Diversity and abundance of epiphytic diatoms and cyanobacteria as bioindicators in Chabahar Bay, Oman Sea

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Abstract

This study investigates the diversity and abundance of epiphytic diatoms and cyanobacteria in Chabahar Bay, emphasizing their role as bioindicators of ecological health. Biodiversity assessments were conducted at six sampling sites during four seasons in 2020-2021. Macroalgal samples were collected, and water samples were analyzed for nutrients, including nitrite, nitrate, phosphate and silicate. Biodiversity in Chabahar Bay varied seasonally. Winter showed the highest diversity (87.22 species, Shannon-Wiener index 4.45, Margalef index 19), followed by summer in abundance (96.22 cells/cm2). Spring peaked at station 3 (82 species, Shannon index 4.38); autumn showed the lowest values (station 2: 47.33 species, 50 cells/cm2). The Simpson index remained stable (~0.98), with a winter peak (0.988). The highest biodiversity was observed in winter. Correlations between biodiversity indices and environmental parameters indicated that lower oxygen levels negatively impacted species diversity, while higher nitrate concentrations were associated with increased taxonomic richness. *Gyrosigma* consistently scored the highest Indicator Value index values throughout all seasons (averaging >0.20), confirming its role as Chabahar Bay's primary bioindicator due to its frequent presence and higher abundance compared to other genera. *Navicula* was the second most important indicator, particularly in spring and autumn (scores 0.16–0.19), while the genera *Mastogloia*, *Nitzschia* and Pleurosigma showed weaker associations (scores <0.15), making them less reliable bioindicators. The findings highlight the need for continuous monitoring and conservation efforts to protect diatom taxocoenoses, particularly in the face of environmental stressors, such as declining dissolved oxygen levels and increasing nutrient concentrations. *Gyrosigma* and *Navicula* provide valuable tools for assessing water quality and ecosystem health, ensuring the sustainable management of the studied marine ecosystem.

Keywords: Diatoms, Cyanobacteria, Biodiversity, Bioindicators, Chabahar Bay

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Introduction

Chabahar Bay, located on the southeastern coast of Iran along the Oman Sea, is a unique marine ecosystem known for its rich biodiversity and intricate environmental dynamics. This bay serves as a vital habitat for a wide array of marine organisms and is characterized by its diverse substrates, ranging from sandy mud to rocky surfaces (Khaledi, 2024). The ecological balance in Chabahar Bay is influenced by both natural phenomena, such as seasonal monsoons and tidal patterns, and anthropogenic activities, including coastal development, fishing and shipping (Pourkerman *et al*., 2022). These interactions create various habitats that support different marine communities, making the bay a critical area for ecological study (Agah *et al*., 2021).

Among the various organisms inhabiting this ecosystem, epiphytic diatoms and cyanobacteria are particularly significant. These microorganisms play an important role in primary production and nutrient cycling, serving as the basis for the aquatic food web (Ershadifar *et al*., 2020). They contribute to the overall productivity of the ecosystem, supporting higher trophic levels and influencing biogeochemical processes (Samini *et al*., 2024). These microorganisms can provide vital insights into the ecological status of the bay, making them important indicators for environmental monitoring (Nazari *et al*., 2023).

Epiphytic diatoms and cyanobacteria are highly responsive to environmental changes, such as nutrient concentrations, salinity and pollution levels (Shevchenko *et al*., 2018). They colonize surfaces, such as rocks, seagrasses and mangroves, forming complex biofilms that can reflect the health of their habitat (Paterson and Hope, 2021). Variations in the diversity and abundance of these organisms can signal shifts in water quality, often serving as early warnings for ecological disturbances (Singh *et al*., 2013; De Carvalho *et al*., 2025). For instance, a decline in benthic diatom diversity might indicate increased nutrient loading or pollution, while resurgence could signal ecosystem recovery (Feng *et al*., 2024). This study hypothesizes that the diversity and abundance of benthic diatoms and cyanobacteria are closely linked to the environmental variables in Chabahar Bay, particularly to the human impact and climate change. Understanding these relationships is crucial for assessing the resilience of the ecosystem and its ability to withstand anthropogenic pressure. In this context, a healthy ecosystem is characterized by high species diversity, functional balance among microbial communities, and the capacity to maintain ecological processes and services despite external stressors.

The primary objective of this research was to conduct a comprehensive survey of the diversity and abundance of epiphytic diatoms and cyanobacteria in Chabahar Bay, aiming to establish their

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effectiveness as bioindicators of ecological health. This research aims to contribute to the preservation of biodiversity and the long-term health of the Oman Sea ecosystem, ensuring that this vital marine resource can be sustained for future generations.

Materials and methods

Biodiversity assessments were conducted at six designated stations in Chabahar Bay, each of them characterized by distinct substrate types. Station 1 (Abshirinkon) featured sandy mud, providing a habitat rich in organic matter. Station 2 (Tis) was composed of sandy rock, supporting a unique assemblage of marine organisms. Station 3 (Lipar) was identified as a rocky habitat, which offers diverse microenvironments for various macrobenthic species. Station 4 (Shilat) consisted of sandy substrate, conducive to a different community structure. Station 5 (Daryakochik) also featured sandy conditions, while Station 6 (Daryabozorgh) was characterized by sandy rock, blending the features of both sandy and rocky environments (Fig. 1).

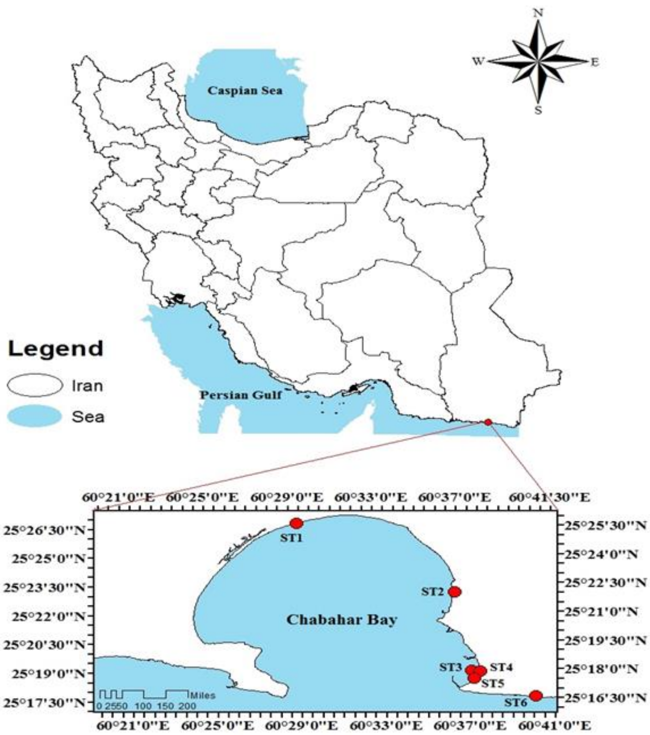

Figure 1: Geographical location of sampling stations in 2020-2021 (ST 1-6).

Samples of epiphytic diatoms and cyanobacteria were collected seasonally in Chabahar Bay during 2020-2021, covering four distinct seasons: spring (mid-May 2020), summer (mid-August 2020), autumn (mid-November 2020), and winter (mid-February 2021). Sampling was conducted at six stations to capture spatial variability across the bay. At each station, three replicate

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samples were taken per season, resulting in a total of 72 samples (6 stations×4 seasons×3 replicates). Sampling depths ranged from approximately 1 to 3 m, targeting epiphytic communities on substrates such as seagrasses, rocks, and other hard surfaces in shallow coastal waters. Collection involved gently scraping the surfaces with sterile tools followed by rinsing with filtered seawater to gather the organisms without damaging their structures. Samples were then preserved and transported to the laboratory for subsequent microscopic identification and quantification.

Water samples for the determination of physicochemical parameters were collected in 500 mL plastic flasks. Inorganic nutrients, including nitrites (NO_2^-, measured in μg/L), nitrates (NO_3^-, μg/L), orthophosphates (PO_4^{3-}, μg/L), and silicates (SiO_4^{4-}, μg/L), were analyzed using a Bran+Luebbe GmbH continuous-flow AutoAnalyzer III (Norderstedt, Germany) equipped with a UV-visible spectrophotometer (JENWAY 6705), following standard protocols (APHA, 2005).

To assess environmental factors influencing the diatom taxocoenoses, key physicochemical parameters were measured at each station. Surface water temperature was recorded in °C using a portable digital thermometer (Model HI98509, Hanna Instruments, Italy). Salinity was measured in practical salinity units (PSU) with a handheld refractometer (Model RHS-10ATC, Atago, Japan). pH was determined using a portable pH meter (Model pHep+, Hanna Instruments, Italy), and dissolved oxygen (DO) concentrations were measured in mg/L using a DO meter (Model DO5509, Lutron, Taiwan). These environmental measurements provided the essential context for analyzing variations in diatom species richness, abundance and diversity.

Laboratory analysis followed a multi-step protocol to prepare and identify epiphytic diatom and cyanobacteria samples. Initially, diatom samples were preserved in a 4% formaldehyde solution to fix the cells and prevent degradation. To remove organic material, samples underwent acid digestion with concentrated hydrochloric acid (HCl, ~37%), applied carefully under a fume hood. The digestion was performed at room temperature and the samples were left for several hours until all organic matter was dissolved; no heating or boiling was involved to avoid damaging delicate frustules.

After digestion, the cleaned diatom frustules were rinsed repeatedly with ultrapure water and then mounted on permanent glass slides using Naphrax® mounting medium (n=1.74), which enhances visibility of fine valve details (including diagnostic morphological features), and examined under a light microscope (LM).

Diatom identification was conducted using both LM and scanning electron microscopy (SEM). LM observations were performed with a Nikon Eclipse E600 microscope equipped with differential interference contrast (DIC) optics at total magnifications ranging from 400× to 1000×. The SEM analysis

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used a JEOL JSM-6510LV microscope, providing detailed ultrastructural images for accurate species identification.

For cyanobacteria, samples were filtered onto 0.45 μm pore size polycarbonate filters to concentrate cells. These filters were stained with 4',6-diamidino-2-phenylindole (DAPI) to visualize nucleic acids and examined under an Olympus BX51 epifluorescence microscope equipped with UV excitation filters suitable for DAPI fluorescence. This technique allowed clear distinction of cyanobacterial cells from other microorganisms. In this study, conventionally, diatoms and cyanobacteria together are referred to as microalgae.

Taxonomic identification for both diatoms and cyanobacteria was based on current specialized literature and identification keys (e.g., Waterbury, 2006; Blanco and Kilroy, 2020), ensuring reliable species-level determination.

To quantify diatom abundance, cells were counted on microscope slides under a light microscope using an ocular micrometer calibrated for area measurement. The number of cells observed within known fields of view was recorded and extrapolated to express abundance as cells per square centimeter (cells/cm^2) of substrate surface area, based on the total sampled area and microscope field dimensions. Cyanobacteria were counted at the cellular level rather than by colonies to provide more precise abundance estimates. While colonies were visually identified, individual cells within these colonies were enumerated using epifluorescence microscopy to enhance visualization. The diversity of taxocoenoses was assessed using multiple indices, including the Simpson diversity index to evaluate dominance and evenness, the Shannon-Wiener index to account for species richness and relative abundance, and the Margalef index to estimate species richness normalized by sample size. Statistical analyses included Pearson correlation coefficients to explore relationships between diversity indices and environmental parameters such as temperature, salinity, pH, and DO. Additionally, one-way ANOVA was used to detect significant seasonal and spatial variations in diversity and abundance across the six sampling stations.

Indicator species analysis

The Indicator Value (IndVal) index was used to identify species strongly associated with specific stations or seasons in Chabahar Bay. This index combines two components: specificity (A), which measures the occurrence of a species within a defined group (e.g., a station or season), and fidelity (B), which assesses the average abundance of the species within that group relative to its abundance across all groups. IndVal was calculated as:

IndVal=$A \times B$

Where, A=total number of sites in the group/number of sites in the group where the species occurs B=a ratio of sum of abundances of the species across

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all groups to sum of abundances of the species in the group.

Species with higher IndVal scores (ranging from 0 to 1) were considered stronger indicators of the group. This method was applied to each species across all stations and seasons to determine their bioindicator potential (Dufrêne and Legendre, 1997).

Results

A total of 84 diatom species belonging to 33 genera (including 30 benthic and 3 planktonic genera) and 7 cyanobacterial species from 7 distinct genera were identified from samples collected in Chabahar Bay. Presence and absence of each species were recorded seasonally. The results indicate seasonal variability in species occurrence, with several diatom species (e.g., *Navicula* , *Nitzschia* and Amphora spp.) showing year-round presence (+), while some others appeared intermittently across different seasons. Cyanobacteria were less diverse but consistently present, with minor seasonal fluctuations (Table 1).

Table 1: Species composition (+ presence / – absence) of diatoms and cyanobacteria in Chabahar Bay in different seasons in 2020-2021.

Species names	Spring	Summer	Autumn	Winter
Bacillariophyta				
Navicula cryptotenella	+	+	+	+
N. cf. *lagunae*	+	+	+	+
N. hamiltonii	+	+	+	+
N. cf. *perminuta*	+	+	+	+
N. ramoissisima	+	+	+	+
N. reichardtiana	+	+	+	+
N. subagnita	+	+	+	+
Navicymbula pusilla	+	+	+	+
Amphora cymbamphora	+	+	+	+
A. abludens	+	+	+	+
A. hamata	+	+	+	+
A. proteus	+	+	+	+
A. coffeaeformis	+	+	+	+
Anomoeoneis sphaerophora	+	+	+	+
Ardissonea sp.	+	+	+	+
Brachysira aponina	+	+	+	+
B. estonarium	+	+	+	+
Campylodiscus sp.	+	+	+	+
Chaetoceros sp.*	+	+	+	+
Cylindrotheca closterium	+	+	+	+
Thalassionema sp.*	+	+	+	+

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Table 1 (continued):

Species names	Spring	Summer	Autumn	Winter
Licmophora gracilis	+	+	+	+
Chammaepinnularia alexandrowiczii	+	+	+	+
Cocconeis costata	+	+	+	+
C. placentula	+	+	+	+
C. scutellum	+	+	+	+
Delphineis australis	+	+	+	+
D. bombus	+	+	+	+
Entomoneis sp.	+	+	+	+
E. adriatica	+	+	+	+
E. gracilis	+	+	+	+
E. ornata	+	+	+	+
E. alata	+	+	+	+
Epithemia sp.	+	+	+	+
E. gibba	+	+	+	+
Fallacia schaeferae	+	+	+	+
Grammatophora angulosa	+	+	+	+
Gyrosigma eximium	+	+	+	+
G. baculum	+	+	+	+
G. balticum	+	+	+	+
G. cali	+	+	+	+
G. coelophilum	+	+	+	+
G. gibbyae	+	+	+	+
G. murphyi	+	+	+	+
G. plagiostomum	+	+	+	+
G. robustum	+	+	+	+
G. scalproides	+	+	+	+
G. variipunctatum	+	+	+	+
G. variistriatum	+	+	+	+
Halamphora coffeaeformis	+	+	+	+
H. acutiuscula	+	+	+	+
H. tenerrima	+	+	+	+
Lyrella sp.	+	+	+	+
Mastogloia acutiuscula	+	+	+	+
M. angulata	+	+	+	+
M. belaensis	+	+	+	+
M. braunii	+	+	+	+
M. crucicula	+	+	+	+
M. lanceolata	+	+	+	+
Nitzschia elegantula	+	+	+	+
N. amphibia	+	+	+	+
N. fontifuga	+	+	+	+

continued):

Species names	**Spring**	**Summer**	**Autumn**	**Winter**
Pseudo-nitzschia cf. *australis**	+	+	+	+
N. inconspicua	+	+	+	+
N. bizertensis	+	+	+	+
Pleurosigma elongatum	+	+	+	+
P. aestuarii	+	+	+	+
P. cuspidatum	+	+	+	+
P. angulatum	+	+	+	+
P. normanii	+	+	+	+
P. strigosum	+	+	+	+
Rhoicosphenia marina	+	+	+	+
Pseudogomphonema plinskii	+	+	+	+
Pseudostaurosira elliptica	+	+	+	+
Seminavis strigosa	+	+	+	+
Tabularia fasciculata	+	+	+	+
T. parva	+	+	+	+
T. tabulata	+	+	+	+
Tryblionella apiculata	+	+	+	+
T. granulata	+	+	+	+
T. pararostrata	+	+	+	+
Cyanobacteria				
Anabaena sp.*	+	+	+	+
Chroococcus sp.*	+	+	+	+
Lyngbya sp.*	+	+	+	+
*Microcystis aeruginosa**	+	+	+	+
*Cylindrospermopsis raciborskii**	+	+	+	+
Nodularia sp.*	+	+	+	+
Trichodesmium sp.*	+	+	+	+

Note: * planktonic species found in the benthic environment of surrounding waters.

Seasonal assessments of species richness, cell abundance, and diversity in Chabahar Bay showed significant variation across the six stations. Spring exhibited the highest biodiversity, with Station 3 recording the greatest species richness (82 species), cell abundance (88 cells/cm²), and high diversity values indicated by the Shannon index (4.38) and the Margalef richness index (18.1). In summer, there was a slight decline in diversity; however, Station 2 still maintained high species richness (82.67 species) and a Margalef index of 17.58. Autumn showed a marked decrease in biodiversity, especially at Station 2, where species richness dropped to 47.33 species and cell abundance to 50 cells/cm², accompanied by lower Shannon and Margalef index values. During winter, biodiversity recovered notably, with Station 1 reaching a species richness of 88.33 species and a cell abundance of 103.33 cells/cm², alongside high diversity indices (Shannon index approximately 4.45 and Simpson index about 0.99). Additionally, Stations 4 and 5 displayed elevated Margalef indices during winter, emphasizing their ecological significance in the colder season (Table 2).

Table 2: Biodiversity indices in Chabahar Bay at sampling stations throughout the seasons in 2020-2021.

Season	Index	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Spring	Number of species	71.33±9.33 a	72±7.55 a	82±1.53 a	72±6.66 a	77.67±3.53 a	72±5.51 a
	Abundance	77.67±9.82 a	77.67±9.61 a	88±3.79 a	74.67±7.51 a	81.67±5.81 a	73.67±5.33 a
	Simpson index	0.98±0.002 a	0.99±0.002 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a
	Shannon-Wiener index	4.22±0.12 a	4.24±0.11 a	4.38±0.01 a	4.26±0.09 a	4.33±0.04 a	4.26±0.08 a
	Margalef index	16.12±1.67 a	16.3±1.29 a	18.1±0.17 a	16.45±1.17 a	17.42±0.52 a	16.5±1.01 a
Summer	Number of species	69.67±10.27 a	82.67±3.18 a	81±0.58 a	73.33±6.69 a	70±6.51 a	76±9.07 a
	Abundance	107±17.16 a	104.33±7.54 a	100.67±3.18 a	84±11.68 a	80.33±12.35 a	101±11.85 a
	Simpson index	0.98±0.002 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a	0.98±0.001 a	0.98±0.002 a
	Shannon-Wiener index	4.17±0.14 a	4.36±0.04 a	4.34±0.001 a	4.25±0.08 a	4.21±0.08 a	4.26±0.13 a
	Margalef index	14.66±1.68 a	17.58±0.42 a	17.35±0.01 a	16.34±1.01 a	15.75±0.94 a	16.22±1.58 a
Autumn	Number of species	62.33±19.88 a	47.33±18.34 a	83±4.73 a	81±2.08 a	81.67±2.4 a	78.67±5.04 a
	Abundance	67±22.05 a	50±18.5 a	90±7.81 a	85.67±2.91 a	84.33±3.67 a	80.67±5.81 a
	Simpson index	0.98±0.01 a	0.97±0.01 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a
	Shannon-Wiener index	3.96±0.42 a	3.7±0.36 a	4.39±0.05 a	4.37±0.02 a	4.39±0.03 a	4.35±0.06 a
	Margalef index	14.35±3.74 a	11.61±3.5 a	18.23±0.7 a	17.97±0.35 a	18.19±0.37 a	17.68±0.86 a
Winter	Number of species	88.67±1.2 a	88±1 a	87±2 a	87.33±1.45 a	86.33±4.18 a	86±1.53 a
	Abundance	103.33±9.06 a	97.33±1.76 a	93±2.65 a	92.67±2.85 a	87.67±4.37 a	89±3.21 a
	Simpson index	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a	0.99±0.001 a
	Shannon-Wiener index	4.45±0.002 a	4.45±0.011 a	4.44±0.022 a	4.45±0.016 a	4.45±0.049 a	4.44±0.012 a
	Margalef index	18.94±0.09 a	19.01±0.17 a	18.97±0.33 a	19.06±0.24 a	19.07±0.73 a	18.94±0.19 a

Note: Different lowercase letters indicate statistically significant differences between stations ($P < 0.05$). Identical letters (e.g., all "a") indicate no significant differences.

The microalgal diversity in Chabahar Bay peaked in winter, with the highest species richness (87.22±0.78 species), the Shannon-Wiener index (4.45±0.01), and the Margalef index values (19±0.12), indicating maximum diversity. Summer recorded the highest abundance (96.22±4.65 cells/cm²),

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while spring and autumn showed lower richness and abundance. The Simpson index remained stable (~0.98) throughout the seasons, with slightly higher values in winter (0.988±0.001). Winter emerged as the most biodiverse season, followed by summer for abundance (Table 3).

Environmental analysis in Chabahar Bay revealed stable surface water temperature (32.18–32.53°C) and salinity (37.18–37.65) across seasons. pH varied, peaking in autumn (7.17±0.11) and being the lowest in summer (6.83 ± 0.11). DO levels were the highest in autumn (9.48±1.28 mg/L) and winter (9.43±0.39 mg/L), with lower values in spring (8.91±0.37 mg/L) and summer (8.75±0.58 mg/L). Nitrite and nitrate concentrations increased seasonally, with nitrates peaking in winter (0.22±0.1 µg/L). Phosphate remained stable (~0.3 µg/L), slightly declining in winter (0.21±0.11 µg/L). Silicate was the highest in autumn (0.48±0.15 µg/L). Generally, autumn and winter showed higher nutrient levels and DO, while temperature and salinity remained consistent (Table 4).

Table 3: Seasonal biodiversity indices in Chabahar Bay in 2020-2021.

Index	Spring	Summer	Autumn	Winter
Taxa	74.5±2.35 b	75.44±2.66 b	72.33±5.07 b	87.22±0.78 a
Individual	78.89±2.77 b	96.22±4.65 a	76.28±5.45 b	93.83±2.04 a
Simpson index	0.985±0.001 ab	0.985±0.001 ab	0.982±0.001 b	0.988±0.001 a
Shannon index	4.28±0.03 b	4.26±0.04 b	4.19±0.1 b	4.45±0.01 a
Margalef index	16.81±0.41 b	16.32±0.45 b	16.34±0.96 b	19±0.12 a

Note: Different lowercase letters indicate statistically significant differences between stations (p<0.05). Identical letters (e.g., all "a") indicate no significant differences.

Table 4: Physicochemical variables throughout seasons in Chabahar Bay in 2020-2021.

Variables	Spring	Summer	Autumn	Winter
Water temperature (°C)	32.38±0.27 a	32.53±0.16 a	32.22±0.09 a	32.18±0.08 a
Salinity	37.6±0.17 a	37.18±0.07 a	37.65±0.17 a	37.4±0.15 a
pH	6.92±0.15 a	6.83±0.11 a	7.17±0.11 a	7±0.13 a
DO (mg/L)	8.91±0.37 a	8.75±0.58 a	9.48±1.28 a	9.43±0.39 a
NO2 (µg/L)	2.51±0.48 a	3.06±0.67 a	3.85±0.47 a	4.17±0.96 a
NO3 (µg/L)	0.06±0.02 a	0.05±0.02 a	0.08±0.05 a	0.22±0.1 a
PO4 (µg/L)	0.31±0.05 a	0.34±0.12 a	0.3±0.12 a	0.21±0.11 a
SiO4 (µg/L)	0.3±0.4 a	0.26±0.09 a	0.48±0.15 a	0.29±0.09 a

Note: Different lowercase letters indicate statistically significant differences between stations ($P < 0.05$). Identical letters (e.g., all "a") indicate no significant differences.

Pearson correlation analysis revealed significant relationships between biodiversity indices and environmental parameters in Chabahar Bay. Species richness showed a negative correlation with the DO levels (r=-0.473, p=0.020), but a positive correlation with nitrate concentrations (r=0.423, p=0.039), suggesting that lower DO and higher nitrate levels may enhance species

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richness. Both the Simpson (r=-0.667, p=0.000) and Shannon (r=-0.589, p=0.002) diversity indices exhibited strong negative correlations with DO, underscoring its critical role in maintaining biodiversity. Similarly, the Margalef index correlated negatively with DO (r=-0.496, p=0.014) and positively with nitrate (r=0.424, p=0.039), further emphasizing DO's importance and nitrate's role in supporting species richness (Table 5).

Table 5: Pearson correlation analysis of biodiversity indices and environmental parameters and nutrient concentrations throughout the seasons of 2020-2021; Temp. – surface water temperature (oC); DO – dissolved oxygen (mg/L).

Pearson correlation		Temp.	Salinity	pH	D	NO_2	NO_3	PO_4	SiO_4
Number of species	Correlation	-0.009	0.103	0.056	-0.473*	-0.063	0.423*	-0.229	-0.114
	Sig. (2-tailed)	0.967	0.631	0.794	0.020	0.770	0.039	0.282	0.597
	N	24	24	24	24	24	24	24	24
Abundance	Correlation	0.061	-0.209	-0.151	-0.315	-0.246	0.250	-0.104	-0.030
	Sig. (2-tailed)	0.776	0.327	0.481	0.133	0.246	0.239	0.630	0.888
	N	24	24	24	24	24	24	24	24
Simpson index	Correlation	-0.135	0.251	0.216	-0.667**	-0.058	0.271	-0.270	-0.181
	Sig. (2-tailed)	0.529	0.236	0.310	0.000	0.789	0.199	0.203	0.397
	N	24	24	24	24	24	24	24	24
Shannon-Wiener index	Correlation	0.047	0.195	0.067	-0.589**	-0.089	0.372	-0.254	-0.129
	Sig. (2-tailed)	0.826	0.361	0.754	0.002	0.681	0.073	0.231	0.548
	N	24	24	24	24	24	24	24	24
Margalef index	Correlation	-0.021	0.196	0.110	-0.496*	-0.012	0.424*	-0.248	-0.129
	Sig. (2-tailed)	0.924	0.358	0.609	0.014	0.956	0.039	0.243	0.549
	N	24	24	24	24	24	24	24	24

Note: * correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed).

Across Chabahar Bay's six sampling stations, Gyrosigma dominated all the seasons, peaking in winter (13.18±0.28 cells/cm2) and remaining stable in spring (12.37±0.46 cells/cm2), summer (12.45±0.19 cells/cm2), and autumn (12.43±0.30 cells/cm2). Navicula followed, with the highest counts in spring (10.83±0.43 cells/cm2) and slight fluctuations in other seasons. Mastogloia maintained a presence (~7.5%), while Nitzschia increased in summer and autumn. Pleurosigma emerged in winter (6.69±0.21 cells/cm2), particularly at Station 4. Station 3 (spring), Station 1 (summer), Station 4 (autumn), and Station 2 (winter) recorded the highest abundances of dominant genera (Table 6). *Gyrosigma* consistently achieved the highest IndVal scores (>0.20)

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throughout all seasons, confirming its role as Chabahar Bay's primary bioindicator due to its frequent occurrence and high abundance. *Navicula* ranked second, with scores between 0.16–0.19 in spring and autumn, suggesting sensitivity to seasonal changes such as temperature or nutrient shifts. In contrast, *Mastogloia*, *Nitzschia*, and Pleurosigma had lower scores (<0.15) (Table 7).

Table 6: Indicator species abundance percentage (%) at sampling stations throughout seasons in Chabahar Bay in 2020-2021.

Season	Genus	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Mean
Spring	*Gyrosigma*	12.88	10.73	13.26	11.16	13.06	13.12	12.37±0.46
	Navicula	9.01	10.30	11.36	11.61	11.84	10.86	10.83±0.43
	Mastogloia	7.73	6.87	8.33	6.70	7.76	6.33	7.29±0.31
	Amphora	5.58	6.01	5.68	7.14	6.12	6.79	6.22±0.25
Summer	*Gyrosigma*	13.08	12.46	11.92	12.30	12.03	12.87	12.45±0.19
	Navicula	8.72	9.58	8.94	8.33	8.30	9.57	8.91±0.23
	Mastogloia	7.48	8.63	7.28	8.33	9.13	7.59	8.07±0.3
	Nitzschia	5.92	7.35	6.95	7.14	5.81	7.26	6.74±0.28
Autumn	*Gyrosigma*	12.44	12.00	12.22	13.62	11.46	12.81	12.43±0.3
	Navicula	10.45	9.33	9.63	10.12	9.88	10.33	9.96±0.17
	Mastogloia	7.96	6.67	6.67	7.78	7.91	7.85	7.47±0.26
	Nitzschia	6.97	6.67	6.67	7.00	7.51	6.20	6.84±0.18
Winter	*Gyrosigma*	13.55	14.38	12.90	12.59	12.55	13.11	13.18±0.28
	Navicula	9.03	9.59	9.68	9.71	10.27	9.36	9.61±0.17
	Mastogloia	6.77	7.88	7.53	7.55	7.22	7.87	7.47±0.17
	Pleurosigma	6.45	6.85	6.81	7.55	6.46	5.99	6.69±0.21

Table 7: IndVal scores for dominant diatom genera at sampling stations in Chabahar Bay by season in 2020-2021.

Season	Genus	IndVal (St-1)	IndVal (St- 2)	IndVal (St-3)	IndVal (St-4)	IndVal (St- 5)	IndVal (St-6)	Mean IndVal
Spring	*Gyrosigma*	0.22	0.18	0.23	0.19	0.22	0.22	0.21
	Navicula	0.15	0.17	0.2	0.2	0.21	0.18	0.19
	Mastogloia	0.13	0.12	0.14	0.11	0.13	0.11	0.12
	Amphora	0.1	0.11	0.1	0.13	0.11	0.12	0.11
Summer	*Gyrosigma*	0.22	0.21	0.2	0.21	0.2	0.22	0.21
	Navicula	0.15	0.16	0.15	0.14	0.14	0.16	0.15
	Mastogloia	0.13	0.15	0.12	0.14	0.16	0.13	0.14
	Nitzschia	0.1	0.13	0.12	0.12	0.1	0.13	0.12
Autumn	*Gyrosigma*	0.21	0.2	0.21	0.23	0.19	0.22	0.21
	Navicula	0.18	0.16	0.17	0.18	0.18	0.18	0.17
	Mastogloia	0.14	0.12	0.12	0.13	0.14	0.14	0.13
	Nitzschia	0.12	0.12	0.12	0.12	0.13	0.11	0.12
Winter	*Gyrosigma*	0.23	0.25	0.22	0.21	0.21	0.22	0.22
	Navicula	0.15	0.16	0.16	0.16	0.17	0.16	0.16
	Mastogloia	0.12	0.13	0.13	0.13	0.12	0.13	0.13
	Pleurosigma	0.11	0.12	0.12	0.13	0.11	0.1	0.11

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Discussion

The findings of this study highlight the intricate relationships between epiphytic microalgae—diatoms and cyanobacteria—and the environmental dynamics in Chabahar Bay. A total of 81 diatom species belonging to 33 genera (30 benthic and 3 planktonic) and 7 cyanobacterial species from 7 genera were identified, reflecting the ecological richness and diversity of the microphytobenthos in this coastal marine ecosystem. Among these, certain species serve as effective bioindicators of environmental health (Biswas *et al*., 2025). For instance,

Navicula and *Mastogloia* are known for their sensitivity to changes in water quality, including nutrient levels and turbidity, making them valuable indicators of ecological conditions in coastal waters (Hasani *et al*., 2025). Seasonal variations in diatom abundance and biodiversity metrics reveal how environmental conditions significantly influence the community dynamics (Smucker *et al*., 2022). The peak biodiversity observed in spring can be attributed to several physicochemical factors, including enhanced light availability, optimal water temperatures and nutrient influx from seasonal runoff (Kudryavtseva *et al*., 2019). These conditions create a favorable environment for the proliferation of diverse diatom taxocoenoses. The high abundance of key genera, such as *Gyrosigma* and *Navicula*, during this period suggests that these species are particularly well-adapted to exploit productive conditions following winter. Their presence not only reflects a thriving ecosystem, but also indicates a stable nutrient balance that supports diverse life forms (Croce *et al*., 2021).

In contrast, the decline in biodiversity during autumn raises important questions about potential stressors affecting the ecosystem. Factors, such as nutrient depletion, increased competition among species, and changes in water chemistry may contribute to this reduction in species richness (Bi *et al*., 2021). The significant drop in the number of species, especially at Station 2, signals the impact of environmental stressors that could lead to shifts in the taxocoenosis structure. For example, a decrease in Amphora species during autumn may indicate declining water quality, as these diatoms are sensitive to changes in nutrient levels and can serve as indicators of eutrophication (Datta *et al*., 2019). The notable recovery in biodiversity during winter emphasizes the adaptability of these microorganisms to fluctuating environmental conditions (Godhe and Rynearson, 2017). Increased nutrient availability, coupled with improved DO levels, likely facilitate the resurgence of diverse diatom communities (Di Costanzo *et al*., 2023). This recovery underscores the inherent resilience of these species, which can rebound when favorable conditions return (Gaiser, 2024). Species, such as *Cylindrotheca closterium* (planktonic-benthic) and *Thalassionema nitzschioides* (planktonic), which thrive under varied nutrient conditions, become more prominent during winter, indicating their role in stabilizing the ecosystem (Ahmad *et al*., 2023; Hamid *et al*., 2023).

The correlations found between biodiversity indices and physicochemical parameters provide valuable insights into the ecological health of Chabahar Bay. The significant negative correlation between species richness and DO levels suggests that hypoxic conditions may threaten biodiversity, particularly in areas where organic decomposition is high (Datta *et al*., 2019). *Gyrosigma*, known for its sensitivity to DO fluctuations, serves as a critical indicator of water quality (Fai *et al*., 2023). Monitoring its abundance can provide early warnings of declining DO levels that could adversely affect aquatic life (Zahir *et al*., 2024). Conversely, the positive correlation with nitrate levels indicates that nutrient enrichment can enhance species richness, but it raises concerns about the impacts of anthropogenic influence on diatom communities (Kafouris *et al*., 2019). While moderate increases in nutrient levels may stimulate growth, excessive nutrient inputs can lead to eutrophication, resulting in harmful algal blooms that disrupt ecological balance (Lan *et al*., 2024). Species, such as Microcystis aeruginosa, although a cyanobacterium, can proliferate under high nutrient conditions, indicating potential ecological shifts that must be managed carefully (Harke *et al*., 2016; Mantzouki *et al*., 2016). The study also emphasizes the significance of specific substrate types in supporting diverse diatom communities. Variations in habitat characteristics between different sampling sites suggest that substrate type influences species composition and abundance (Chen *et al*., 2019).

The Indicator Value analysis of diatom genera can reveal a hierarchical bioindicator framework shaped by species-specific ecological adaptations (Cantonati *et al*., 2024). *Gyrosigma's* consistently high scores (>0.20) during the seasons highlight its strong affinity for the Chabahar Bay's stable physicochemical conditions, such as silicate-rich waters and consistent nutrient availability, confirming its role as a primary bioindicator of baseline ecological health. This pattern aligns with observations that some benthic diatom taxa maintain dominance under stable regimes and resist ecological trivialization over time (Virta *et al*., 2020). In contrast, *Navicula's* moderate scores (0.16–0.19) in spring and autumn suggest that it is particularly responsive to seasonal transitions, such as temperature fluctuations and nutrient pulses — consistent with its classification as a tolerant and opportunistic genus responsive to dynamic conditions (Blanco, 2024). The low IndVal scores (<0.15) of *Mastogloia*, *Nitzschia* and *Pleurosigma* indicate weaker associations with broad environmental conditions, likely due to their niche-specific responses to localized factors, such as organic matter accumulation or microhabitat variability (Taurozzi *et al*., 2024). This differentiation underscores the importance of ecological traits in determining bioindicator potential: *Gyrosigma* reflects environmental

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stability, *Navicula* captures seasonal dynamics, and the other genera serve as indicators of localized or disturbance-driven shifts. By integrating these findings, researchers can develop a comprehensive, trait-informed monitoring framework for Chabahar Bay, enhancing understanding of the ecosystem dynamics and supporting assessments of climate change, pollution and coastal development impacts.

Conclusion

The findings of this study demonstrate that epiphytic diatoms and cyanobacteria play a vital role in reflecting environmental conditions in Chabahar Bay. The IndVal analysis confirms that genera, such as *Gyrosigma*, indicate environmental stability, *Navicula* reflects seasonal transitions, and *Mastogloia*, *Nitzschia* and Pleurosigma serve as indicators of localized disturbances. These results highlight the importance of species-specific ecological traits in assessing ecosystem health. Moreover, the observed correlations between biodiversity and environmental parameters reveal the sensitivity of diatom taxocoenoses to changes in nutrient levels, DO availability and substrate types. Generally, this study supports the development of a trait-based, indicator-driven monitoring framework for coastal ecosystems under environmental stress and emphasizes the need for continued ecological assessment to manage impacts from climate change and human activities.

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