Seasonal Diversity Analysis of Epiphytic Diatom Species Gyrosigma and Pleurosigma in Chabahar Bay

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ABSTRACT

Chabahar Bay, situated on the southeastern coast of Iran, is a unique marine ecosystem distinguished by its rich biodiversity and complex ecological interactions. This study investigates the seasonal dynamics of epiphytic diatoms, specifically the genera Gyrosigma and Pleurosigma, which are integral to primary productivity and nutrient cycling within the bay. Over a one-year period, diatom samples were collected from six strategically selected stations, each representing diverse habitats, including rocky substrates, seagrass beds, and algal mats. A total of 12 species from Gyrosigma and 6 species from Pleurosigma were identified, demonstrating their adaptability and resilience in response to varying environmental conditions. The research highlighted significant seasonal variations in diatom abundance and diversity, with notable species such as Gyrosigma eximium, Gyrosigma baculum, and Pleurosigma elongatum consistently present across all seasons. Statistical analyses, including the calculation of diversity indices (Simpson and Shannon), revealed fluctuating community structures influenced by factors such as water temperature, salinity, and nutrient concentrations (nitrite, nitrate, and phosphate). Principal Component Analysis (PCA) identified temperature, salinity, silicate, dissolved oxygen, and pH as critical parameters shaping diatom distribution and abundance. Moreover, the study underscores the role of epiphytic diatoms as sensitive bioindicators of environmental health, reflecting shifts in water quality and ecosystem changes due to anthropogenic pressures. Understanding the intricate relationships between diatoms and their environment is crucial for developing effective conservation strategies. This research contributes valuable insights into the ecological dynamics of Chabahar Bay and emphasizes the necessity of ongoing monitoring of diatom populations to inform sustainable management practices. By integrating findings from diatom studies with broader environmental assessments, we can enhance our strategies to protect and sustain this vital marine ecosystem against the backdrop of ongoing ecological challenges.

Keywords: **Epiphytic diatoms, Gyrosigma, Pleurosigma, Biodiversity, Environmental factors, Chabahar Bay**

1. *INTRODUCTION*

Chabahar Bay, nestled along the southeastern coast of Iran, is a remarkable marine ecosystem characterized by its unique geographical features and rich biodiversity. This coastal region serves as a crucial habitat for a variety of marine organisms, contributing significantly to the ecological balance and economic activities in the area [1]. The bay's intricate interplay of land and sea creates an environment teeming with life, where various species coexist and interact within a delicate ecosystem [2]. Among the diverse assemblage of life forms, diatoms—especially epiphytic species—emerge as key players in the marine food web, playing an indispensable role in primary productivity and nutrient cycling. Their presence is vital, as they serve not *only as a food source for a range of marine species but also as crucial components in the cycling of nutrients that sustain life in this vibrant ecosystem [3].*

Epiphytic diatoms, such as those belonging to the genera Gyrosigma and Pleurosigma, are particularly noteworthy due to their remarkable ability to thrive on various substrates, including algae and other aquatic plants [4]. This adaptability allows them to occupy a diverse range of ecological niches within the bay. These diatoms are not only essential contributors to phytoplankton communities, which form the base of the marine food web, but also serve as sensitive bioindicators of environmental changes, reflecting shifts in water quality and ecosystem health [5]. Their intricate patterns of seasonal diversity offer valuable insights into the underlying ecological processes and environmental factors that govern their distribution and abundance. By studying these patterns, researchers can uncover critical information about the health of the marine ecosystem and the impacts of external stressors, such as pollution and climate change [6, 7].

The dynamic nature of Chabahar Bay, influenced by various factors such as water temperature, salinity, nutrient availability, and light conditions, creates a complex environment for diatom populations [8]. This variability fosters a unique ecological landscape where diatoms must continually adapt to changing conditions. Understanding the seasonal dynamics of Gyrosigma and Pleurosigma is crucial for elucidating how these factors interact to shape the ecological landscape of the bay. This research endeavors to investigate the patterns of abundance and diversity of these epiphytic diatom species throughout different seasons, examining how varying environmental conditions impact their life cycles and community structures.

2. MATERIALS AND METHODS

The study was conducted in Chabahar Bay, located on the southeastern coast of Iran, a region renowned for its unique marine environment and ecological significance. Six sampling stations were established throughout the bay, each chosen for its diverse habitats, including rocky substrates, seagrass beds, and algal mats (Figure 1). Field sampling occurred seasonally over one year, from summer 2020 to winter 2021, with samples collected during the morning hours to minimize diurnal variation. At each of the six stations, water temperature, salinity, and pH were measured using a multiparameter probe (e.g., YSI ProDSS). Substrates were sampled using a 10 cm diameter corer, and epiphytic diatoms were removed from the surface of the collected substrates using a toothbrush and distilled water.

The collected samples were preserved in a 4% formaldehyde solution for subsequent laboratory analysis. For diatom identification and enumeration, a subsample of the preserved material was acid digested with concentrated nitric acid (HNO_2) to remove organic matter. The diatom frustules were rinsed with distilled water and mounted on glass slides using Naphrax mounting medium. Diatom species were identified using a light microscope (e.g., Olympus CX41) equipped with a camera for photomicrography, based on standard taxonomic keys and literature [9]. A minimum of 400 valves were counted per sample to ensure statistical robustness, with the relative abundance of each species calculated as a percentage of the total diatom count.

Data analysis was performed using statistical software (e.g., R or SPSS), encompassing several analytical approaches. Species richness (S), Shannon-Wiener diversity index (H'), and Simpson's diversity index (D) were calculated to assess the diversity of diatom communities across different seasons. A Principal Component Analysis (PCA) was conducted to explore the relationships between diatom composition and environmental variables (temperature, salinity, and pH), providing insights into how these factors influence diatom distribution and abundance. ANOVA tests were employed to compare the mean abundance of Gyrosigma and Pleurosigma across different seasons, with post-hoc tests (e.g., Tukey's HSD) used to identify significant differences between seasonal means. Additionally, Spearman's rank correlation coefficients were calculated to evaluate the relationships between environmental parameters and diatom abundance. All statistical analyses were conducted at a significance level of $\alpha = 0.05$, with the results interpreted to offer a comprehensive understanding of the seasonal dynamics and ecological roles of Gyrosigma and Pleurosigma in Chabahar Bay.

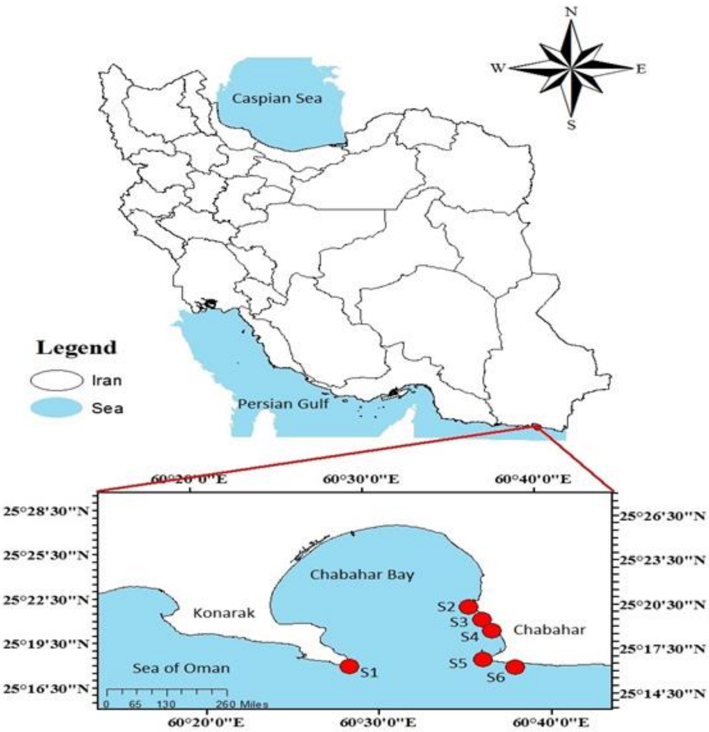

Fig. 1. *Sampling Stations in Chabahar Bay*

3. ***RESULT***

In the seasonal diversity analysis conducted in Chabahar Bay, a total of 12 species from the genus Gyrosigma and 6 species from the genus Pleurosigma were identified. The presence of species such as Gyrosigma eximium, Gyrosigma baculum, and Gyrosigma balticum among others, indicates a consistent presence of the Gyrosigma genus throughout all seasons. Similarly, the Pleurosigma species, including Pleurosigma elongatum and Pleurosigma aestuarii, were also found to be present year-round (Table 1).

Table 1. *Seasonal Diversity of Gyrosigma and Pleurosigma Species in Chabahar Bay*

Species	Spring	Summer	Autumn	Winter
Gyrosigma eximium	+	+	+	+
Gyrosigma baculum	+	+	+	+
Gyrosigma balticum	+	+	+	+
Gyrosigma cali	+	+	+	+
Gyrosigma coelophilum	+	+	+	+
Gyrosigma gibbyae	+	+	+	+
Gyrosigma murphyi	+	+	+	+
Gyrosigma plagiostomum	+	+	+	+

Gyrosigma robustum	+	+	+	+
Gyrosigma scalproides	+	+	+	+
Gyrosigma variipunctatum	+	+	+	+
Gyrosigma variistriatum	+	+	+	+
Pleurosigma elongatum	+	+	+	+
Pleurosigma aestuarii	+	+	+	+
Pleurosigma cuspidatum	+	+	+	+
Pleurosigma angulatum	+	+	+	+
Pleurosigma normanii	+	+	+	+
Pleurosigma strigosum	+	+	+	+

The table presents the concentration of diatom species from the genera Gyrosigma and Pleurosigma at various stations during the spring season, with values reported as mean ± standard error (SE) in cells per unit wet weight. Different species within the Gyrosigma genus exhibit varying concentrations across the stations. For instance, G. eximium shows a consistent concentration of about 1 cell at all stations, while G. baculum has a higher concentration at Station 3 (1.33±0.29), suggesting a stable distribution of this species in the region. Similarly, the Pleurosigma genus demonstrates diversity, with P. elongatum recorded at a concentration of 1 cell at Station 3 and variable concentrations at other stations (Table 2).

***Table 2**. Concentration of Diatom Species (cells per unit wet weight) from Gyrosigma and Pleurosigma Genera across Sampling Stations in spring.*

Species	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Gyrosigma eximium	1±0.5	1±0	1±0	1±0	1.33±0.76	1±0
Gyrosigma baculum	1±0	1±0.5	1.33±0.29	0.67±0.29	1±0	1±0
Gyrosigma balticum	0.67±0.29	1±0	1±0	0.67±0.29	0.67±0.29	0.67±0.29
Gyrosigma cali	0.67±0.29	0.67±0.29	1±0	1±0	1±0	0.67±0.29
Gyrosigma coelophilum	0.67±0.29	1±0	1.33±0.29	0.33±0.29	0.67±0.29	0.67±0.29
Gyrosigma gibbyae	1±0	0.67±0.29	1±0	1±0	1±0	1±0
Gyrosigma murphyi	1±0.5	0.33±0.29	0.67±0.29	0.33±0.29	1±0	0.67±0.29
Gyrosigma plagiostomum	1±0	0.67±0.29	1±0	0.67±0.29	1±0	0.67±0.29
Gyrosigma robustum	0.67±0.29	0.33±0.29	0.67±0.29	0.33±0.29	0.67±0.29	1±0
Gyrosigma scalproides	0.67±0.29	0±0	1±0	0.33±0.29	0.67±0.29	1±0
Gyrosigma variipunctatum	0.67±0.29	1±0	1±0	1±0	1±0	0.67±0.29
Gyrosigma variistriatum	1±0	0.67±0.29	0.67±0.29	1±0	0.67±0.29	0.67±0.29
Pleurosigma elongatum	0.67±0.29	0.67±0.29	1±0	1±0	1±0	0.67±0.29
Pleurosigma aestuarii	0.67±0.29	1±0	1.67±0.29	0.33±0.29	1±0	0.67±0.29
Pleurosigma cuspidatum	1±0	0.67±0.29	0.67±0.29	1±0	1±0	1±0
Pleurosigma angulatum	1±0.5	0.33±0.29	0.67±0.29	0.33±0.29	1±0	0.67±0.29
Pleurosigma normanii	1±0	0.67±0.29	1±0	1±0.5	1±0	1±0
Pleurosigma strigosum	0.67±0.29	0.67±0.58	0.67±0.29	0..33±0.29	0.67±0.29	0.67±0.29

The table presents the concentration of diatom species from the genera Gyrosigma and Pleurosigma across various stations during the summer season, with values reported as mean ± standard error (SE) in cells per unit wet weight. In the summer, the Gyrosigma genus shows notable variations in concentration across the different stations. For example, G. balticum reaches its peak concentration of 2 cells at Station 1, while G. coelophilum exhibits a higher concentration at Station 6 (1.67±0.29). Additionally, G. gibbyae also shows strong presence at Station 1 with 2 cells, indicating a robust population in this area. Other species, such as G. baculum and G. murphyi, maintain relatively stable concentrations, reflecting consistent distribution patterns during this season. The Pleurosigma genus also showcases diversity in its summer concentrations. Species such as P. cuspidatum show a high concentration of 2 cells at Station 1, while P. aestuarii maintains a concentration of 1.67±0.29 at Station 1 (Table 3).

Table 3. *Concentration of Diatom Species (cells per unit wet weight) from Gyrosigma and Pleurosigma Genera across Sampling Stations in summer*

Species	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Gyrosigma eximium	1±0.5	1±0.5	0.67±0.29	0.67±0.29	0.67±0.29	1±0
Gyrosigma baculum	1.33±0.29	1.33±0.29	0.33±0.29	1±0	0.33±0.29	1.33±0.29
Gyrosigma balticum	2±0	0.67±0.29	1.33±0.29	1±0	1±0	0.33±0.29
Gyrosigma cali	1±0.5	1±0.5	0.33±0.29	0.67±0	1.33±0.29	1.33±0.29
Gyrosigma coelophilum	0.67±0.29	1±0	0.67±0.29	0.67±0	0.33±0.29	1.67±0.29
Gyrosigma gibbyae	2±0	1±0.5	1±0	0.67±0	1.33±0.29	0.67±0.29
Gyrosigma murphyi	1±0.5	1.33±0.29	1.33±0.29	0.67±0	0.67±0.29	1.33±0.29
Gyrosigma plagiostomum	0.67±0.29	1±0	1±0	1±0	0.33±0.29	1.33±0.29
Gyrosigma robustum	2±0	1±0	1.33±0.29	1±0	1±0	0.67±0.29
Gyrosigma scalproides	2±0	1.33±0.29	1.67±0.29	1.33±0	1.33±0.58	1±0.5
Gyrosigma variipunctatum	0.67±0.29	1.33±0.29	1±0	0.67±0	1±0	1.33±0.29
Gyrosigma variistriatum	0.67±0.29	1±0	1.33±0.29	1±0	0.33±0.29	1±0.29
Pleurosigma elongatum	0.67±0.29	1±0	1±0.5	1.33±0	0±0	1.33±0.29
Pleurosigma aestuarii	1.67±0.29	1±0	1±0	1±0	1±0	0.67±0.29
Pleurosigma cuspidatum	2±0	1±0	1±0	1.67±0	1±0	0.67±0.29
Pleurosigma angulatum	0.67±0.29	1.67±0.29	1.33±0.29	0.67±0	0.67±0.29	1.33±0.29
Pleurosigma normanii	0.67±0.29	1.33±0.29	0.67±0.29	1±0	0.33±0.29	1.67±0.29
Pleurosigma strigosum	1.67±0.29	1.33±0.29	1±0	1±0	1±0	0.67±0.29

The table provides the concentration of diatom species from the genera Gyrosigma and Pleurosigma across various stations during the autumn season, with values reported as mean ± standard error (SE) in cells per unit wet weight. In autumn, the Gyrosigma genus shows a varied distribution across the stations. For instance, G. eximium displays concentrations ranging from 0.33±0.29 to 1.33±0.29 across the different stations, indicating a moderate presence. G. baculum maintains a relatively stable concentration of around 1 cell at most stations, with a peak of 1.67±0.29 at Station 4. On the other hand, species like G. balticum exhibit lower concentrations, particularly at Stations 2 and 5, where they are found at 0.33±0.29. The Pleurosigma genus also reflects a diverse distribution in autumn. For example, P. elongatum shows a concentration of 1.33±0.29 at Station 3, while P. aestuarii remains consistent across most stations with a concentration of approximately 0.67±0.29. Additionally, P. cuspidatum has a varied concentration, reaching 1 cell at multiple stations (Table 4).

Table 4. *Concentration of Diatom Species (cells per unit wet weight) from Gyrosigma and Pleurosigma Genera across Sampling Stations in autumn*

Species	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Gyrosigma eximium	0.67±0.29	0.33±0.29	1.33±0.29	1.33±0.29	1.33±0.29	1.33±0.29
Gyrosigma baculum	1±0.5	1±0.5	1±0	1.67±0.29	1±0	1±0
Gyrosigma balticum	0.67±0.29	0.33±0.29	0.67±0.29	1±0	0.33±0.29	0.67±0.29

Gyrosigma cali	1±0	0.33±0.29	1.33±0.29	0.67±0.29	1±0	1±0
Gyrosigma coelophilum	0.67±0.29	0.33±0.29	1±0	1±0	0.67±0.29	1±0
Gyrosigma gibbyae	0.67±0.29	0.33±0.29	0.67±0.29	1±0	1±0	0.67±0.29
Gyrosigma murphyi	0.67±0.29	0.67±0.29	0.67±0.29	0.67±0.29	0.67±0.29	0.67±0.29
Gyrosigma plagiostomum	0.67±0.29	0.67±0.29	1±0	1±0	0.67±0.29	1±0
Gyrosigma robustum	0.67±0.29	0.33±0.29	0.67±0.29	0.67±0.29	0.67±0.29	0.67±0.29
Gyrosigma scalproides	0.33±0.29	0.33±0.29	0.67±0.29	1±0	1±0	1±0
Gyrosigma variipunctatum	1±0	1±0	1±0	0.67±0.29	0.67±0.29	0.33±0.29
Gyrosigma variistriatum	0.33±0.29	0.33±0.29	1±0	1±0	0.67±0.29	1±0
Pleurosigma elongatum	0.67±0.29	0.33±0.29	1.33±0.29	1±0	0.67±0.29	1±0
Pleurosigma aestuarii	0.67±0.29	0.67±0.29	0.67±0.29	1±0	0.67±0.29	1±0
Pleurosigma cuspidatum	0.67±0.29	1±0.5	1±0	1±0	0.67±0.29	1±0
Pleurosigma angulatum	0.67±0.29	0.67±0.29	1±0	1±0	1±0	0.67±0.29
Pleurosigma normanii	1±0	0.33±0.29	1±0	0.33±0.29	1±0	0.67±0.29
Pleurosigma strigosum	0.67±0.29	0.67±0.29	0.67±0.29	1.33±0.29	0.67±0.29	1±0

The table outlines the concentration of diatom species from the genera Gyrosigma and Pleurosigma at various stations during the winter season, with values reported as mean ± standard error (SE) in cells per unit wet weight. In winter, the Gyrosigma genus shows a stable presence across the stations. For instance, G. eximium maintains a consistent concentration of 1 cell at all stations, reflecting a strong and uniform distribution. Similarly, G. balticum also exhibits a steady concentration of 1 cell across all locations, indicating its resilience during this season. Other species, such as G. baculum, show slight variations, with concentrations ranging from 0.67±0.29 at Station 4 to 1.67±0.29 at Station 2. The Pleurosigma genus also displays consistent concentrations in winter. For example, P. elongatum and P. cuspidatum both maintain a concentration of 1 cell at most stations. In contrast, P. aestuarii shows a slightly higher concentration of 1.67±0.29 at Station 1, suggesting a robust presence in this area (Table 5).

***Table 5**. Concentration of Diatom Species (cells per unit wet weight) from Gyrosigma and Pleurosigma Genera across Sampling Stations in winter*

Species	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Gyrosigma eximium	1±0	1±0	1±0.5	1±0	1±0	1±0
Gyrosigma baculum	1.33±0.29	1.67±0.29	1±0	0.67±0.29	1±0	1±0
Gyrosigma balticum	1±0	1±0	1±0	1±0	1±0	1±0
Gyrosigma cali	1.67±0.29	1±0	1±0	1±0	0.67±0.29	1±0
Gyrosigma coelophilum	1.33±0.29	1±0	1±0	1±0	1±0	1±0
Gyrosigma gibbyae	1±0	1.67±0.29	1±0.5	1±0	1±0	1±0
Gyrosigma murphyi	1±0	1.33±0.29	1±0	0.67±0.29	1±0	1±0
Gyrosigma plagiostomum	1.33±0.29	1±0	1±0	1.33±0.29	1±0	1±0
Gyrosigma robustum	0.67±0.29	1±0	0.67±0.29	1±0	0.67±0.29	1±0
Gyrosigma scalproides	1.33±0.29	1±0	1±0	1±0	1±0	0.67±0.29
Gyrosigma variipunctatum	1±0	1±0	1.33±0.29	1±0	1±0	1±0
Gyrosigma variistriatum	1.33±0.29	1.33±0.29	1±0	1±0	0.67±0.29	1±0
Pleurosigma elongatum	1±0	1±0	1±0	1±0.5	1±0	1±0
Pleurosigma aestuarii	1.67±0.29	1±0.5	1±0	1±0	1±0	0.67±0.29

The table summarizes various ecological parameters of diatom communities across spring, summer, autumn, and winter at six stations, with each parameter presented as mean ± standard error (SE). In spring, the average number of taxa ranges from 11.67 to 16, peaking at Station 3 with

16±0.58. Total individuals vary from 12.33 to 17.33, again highest at Station 3. The Simpson diversity index indicates high diversity, ranging from 0.9 to 0.93, while the Shannon diversity index values range from 2.36 to 2.75, reflecting a moderately diverse community. The Margalef richness index shows values between 4.22 and 5.27, with Station 3 exhibiting the highest richness. In summer, taxa numbers remain stable, ranging from 12.33 to 16.67, with the highest count at Station 2. Individual counts peak at Station 1, ranging from 13.67 to 21.33. The Simpson diversity index remains high, between 0.91 and 0.93, and the Shannon index values range from 2.48 to 2.76, indicating good diversity. The Margalef index varies from 4.23 to 5.21. Autumn sees a decline in taxa, with averages between 9 and 16, the highest being at Station 4. Individual counts drop to between 9 and 17.33, reflecting reduced populations at certain stations. The Simpson index decreases to between 0.84 and 0.93, while the Shannon values range from 2 to 2.75, indicating variable diversity. The Margalef richness index shows values from 3.4 to 5.26. In winter, the number of taxa increases again, ranging from 16.67 to 17.67, demonstrating stability across stations. Individual counts maintain stability, ranging from 16.67 to 20.67. The Simpson diversity index is consistently high at 0.94 across all stations, and the Shannon index values are steady, ranging from 2.8 to 2.83, indicating stable diversity. The Margalef richness index ranges from 5.42 to 5.65, suggesting a rich community (Table 6).

***Table 6**. Ecological Parameters of Diatom Communities by Season and Station in Chabahar Bay*

Season	Parameter	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Spring	Taxa	14±2 a	11.67±2.96 a	16±0.58 a	12±3.21 a	15.67±1.2 a	14.33±2.33 a
	Individuals	15±1.73 a	12.33±0.03 a	17.33±1.2 a	12.33±3.53 a	16.33±1.86 a	14.33±2.33 a
	Simpson D	0.92±0.01 a	0.9±0.03 a	0.93±0.001 a	0.9±0.04 a	0.93±0.001 a	0.93±0.01 a
	Shannon H	2.6±0.14 a	2.36±0.29 a	2.75±0.03 a	2.41±0.46 a	2.73±0.06 a	2.63±0.17 a
	Margalef	4.79±0.56 a	4.22±0.73 a	5.27±0.14 a	4.34±1.35 a	5.26±0.22 a	4.99±0.58 a
Summer	Taxa	14±2 a	16.67±0.67 a	15.33±0.88 a	15±1.53 a	12.33±0.88 a	15±2.08 a
	Individuals	21.33±2.33 a	20.33±1.2 ab	18±2.31 ab	17±2.52 ab	13.67±1.76 b	19.33±2.6 ab
	Simpson D	0.92±0.01 a	0.93±0.001 a	0.93±0.001 a	0.93±0.01 a	0.91±0.001 a	0.92±0.01 a
	Shannon H	2.57±0.13 a	2.76±0.07 a	2.69±0.04 a	2.67±0.09 a	2.48±0.06 a	2.63±0.15 a
	Margalef	4.23±0.49 a	5.21±0.29 a	4.98±0.1 a	4.95±0.27 a	4.35±0.12 a	4.71±0.51 a
Autumn	Taxa	12.33±4.26 a	9±4 a	15.67±1.45 a	16±0.58 a	14±1.15 a	15.33±0.88 a
	Individuals	12.67±4.37 a	9.67±3.71 a	16.67±2.03 a	17.33±0.67 a	14.33±1.45 a	15.67±1.2 a
	Simpson D	0.87±0.06 a	0.84±0.05 a	0.93±0.001 a	0.93±0.001 a	0.93±0.01 a	0.93±0.001 a
	Shannon H	2.32±0.47 a	2±0.42 a	2.72±0.09 a	2.75±0.04 a	2.63±0.08 a	2.72±0.05 a
	Margalef	4.37±1.13 a	3.4±1.13 a	5.22±0.29 a	5.26±0.14 a	4.88±0.25 a	5.21±0.18 a
Winter	Taxa	17.33±0.67 a	17.67±0.33 a	17±1 a	17±0.58 a	16.67±1.33 a	17±0.58 a
	Individuals	20.67±2.33 a	20.67±0.88 a	18.33±1.2 a	18.67±0.88 a	16.67±2.31 a	17±0.58 a
	Simpson D	0.94±0.001 a	0.94±0.001 a	0.94±0.001 a	0.94±0.001 a	0.94±0.01 a	0.94±0.001 a
	Shannon H	2.81±0.05 a	2.83±0.01 a	2.8±0.06 a	2.8±0.04 a	2.81±0.14 a	2.83±0.03 a
	Margalef	5.42±0.13 a	5.51±0.04 a	5.5±0.23 a	5.47±0.15 a	5.56±0.32 a	5.65±0.14 a

The table presents key ecological parameters of diatom communities across different seasons: spring, summer, autumn, and winter. In terms of taxa, the average counts are relatively consistent, with spring recording 13.94±0.74; summer slightly higher at 14.72±0.59, and autumn showing a slight decline to 13.72±1.09. However, winter sees a significant increase in taxa to 17.11±0.14, indicating a diverse community during this season. For individuals, spring has an average of 14.61±0.84, while summer shows a notable increase to 18.28±1.12, marking it as the season with the highest individual count. Autumn sees a decrease to 14.39±1.17, but winter returns to a high level with 18.67±0.7, reflecting a stable population. The Simpson diversity index remains relatively high across seasons, with values of 0.92±0.01 in both spring and summer, slightly lower in autumn at 0.91±0.02, and peaking in winter at 0.94±0.001. Similarly, the Shannon diversity index shows a pattern of stability, with spring at 2.58±0.07, summer at 2.63±0.04, and autumn at 2.52±0.12, with winter reaching the highest value of 2.81±0.01, suggesting increased diversity. Finally, the Margalef richness index reflects a similar trend, with spring (4.81±0.18), summer (4.74±0.16), and autumn

(4.72±0.3) showing comparable values, while winter stands out with a higher richness index of 5.52±0.03 (Table 7).

Table 7. *Seasonal Variation of Ecological Parameters in Diatom Communities*

Parameter	Spring	Summer	Autumn	Winter
Taxa	13.94±0.74 b	14.72±0.59 b	13.72±1.09 b	17.11±0.14 a
Individuals	14.61±0.84 b	18.28±1.12 a	14.39±1.17 b	18.67±0.7 a
Simpson D	0.92±0.01 ab	0.92±0.01 ab	0.91±0.02 b	0.94±0.001 a
Shannon H	2.58±0.07 b	2.63±0.04 ab	2.52±0.12 b	2.81±0.01 a
Margalef	4.81±0.18 b	4.74±0.16 b	4.72±0.3 b	5.52±0.03 a

The table summarizes key environmental parameters—temperature, salinity, pH, oxygen, and nutrient concentrations (NO2, NO3, PO4, and SiO4)—across different seasons: spring, summer, autumn, and winter. Temperature remains fairly consistent throughout the seasons, with spring averaging 32.38±0.27°C, summer slightly higher at 32.53±0.16°C, and both autumn and winter showing slightly lower averages at 32.22±0.09°C and 32.18±0.08°C, respectively. Salinity values are also stable, with spring recording 37.6±0.17, summer at 37.18±0.07, autumn slightly higher at 37.65±0.17, and winter at 37.4±0.15, indicating a relatively constant saline environment. The pH levels exhibit some variation, starting at 6.92±0.15 in spring, decreasing slightly to 6.83±0.11 in summer, and then rising to 7.17±0.11 in autumn, before settling at 7±0.13 in winter, suggesting a shift towards more neutral conditions in the cooler months. Oxygen levels are highest in autumn at 9.48±1.28, with spring at 8.91±0.37, summer slightly lower at 8.75±0.58, and winter remaining stable at 9.43±0.39, indicating a healthy oxygen presence, particularly in autumn. For nitrite (NO2), concentrations increase progressively from spring (2.51±0.48) to winter (4.17±0.96), reflecting a potential buildup of nitrogen compounds in the colder months. Nitrate (NO3) levels are low across the seasons, with spring at 0.06±0.02 and a slight increase to 0.22±0.1 in winter. Phosphate (PO4) concentrations are relatively stable, with values of 0.31±0.05 in spring, 0.34±0.12 in summer, 0.3±0.12 in autumn, and a decrease to 0.21±0.11 in winter. Finally, silicate (SiO4) shows minor fluctuations, ranging from 0.3±0.4 in spring to 0.26±0.09 in summer, peaking at 0.48±0.15 in autumn, and returning to 0.29±0.09 in winter (Table 8).

Table 8. *Seasonal Variations of Key Environmental Parameters in Chabahar Bay*

Parameter	Spring	Summer	Autumn	Winter
Temperature	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
Oxygen	8.91±0.37 a	8.75±0.58 a	9.48±1.28 a	9.43±0.39 a
NO2	2.51±0.48 a	3.06±0.67 a	3.85±0.47 a	4.17±0.96 a
NO3	0.06±0.02 a	0.05±0.02 a	0.08±0.05 a	0.22±0.1 a
PO4	0.31±0.05 a	0.34±0.12 a	0.3±0.12 a	0.21±0.11 a
SiO4	0.3±0.4 a	0.26±0.09 a	0.48±0.15 a	0.29±0.09 a

Based on the PCA results obtained, in the stations exhibiting the highest abundance and diversity, the most influential environmental parameters were identified as temperature, salinity, silicate, dissolved oxygen, and pH. These factors played a significant role in shaping the ecological dynamics of these stations. Conversely, in the stations that recorded the highest number of taxa, phosphate and nitrite emerged as the most impactful parameters, indicating their critical role in supporting biodiversity. This distinction highlights the varying influences of different environmental *factors on aquatic ecosystems, depending on the specific context of abundance and diversity (Figure 2).*

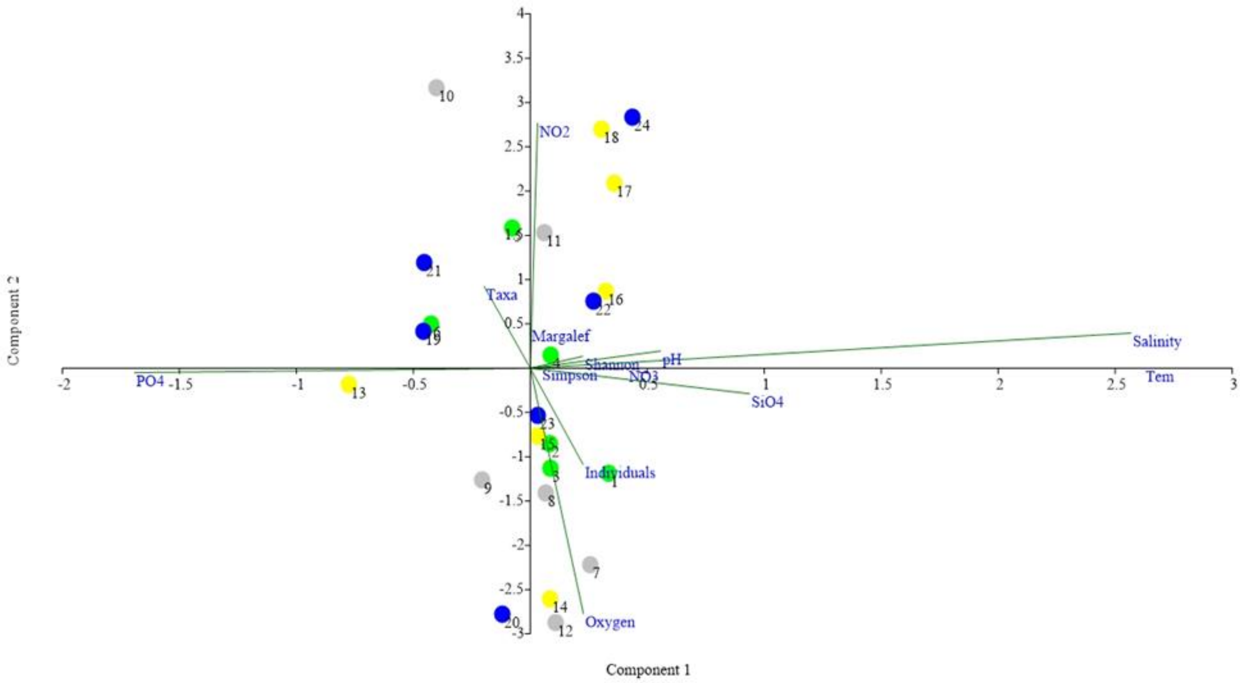

Figure 2. *Influence of Environmental Parameters and nutrients on Diatom Abundance and Diversity in Chabahar Bay: Insights from PCA Results (Spring: Green; Summer: Gray; Autumn: Yellow; Winter: Blue)*

4. DISCUSSION

The study of epiphytic diatoms, particularly the genera Gyrosigma and Pleurosigma, offers significant insights into the ecological dynamics of Chabahar Bay, a complex marine ecosystem characterized by high biodiversity. The identification of 12 species from Gyrosigma and 6 species from Pleurosigma illustrates the intricate biological tapestry that exists within this region. Notably, the consistent presence of key species such as Gyrosigma eximium and Pleurosigma elongatum across all seasons highlights their ecological resilience. This resilience can be attributed to their specialized adaptations that allow them to thrive in the specific environmental conditions found in the Bay [10, 11, 12].

These diatom species play crucial roles in primary productivity, serving as foundational elements in the marine food web [13]. Their ability to convert sunlight into energy not only sustains themselves but also provides a vital food source for various marine organisms [14]. Furthermore, their presence serves as bioindicators of ecological health, reflecting shifts in water quality and habitat integrity. Changes in diatom populations can signal broader ecological changes, making them essential for monitoring the overall health of the marine environment [15].

The spatial distribution patterns of diatom populations underscore the heterogeneity of Chabahar Bay's marine ecosystem. For instance, peak concentrations of Gyrosigma balticum at Station 1 during the summer indicate localized conditions that favor the growth of specific diatom species. This spatial variability is influenced by a range of factors, including substrate characteristics, hydrodynamics, and the dynamics of nutrient inputs [16]. Understanding these localized patterns is vital for elucidating how different habitats contribute to the overall biodiversity and ecological *functioning of the bay, particularly in response to environmental stressors such as pollution and climate change [14, 17].*

Fluctuations in environmental parameters, especially nutrient concentrations, play a significant role in shaping diatom community structures [10, 18]. While temperature and salinity remained relatively stable throughout the study, variations in nutrient levels—particularly phosphates and nitrites—were notable. The observed increase in nitrite concentrations from spring to winter suggests a potential accumulation of nitrogen compounds, which likely stimulates primary productivity and enhances the diversity of diatom assemblages during the colder months. These findings align with existing literature that emphasizes the critical role of nutrient availability in regulating phytoplankton dynamics, further reinforcing the need for effective nutrient management in marine ecosystems [19, 20, 21].

The analysis of diversity indices, including Simpson and Shannon metrics, provides further clarity on seasonal shifts in community composition [22, 23]. The higher diversity indices observed in winter indicate that cooler temperatures may reduce competition among species, allowing for a more varied assemblage to thrive. This seasonal pattern underscores the importance of nutrient dynamics and temperature fluctuations in driving diatom diversity. Consequently, management strategies should prioritize maintaining optimal nutrient conditions to support diverse diatom communities, which are essential for the overall health of the ecosystem (Wu et al., 2024; Ristea et al., 2025)[24, 25].

Principal Component Analysis (PCA) results reveal that environmental parameters such as temperature, salinity, and dissolved oxygen significantly influence diatom distribution patterns. The identification of phosphate and nitrite as key factors supporting biodiversity highlights the need for ongoing monitoring of nutrient inputs into Chabahar Bay. This understanding is critical for developing effective conservation strategies, particularly in mitigating the impacts of anthropogenic activities that may alter nutrient dynamics and adversely affect the health of diatom populations [26, 27, 28, 29].

5. CONCLUSION

In conclusion, the continued study of epiphytic diatoms like Gyrosigma and Pleurosigma is vital for the sustainable management of Chabahar Bay. Their roles as bioindicators provide a valuable framework for monitoring ecological health, allowing researchers and policymakers to identify and respond to environmental changes effectively. Understanding how these diatoms respond to varying environmental conditions enhances our ability to preserve this vital marine ecosystem for future generations. By integrating findings from diatom research with broader environmental assessments, we can develop comprehensive strategies aimed at protecting and promoting the resilience of Chabahar Bay amidst ongoing ecological challenges. This holistic approach will ensure the sustainability of its rich biodiversity and the ecological services it provides, fostering a healthy marine environment for years to come.

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