied notably among sites, with Versova exhibiting the highest diversity (16 species), followed by Karanja (12 species) and Ferry Wharf (11 species). Earlier studies from Indian coastal and estuarine ecosystems show considerable variability in dinoflagellate diversity. Bhowal *et al.* (2023) reported 14 dinoflagellate species from Kakinada, while Akter *et al.* (2024b) documented 25 species from the Karanja Estuary. Sadasivan *et al.* (2019) recorded 47 phytoplankton genera from the Patalganga Estuary with Dinophyceae contributing 3.7%. In Mumbai waters, Shahi *et al.* (2015) identified 82 dinoflagellate species from Mahim Bay and Manori Creek, highlighting the region's high productivity. In comparison, the present study documents a moderate species richness typical of nearshore, mixed-impact coastal systems.

Site-wise, Versova exhibited the highest species richness and dinoflagellate density (0.501–2.724 cells/L), likely due to moderate nutrient levels and lower disturbance. Karanja showed intermediate densities (0.334–2.375 cells/L), reflecting estuarine influences such as salinity gradients and freshwater input. In contrast, Ferry Wharf recorded the lowest densities (0.167–1.666 cells/L), suggesting that intense maritime activity and pollution may suppress dinoflagellate abundance, consistent with findings by Nair and Kumar (2005), who noted reduced phytoplankton abundance in heavily trafficked harbour zones.

At the taxonomic level, the orders Gonyaulacales and Peridiniales were dominant, each contributing seven species. Both groups are predominantly thecate (armoured) and exhibit diverse nutritional modes, including autotrophy, heterotrophy, and mixotrophy, enabling them to adapt to varying environmental conditions. Peridiniales were particularly rich in the genus *Protoperidinium*, which is primarily heterotrophic and utilises a specialised feeding structure called a pallium for extracellular digestion (Menden *et al.* 2005). The widespread occurrence of *Protoperidinium* across all study sites highlights its ecological adaptability and ability to thrive under diverse environmental conditions, particularly in nutrient-influenced coastal systems. Similar dominance patterns of Gonyaulacales and Peridiniales have also been reported from Kakinada waters (Bhowal *et al.* 2023).

Distinct species assemblages were observed across the study sites. Versova hosted six exclusive species, including *Heterocapsa* sp., *Margalefidinium* sp., and *Tripos macroceros*, reflecting its relatively favorable ecological conditions. Ferry Wharf contained three exclusive species, likely representing taxa that are tolerant to disturbed environments. Karanja recorded two unique species *Alexandrium catenella* and *Pyrophacus steinii*, which were also reported by Akter *et al.* (2024a). Eight species were common to all three sites, with *Tripos furca* emerging as the most dominant species, followed by *Tripos fusus*, demonstrating their ecological resilience (strong-armoured, large sized cells, mixotrophy) and broad environmental tolerance. The widespread dominance of *T. furca* may be attributed to its strongly armoured theca, large cell size, and ability to tolerate fluctuating salinity and nutrient conditions commonly observed in coastal and estuarine waters (Huynh *et al.* 2022). Its mixotrophic nature may also provide a competitive advantage under varying environmental conditions (Eom *et al.* 2021). Sadasivan *et al.* (2019) also reported the dominance of *Ceratium* (= *Tripos*) in the Patalganga Estuary.

4.3 Harmful algal bloom (HAB) risk assessment

The presence of toxigenic and bloom-forming species such as *Alexandrium catenella* and *Cochlodinium* sp. is of particular concern. The presence of *A. catenella* in Karanja holds special importance as this particular organism is known for its capability of producing saxitoxins, which can cause paralytic shellfish poisoning (PSP) (Kao 1993). Estuarine and coastal near-shore waters such as Karanja contain shellfish resources in the form of bivalves (Dineshbabu 2024). These organisms tend to filter feed and thus accumulate the saxitoxins produced by the dinoflagellate (Manfrin *et al.* 2012). The consumption of such toxic shellfish can be lethal for humans and causes neurological problems, respiratory paralysis, and even death (Etheridge 2010). Thus, the presence of *A. catenella* in our case study constitutes an important early warning system for the possible threat to food safety of the region. It is also noteworthy that this species tends to multiply in water bodies that have been exposed to enrichment through nutrients, especially common in coastal waters affected by anthropogenic influence and fluctuation in salinity (Wurtsbaugh *et al.* 2019). The presence of *Cochlodinium* sp. is important because it is related to harmful algal blooms and fish deaths in coastal ecosystems (Anderson 2021; Kudela and Gobler 2012). Blooms of this type are frequently connected to nutrient enrichment and nutrient-rich conditions, which may rise due to increasing human activity along the Maharashtra coast (D'Silva *et al.* 2012). Their occurrence in Mumbai and Raigad coastal waters underscores the increasing vulnerability of these regions to HAB events, potentially exacerbated by nutrient loading, warming waters, and anthropogenic disturbances. Previous reports from the Indian coast highlight similar concerns (Gopakumar *et al.* 2009).

This spatial variation reflects differences in environmental conditions, hydrodynamic processes, and anthropogenic influences along the Maharashtra Coast (Pérez-Ruzafa *et al.* 2007). The simultaneous detection of two independently toxigenic/bloom-forming genera at two of the three study sites, geographically separated by approximately 40 km, suggests that HAB risk along the Mumbai–Raigad Coast is systemic rather than site-specific. Comprehensive HAB early warning requires the integration of high-frequency water sampling, remote sensing-based chlorophyll monitoring, and molecular detection (qPCR-based species-specific assays or metabarcoding) to supplement conventional microscopy-based identification, as morphological similarity between species can confound accurate identification at bloom concentrations.

4.4 Biodiversity indices

The Shannon–Wiener index, which shows both species richness and evenness, indicated the highest dinoflagellate diversity at Versova (H' = 1.43), followed by Karanja (1.15), and the lowest at Ferry Wharf (0.93). Higher Shannon values typically reflect healthier and more balanced ecosystems. Bhowal *et al.* (2023) recorded an H' of 1.433 in the coastal waters of Andhra Pradesh. In comparison, Jacob *et al.* (2024) reported a Shannon index of 1.94 in the coastal waters of central Chile, suggesting that Versova, while diverse, still falls within a moderate diversity range. The relatively low diversity at Ferry Wharf likely signals environmental stress or pollution-related impacts. Supporting these results, the Simpson Index of Diversity (1–D), which emphasizes the dominance of common species, also showed the highest diversity at Versova (0.70), moderate levels at Karanja (0.63), and the lowest at Ferry Wharf (0.51). These values align with patterns noted in earlier studies (Kulkarni *et al.* 2011; Gao and Su 2023; Jacob *et al.* 2024), reinforcing the idea that Versova hosts a more diverse and less dominant community structure. The Brillouin Index (HB), which is particularly effective in situations when randomness of the sample cannot be guaranteed (Magurran 2013) or for small sample sizes, presented comparable values at Karanja (0.51) and Versova (0.49), while being significantly lower at Ferry Wharf (0.24). Brillouin's sensitivity to limited samples makes it a reliable index for this study. Pielou's Evenness Index (*J'*), which quantifies how evenly individuals are spread across species, was highest at Karanja (0.95), followed by Versova (0.87), and lowest at Ferry Wharf (0.73). Bhowal *et al.* (2023) reported *J'* of 0.698 in Kakinada waters. The elevated evenness at Karanja suggests a balanced community where no single species dominates, likely due to its semi-enclosed estuarine nature and moderate hydrodynamic conditions, highlighting the unique ecological balance at Karanja despite its moderate species richness. Jacob *et al.* (2024) reported a significantly lower evenness value (0.34), while the evenness was relatively higher in the present study sites.

5 | CONCLUSIONS

The study indicates that dinoflagellate distribution along the Mumbai–Raigad Coast is shaped by environmental variability and anthropogenic pressures. Ferry Wharf, characterized by intense maritime activity and pollution, exhibited lower species diversity, whereas Versova showed higher richness under comparatively lower disturbance. Karanja, an estuarine system, displayed high species evenness, suggesting a relatively stable environment. The occurrence of HAB-forming species highlights potential ecological and food safety risks. Karanja may function as a regional biodiversity refugium and warrants protection from increasing developmental pressures. Although all three sites support important fishing activities, they are increasingly threatened by pollution from ballast water discharge, jetty construction, transportation, and sewage inputs. Physicochemical parameters significantly influence dinoflagellates abundance and biodiversity indices reflect ecosystem health.

The findings suggest that the Ferry Wharf site might turn into a vulnerable ecosystem due to pollution, leading to the unexpected occurrence of harmful algal blooms as well as declining biodiversity. Thus, the use of proper coastal management methods, together with continuous assessment of biodiversity through morphological analysis and environmental DNA approach, is needed in order to identify the invasive and bloom-forming species. The relatively stable and rich species composition at Karanja demonstrates that it may serve as a regional refuge for biodiversity and requires conservation and protection against any future development of industries and maritime transport in the area. The present study highlights the need for continuous ecosystem-based monitoring and sustainable coastal management practices to conserve biodiversity and maintain ecological stability along the Mumbai and Raigad coasts.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Director, ICAR-Central Institute of Fisheries Education, Mumbai, for providing the research facilities necessary to carry out this study. The authors express sincere gratitude to the fishers and harbour authorities at Versova, Ferry Wharf, and Karanja for facilitating field access.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHORS' CONTRIBUTION

All authors contributed to the design of the study BB Nayak, Annam Pavan Kumar conceived the study; material preparation, sample collection and laboratory work was performed by Agalya B, Raahavishree T, and Sonam Angmo. Data curation, statistical analysis, and interpretation of results were done by BBNayak, Annam Paavan Kumar, Asha T landge, and Abuthagir Iburahim. All authors contributed to writing and editing the final manuscript.

AI USE DECLARATION

The authors declare that artificial intelligence (AI) tools were used only to assist with language editing and improvement of grammar and readability. AI was not used for data collection, analysis, interpretation, or the generation of scientific results.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on a reasonable request from the corresponding author.

REFERENCES

Akter S, Deshmukhe G, Ramteke K, Nama S, Abhilash Wodeyar, ... Landge AT (2024a) Spatio-temporal dynamics of phytoplankton diversity and community structure in relation to environmental variables in the Northwest Coasts of India. Arabian Journal of

Geosciences 17(3): 93.

Akter S, Nama S, Wodeyar KA, Deshmukhe G, Nayak BB, ... Ramteke K (2024b) Unravelling tropical estuary health through a multivariate analysis of spatiotemporal phytoplankton diversity and community structure in relation to environmental interactions. Aquatic Sciences 86(4): 109.

Anderson DM, Fachon E, Pickart RS, Lin P, Fischer AD, ... Fukai Y (2021) Evidence for massive and recurrent toxic blooms of *Alexandrium catenella* in the Alaskan Arctic. Proceedings of the National Academy of Sciences 118(41): e2107387118.

APHA (2005) Standard methods for the examination of water and wastewater, 21st edition, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Barathan BP, Sarangi RK (2024) Intensification and spread of algal blooms over two decades in the coasts of India. Discover Oceans 1(1): 32.

Baweja P, Sahoo D (2015) Classification of algae (pp. 31–55). In: The algae world. Springer Netherlands, Dordrecht.

Best MA, Wither AW, Coates S (2007) Dissolved oxygen as a physico-chemical supporting element in the Water Framework Directive. Marine Pollution Bulletin 55(1–6): 53–64.

Bhowal A, Purushothaman J, Siddique A (2023) Taxonomic studies of marine dinoflagellates and distribution in the coastal waters of Kakinada, Andhra Pradesh, India. Indian Journal of Geo-Marine Sciences 52(08): 390–401.

Botes L (2001) Identification catalogue Saldanha Bay, South Africa, April 2001. GloBallast Monograph Series No. 7. IMO London.

Calbet A (2025) The ocean of today, the legacy of tomorrow: navigating the future of marine life and ecosystems. Springer Nature, Switzerland AG.

Carstensen J, Klais R, Cloern JE (2015) Phytoplankton blooms in estuarine and coastal waters: seasonal patterns and key species. Estuarine, Coastal and Shelf Science 162: 98–109.

D'Silva MS, Anil AC, Naik RK, D'Costa PM (2012) Algal blooms: a perspective from the coasts of India. Natural Hazards 63(2): 1225–1253.

Dineshbabu AP (2024) Shellfish fisheries in India with special reference to Maharashtra (pp. 30–42). In: Training manual on fisheries management practices and techniques. CMFRI Training Manual Series No. 43/2024. ICAR- Central Marine Fisheries Research Institute, Kochi, India.

Dugdale RC (1967) Nutrient limitation in the sea: Dynamics, identification, and significance. Limnology and Oceanography 12(4): 685–695.

Eom SH, Jeong HJ, Ok JH, Park SA, Kang HC, ... Lee MJ (2021) Interactions between common heterotrophic protists and the dinoflagellate *Tripos furca*: implication on the long duration of its red tides in the South Sea of Korea in 2020. Algae 36(1): 25–36.

Etheridge SM (2010) Paralytic shellfish poisoning: seafood safety and human health perspectives. Toxicon 56(2): 108–122.

Falkowski PG (1994) The role of phytoplankton photosynthesis in global biogeochemical cycles. Photosynthesis Research 39(3): 235–258.

FAO (1989) Plant genetic resources: their conservation in situ for human use. Food and Agriculture Organization of the United Nations, Rome.

Gao J, Su Q (2023) The relationship between inorganic nutrients and diversity of dinoflagellate cysts: an evaluation from the perspective of species abundance distribution. Frontiers in Marine Science 9: 1089331.

Gaonkar CA, Sawant SS, Anil AC, Krishnamurthy V, Harkantra SN (2010) Changes in the occurrence of hard substratum fauna: a case study from Mumbai harbour, India. Indian Journal of Geo-Marine Sciences 39(1): 74–84.

George B, Kumar JN, Kumar RN (2012) Study on the influence of hydro-chemical parameters on phytoplankton distribution along Tapi estuarine area of Gulf of Khambhat, India. Egyptian Journal of Aquatic Research 38(3): 157–170.

Gómez F (2020) Diversity and classification of dinoflagellates. Dinoflagellates: classification, evolution, physiology, and ecological significance; Rao, DVS, Ed 38.

Gopakumar G, Sulochanan B, Venkatesan V (2009) Bloom of *Noctiluca scintillans* (Macartney) in Gulf of Mannar, southeast coast of India. Journal of the Marine Biological Association of India 51(1): 75–80.

Guiry MD (2024) How many species of algae are there? Journal of Phycology 48(5): 1057–1063.

Haddock SH, Moline MA, Case JF (2010) Bioluminescence in the sea. Annual Review of Marine Science 2: 443–493.

Hallegraeff GM (1993) A review of harmful algal blooms and their apparent global increase. Phycologia 32(2): 79–99.

Hasle GR (1978) The inverted microscope method (pp. 88–96). In: Sournia A (Ed) Phytoplankton manual. UNESCO.

Huynh NDT, Nguyen-Ngoc L, Voss M, Doan-Nhu H (2022) Dinoflagellate *Tripos furca* and *Tripos fusus* niches in the South China Sea: maximum entropy assessment of environmental factors. Regional Studies in Marine Science 55: 102601.

Jacob BG, Astudillo O, Dewitte B, Valladares M, Alvarez Vergara G, ... Yanicelli B (2024) Abundance and diversity of diatoms and dinoflagellates in an embayment off central Chile (30° S): evidence of an optimal environmental window driven by low and high frequency winds. Frontiers in Marine Science 11: 1434007.

Kao CY (1993) Paralytic shellfish poisoning. In: Falconer IR (Ed) Algal toxins in seafood and drinking water, Academic Press, London.

Karati KK, Vineetha G, Madhu NV, Anil P, Dayana M, ... Raveendran TV (2017) Variability in the phytoplankton community of Kavaratti reef ecosystem (northern Indian Ocean) during peak and waning periods of El Niño 2016. Environmental Monitoring and Assessment 189(12): 653.

Kudela RM, Gobler CJ (2012) Harmful dinoflagellate blooms caused by *Cochlodinium* sp.: global expansion and ecological strategies facilitating bloom formation. Harmful Algae 14: 71–86.

Kulkarni VA, Naidu VS, Jagtap TG (2011) Marine ecological habitat: a case study on projected thermal power plant around Dharamtar Creek, India. Journal of Environmental Biology 32(2): 213–219

Lovelock JE, Maggs RJ, Rasmussen RA (1972) Atmospheric dimethyl sulphide and the natural sulphur cycle. Nature 237(5356): 452–453.

Magurran AE (2013) Measuring biological diversity. John Wiley & Sons.

Manfrin CHIARA, De Moro GIANLUCA, Torboli V, Venier P, Pallavicini A, Gerdol MARCO (2012) Physiological and molecular responses of bivalves to toxic dinoflagellates. Invertebrate Survival Journal 9(2): 184.

Menden-Deuer S, Lessard EJ, Satterberg J, Grünbaum D (2005) Growth rates and starvation survival of three species of the pallium-feeding, thecate dinoflagellate genus *Protoperidinium*. Aquatic Microbial Ecology 41: 145–152.

Ministry of Ports, Shipping and Waterways (2025) Revised length of India's coastline. Government of India.

Mohan R, Sathish T, Purushothaman A, Afnitha KH, Ajayakumar P, Padmakumar KB (2025) Emergence of mixoplanktonic dinoflagellates in the eastern Arabian Sea: an annotated checklist: Journal of Earth System Science 134(4): 191.

Nair P, Kumar D (2005) Mumbai urban transport project-Development and challenges. University Library of Munich, Germany.

Naselli-Flores L, Padisák J (2023) Ecosystem services provided by marine and freshwater phytoplankton. Hydrobiologia 850(12): 2691–2706.

Pawar, Prabhakar R, Kulkarni, Balasaheb G (2007) Assessment of water quality in Karanja Creek (Dist-Raigad), Maharashtra, west coast of India. Journal of Ecophysiology and Occupational Health 7: 61–72.

Pérez-Ruzafa A, Marcos C, Pérez-Ruzafa IM, Barcala E, Hegazi MI, Quispe J (2007) Detecting changes resulting from human pressure in a naturally quick-changing and heterogeneous environment: Spatial and temporal scales of variability in coastal lagoons. Estuarine, Coastal and Shelf Science 75(1–2): 175–188.

R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/

Ryther JH, Dunstan WM (1971) Nitrogen, phosphorus, and eutrophication in the coastal marine environment. Science 171(3975): 1008–1013.

Sadasivan S, Shukla SP, Jaiswar AK, Shenoy L, Deshmukhe G (2019) Study on phytoplankton composition, abundance and the productivity of Patalganga Estuary, Maharashtra, India. International Journal of Fisheries and Aquatic Studies 7(4): 411–415.

Saravanakumar M, Murugesan P, Damotharan P, Punniyamoorthy R (2021) Multivariate approach to determine the ecological preferences of phytoplankton in Uppanar Estuary, southeast coast of India. International Journal for Modern Trends in Science and Technology 7: 23–33.

Sathish Kumar P, Dharani G, Santhanakumar J, Jha DK, Pandey V, ... James RA (2023) Assessment of phytoplankton diversity, distribution, and environmental variables along the southeast coast of India. Frontiers in Marine Science 10: 1215627.

Sathish T, Nazrin AK, Thomas LC, Padmakumar KB (2022) Seasonal dynamics of dinoflagellates with special emphasis on potentially harmful species in a tropical estuarine system along the southwest coast of India. Journal of Oceanography 78(5): 397.

Shahi N, Godhe A, Mallik SK, Härnström K, Nayak BB (2015) The relationship between variation of phytoplankton species composition and physico-chemical parameters in northern coastal waters of Mumbai, India. Indian Journal of Geo-Marine Sciences 44(5): 673–684.

Sharma RC, Singh S (2018) Water quality and phytoplankton diversity of high altitude wetland, Dodi Tal of Garhwal Himalaya, India. Biodiversity International Journal 2(6): 484–493.

Smayda TJ (1997) Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea. Limnology and Oceanography 42: 1137–1153.

Sobha Rani S (2016) Seasonal changes in physico-chemical characteristics of the water of Gosthani Estuary in Visakhapatnam District-Andhra Pradesh, India. European Academic Research 3(12): 12805–12814.

Sournia A (1978) Phytoplankton manual. Monographs on oceanographic methodology, No. 6. Paris.

Sridhar R, Thangaradjou T, Kumar SS, Kannan L (2006) Water quality and phytoplankton characteristics in the Palk Bay, southeast coast of India. Journal of Environmental Biology 27(3): 561–566.

Stefels J, Steinke M, Turner S, Malin G, Belviso S (2007)

Environmental constraints on the production and removal of the climatically active gas dimethylsulphide (DMS) and implications for ecosystem modelling. Biogeochemistry 83(1): 245–275.

Subrahmanyan R (1946) A systematic account of the marine plankton diatoms of the Madras Coast. In: Proceedings of the Indian Academy of Sciences 24(4): 85–197.

Suthers I, Rissik D, Richardson A (2019) Plankton: a guide to their ecology and monitoring for water quality. CSIRO publishing, Australia.

Taylor FJR (1987) General group characteristics; special features of interest; short history of dinoflagellate study (pp. 1–23). The biology of dinoflagellates, botanical monographs. Blackwell Scientific, Oxford.

Tomas CR (1997). Identifying marine phytoplankton. Elsevier.

Vajravelu M, Martin Y, Ayyappan S, Mayakrishnan M (2018) Seasonal influence of physico-chemical parameters on phytoplankton diversity, community structure and abundance at Parangipettai coastal waters, Bay of Bengal, South East Coast of India. Oceanologia 60(2): 114–127.

Van Aken HM (2008) Variability of the salinity in the western Wadden Sea on tidal to centennial time scales. Journal of Sea Research 59(3): 121–132.

Vase VK, Dash G, Sreenath KR, Temkar G, Shailendra R, ... Jayasankar J (2018) Spatio-temporal variability of physico-chemical variables, chlorophyll *a*, and primary productivity in the northern Arabian Sea along India coast. Environmental Monitoring and Assessment 190(3): 148.

Wetzel RG (2001) Limnology: lake and river ecosystems. Gulf Professional Publishing. Elsevier.

Wurtsbaugh WA, Paerl HW, Dodds WK (2019) Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. Wires Water 6(5): e1373.

Agalya B http://orcid.org/0009-0004-0934-5942
Raahavishree T. http://orcid.org/0009-0000-5304-3838
Sonam Angmo http://orcid.org/0009-0007-9253-1384
AP Kumar http://orcid.org/0000-0002-6402-4111
AT Landge http://orcid.org/0000-0002-7336-2702
A Iburahim S http://orcid.org/0000-0002-7354-2690
BB Nayak http://orcid.org/0000-0002-1822-9167