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SEASONAL DYNAMICS OF INTEGRATED WATER COLUMN PHYTOPLANKTON DIVERSITY IN THE COASTAL WATERS OF JEDDAH, SAUDI ARABIA

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Abstract

The study focused on the vertical distribution of phytoplankton in the coastal waters of Jeddah, examining their interactions with various biotic and abiotic factors. The temperature and salinity pattern, notably reflecting the traditional traits of the Red Sea, showcased higher temperatures in summer and increased salinities during autumn. Nutrient distribution, typically restricted, occasionally surged, notably in central stations. During the summer months, the central stations showed notably higher values of phytoplankton biomass. Diatoms emerged as the dominant group in the total phytoplankton abundance, with centric diatoms prevailing in their distribution. The central zone witnessed a notable diatom proliferation during the summer season. In contrast, dinoflagellates contributed less to the overall densities but exhibited dominance over diatoms in terms of species diversity. Cyanophytes displayed lower dominance both in terms of density and diversity. Examining the species diversity, centric diatom genera, specifically *Chaetoceros* and *Rhizosolenia*, surpassed other diatoms. Similarly, the dinoflagellate genera *Tripos* and *Protoperidinium* dominated over other dinoflagellate genera. The study identified a total of 208 species, providing a comprehensive overview of the phytoplankton diversity in the coastal waters of Jeddah. The current study also noted the presence of harmful algal bloom-inducing diatoms and dinoflagellates, such as *Pseudo-nitzschia delicatissima* and various *Alexandrium* species.

Key words: Phytoplankton; Vertical distribution; Coastal waters; Red Sea; Jeddah

Introduction

Phytoplankton, the microscopic plant-like organisms inhabiting aquatic ecosystems, play a fundamental role in marine environments as primary producers (Reynolds, 2006; Sournia, 1982). Their abundance and distribution significantly influence ecosystem dynamics, nutrient cycling, and ultimately impact higher trophic levels, making them key indicators of the ecological health of coastal waters (Jakhar, 2013; Makarewicz, 1993; Meddeb *et al*., 2018; Shao *et al*., 2019; Tett *et al*., 2008) Monitoring phytoplankton in these areas is essential for understanding the intricate interplay between environmental factors and biological responses. (Garmendia *et al*., 2013; Sathicq *et al*., 2017). The importance of phytoplankton monitoring in coastal waters lies in its ability to provide critical insights into the broader health and functioning of marine ecosystems (Anderson *et al*., 2012; Rombouts *et al*., 2013). Changes in phytoplankton abundance and composition can reflect alterations in nutrient availability, water quality, and climate conditions (Paerl *et al*., 2007, 2010). Moreover, phytoplankton serves as the base of the marine food web, influencing the abundance and distribution of zooplankton and ultimately affecting fish populations and fisheries productivity (Cury *et al*., 2003). Effective phytoplankton monitoring programs contribute to our understanding of the impacts of anthropogenic activities, such as coastal development and climate change, on marine ecosystems (Crain *et al*., 2009; McQuatters-Gollop *et al*., 2009). Coastal zones are particularly vulnerable to environmental stressors due to their proximity to human activities and terrestrial influences (D'Angelo *et al*., 2014; Zhang *et al*., 2010). Monitoring phytoplankton dynamics help assess the resilience of coastal ecosystems and facilitates the development of informed management strategies for sustainable marine resource utilization (Tam *et al*., 2017). Several studies underscore the importance of phytoplankton monitoring for ecosystem management. For instance, Behrenfeld *et al*., (2006) demonstrated the critical role of phytoplankton in global carbon cycling, emphasizing the need for accurate monitoring to comprehend carbon fluxes in marine environments. Additionally, the work of Hallegraeff (2014) highlighted the ecological consequences of harmful algal blooms, further emphasizing the importance of continuous phytoplankton surveillance. In recent years, urban coastal areas have witnessed notable shifts in phytoplankton abundance and dynamics, which have significant ecological and socio-economic implications. Several factors are driving these changes. Urbanization often leads to increased nutrient inputs into coastal waters, primarily from wastewater discharge, agricultural runoff, and industrial activities. Elevated levels of nutrients such as nitrogen and phosphorus can stimulate phytoplankton growth, leading to algal blooms and shifts in species composition (Davidson *et al*., 2014; Heil & Muni-Morgan, 2021).

The Red Sea, located between north-eastern Africa and the Arabian Peninsula, stands as a unique and biologically diverse marine environment, characterized by its high salinity, elevated temperatures, and vibrant coral reefs (Morcos, 1970; Sofianos *et al*., 2002). One of the key components shaping the ecological dynamics in the Red Sea is phytoplankton (Halim, 1984). These microscopic,

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photosynthetic organisms play a fundamental role in the marine food web and contribute significantly to the region's overall ecosystem health (Devassy *et al*., 2017; Kurten *et al*., 2015). The Red Sea's phytoplankton community adapts to extreme environmental conditions, showcasing remarkable resilience to elevated temperatures and salinity levels (Sommer, 2000; Qurban *et al*., 2014). The diverse assemblage of phytoplankton species in the Red Sea contributes to the overall productivity and sustenance of marine life, serving as a primary food source for various organisms, including zooplankton and coral reef inhabitants (Kurten *et al*., 2015). The Red Sea's phytoplankton communities exhibit seasonal variations influenced by factors such as temperature, nutrient availability, and the Red Sea's unique hydrodynamics (Devassy *et al*., 2017; Kurten *et al*., 2015; Pearman *et al*., 2016). Understanding the dynamics of phytoplankton in the Red Sea are crucial for unravelling the intricacies of its marine ecosystems, from supporting commercially important fish stocks to sustaining the biodiversity of coral reefs (Alsaaq, 2023; Racault *et al*., 2015). Long recognized as one of the most oligotrophic systems globally (Klinker *et al*., 1978; Reiss and Hottinger, 1984), the Red Sea has traditionally been characterized by lower phytoplankton biomasses and abundances. However, this longstanding characteristic is undergoing a noteworthy shift, as recent studies reveal a substantial challenge to the coastal ecosystems specifically (Pena-Garcia *et al*.,2014), there has been a sudden and significant proliferation, leading to higher dominance of phytoplankton (Al-Amri *et al*., 2020; Devassy *et al*., 2017; El-Sherbiny *et al*., 2021). This shift is not without consequences, as these increased phytoplankton levels have, at times, escalated to the point of forming harmful algal blooms (Al-Aidaroos *et al*., 2019; Banguera-Hinestroza *et al*., 2016). The once stable and low phytoplankton abundance in the Red Sea is now witnessing a dynamic transformation, emphasizing the need for a comprehensive understanding of the factors driving these changes and the potential ecological impacts on this unique marine environment. While there are limited studies (Al-Amri *et al*., 2020; El-Sherbiny *et al*., 2021; Touliabah *et al*., 2010) addressing horizontal phytoplankton dynamics in the coastal waters of Jeddah, the present study represents a pioneering effort. This research primarily concentrates on the vertical phytoplankton diversity within the coastal waters of the rapidly expanding metropolitan city of Jeddah, marking a unique contribution in its focus and approach. The vertical distribution of phytoplankton in marine systems plays a crucial role in nutrient transport and primary production, influencing ecosystem dynamics. Phytoplankton residing at different depths utilize nutrients variably, contributing to nutrient cycling and energy transfer within the marine food web (Falkowski *et al*., 1998). Additionally, vertical stratification of phytoplankton communities facilitates efficient light harvesting, maximizing photosynthetic activity and primary production rates in the euphotic zone (Behrenfeld *et al*., 2006).

The principal aim of this research on phytoplankton vertical distribution in the coastal waters of Jeddah, Saudi Arabia, is to investigate the intricate patterns and variations in phytoplankton abundance and composition across different depths in relation to different biotic and abiotic parameters. By employing systematic sampling techniques, the study aims to delineate the vertical stratification of phytoplankton communities in relation to key environmental factors. The aim is to deepen our comprehension of the responses exhibited by phytoplankton to depth-specific conditions, evolving coastal geographies, escalating anthropogenic influences, and the consequent eutrophication. This endeavour seeks to illuminate the ecological roles and dynamics of phytoplankton within the distinctive marine environment of the Red Sea. This research endeavours to contribute valuable insights that can inform effective coastal management strategies and further our comprehension of the ecological processes shaping phytoplankton distribution in this region. Continuous monitoring is crucial for a coastal city like Jeddah, where daily anthropogenic influences are increasing. Such monitoring is essential to mitigate the risk of catastrophic blooming events, which can cause severe damage to both human well-being and the coastal economy.

Materials and Methods

Study sites: During the period spanning 2021 to 2022, the current research focused on six strategically selected stations along the coast of Jeddah, a rapidly expanding metropolitan city, situated in the central Red Sea region (Fig. 1). These stations were purposefully chosen to encompass the northern, central, and southern regions of the coastline. The northern sector is characterized by a pristine environment; the central region features a sewage disposal site and a desalination plant, while the southern zone is marked by a bustling international port and a larger sewage disposal area. To gain a comprehensive understanding of phytoplankton vertical distribution, our study spanned four distinct seasons starting with winter (January), spring (April), summer (July) and autumn (October).

Collection and analysis: Subsurface water salinity and temperature were systematically gauged at each site employing an environmental parameter monitoring device, specifically the Horiba U50. To assess chlorophyll *a* and nutrient levels, subsurface water samples were obtained using Hydrobios Niskin bottles. Notably, 10 litres were collected in meticulously pre-cleaned carboys for chlorophyll analysis, while 500 ml were carefully collected in new Nalgene bottles for nutrient assessments. Maintaining the integrity of the samples, all collected materials were swiftly transferred to cool boxes equipped with ice and shielded from direct sunlight thereby ensuring the preservation of sample quality during transportation to the shoreline laboratory for subsequent analysis. Phytoplankton samples were systematically acquired from a depth spanning 20 meters to the water's surface using a Hydrobios vertical phytoplankton net with a mesh size of 10 microns. The collection depth and mesh size of the net remained consistent throughout the sampling period. These samples were carefully collected in amber-colored glass bottles and promptly treated with Lugol’s iodine (5%) and a few drops of concentrated formaldehyde (36%) for preservation (Kurten *et al*., 2015). Upon arrival at the shoreline laboratory, 3-liter seawater samples underwent filtration through Whatman GF/F filter paper with a pore size of 0.7 microns for subsequent chlorophyll analysis. This filtration process was duplicated, and both filter papers were then securely stored in a -20°C freezer until analysis. The chlorophyll analysis followed the established protocol outlined by Parson *et al*., (1984) and was conducted using a spectrophotometer. For nutrient analysis, the initial step involved filtering the samples through a 0.2-micron membrane filter. Subsequent analysis followed the procedures outlined by Strickland & Parsons (1972). The analysis of phytoplankton samples involved the utilization of a Leica DMI 3000 microscope following the protocols mentioned by LeGresley & McDermott (2010) and taxonomic nomenclature was assigned following the guidelines outlined by Taylor (1976) and Tomas (1997). Following the thorough homogenization of the phytoplankton samples, one milliliter was transferred to the Sedgwick after using a transfer pipette. The sample was then allowed to settle in the counting chamber for a specified period before enumeration and identification. Random rows (4 rows, consisting of 200 squares each with dimensions of 50 mm × 20 mm × 1 mm) were examined for the presence of specific symbiotic associations. Triplicate counts were conducted for each sample, and the total abundances (individual m^{-3}) were determined using standard equations. All identified species further were verified with the World Register of Marine Species (WORMS) at www.marinespecies.org to ensure the adoption of the latest available nomenclature for each taxon. The entire graphical representations essential for this study were generated using ORIGIN 10.0 software. The statistical analyses, crucial for deriving meaningful insights from the data, involved the use of both SPSS 21 and PAST 3.0 software tools. Major analyses focused on exploring the relationship between the datasets, employing Pearson correlation and one-way analysis of variance.

Results

Temperature and salinity: The spatial distribution of temperature across various stations exhibited minimal variation during each season. However, significant temporal disparities were observed among different seasons (F= 1912, p<0.05) (Table 1). The winter season registered the lowest recorded temperatures, with an average of 26.6±0.11°C across the entire study area. On the other hand, the summer season documented the highest temperatures, averaging 31.8±0.07°C (Fig. 2a). Uniform salinity characterized the entire study region, with slight variations evident both spatially and temporally. During the winter season, the recorded average salinity reached its lowest point at 39.1± 0.04 PSU (Practical Salinity Unit), while the autumn season displayed the highest salinity levels at 39.3± 0.003 PSU, as illustrated in (Fig. 2b).

Inorganic nutrients

Nitrates (NO_3-): Across the study region, nitrate levels displayed a relatively consistent pattern, indicating a degree of uniformity. Notably, the lowest average nitrate concentration was observed during the summer season, with a value of 0.19±0.13 µmol L^{-1}. In contrast, the winter season recorded the highest average nitrate concentration, reaching 0.40±0.21 µmol L^{-1} (Fig. 3A)· The results of the ANOVA revealed a statistically significant variation among the sampling stations (F= 6.864, p<0.05) (Table 1).

Table 1. The One-way ANOVA of different parameters obtained during the study period.

Parameters		Sum of squares	ANOVA	Mean square	F	P
			df			
Temperature	Between seasons	111.391	3	37.13	1912	0
	Between stations	0.237	5	0.05	0.008	1
Salinity	Between seasons	0.168	3	0.06	37.407	0
	Between stations	0.013	5	0.00	0.259	0.929
Nitrate	Between seasons	0.141	3	0.05	1.179	0.343
	Between stations	0.617	5	0.12	6.864	0.001
Nitrite	Between seasons	0.045	3	0.02	1.702	0.199
	Between stations	0.129	5	0.03	4.959	0.005
Ammonia	Between seasons	0.517	3	0.17	4.732	0.012
	Between stations	0.267	5	0.05	0.981	0.456
Phosphate	Between seasons	0.016	3	0.01	2.091	0.134
	Between stations	0.021	5	0.00	1.616	0.206
Silicate	Between seasons	0.594	3	0.20	1.457	0.256
	Between stations	1.764	5	0.35	4.107	0.012
Chlorophyll	Between seasons	0.627	3	0.21	4.984	0.01
	Between stations	0.382	5	0.08	1.268	0.32
Total density	Between seasons	72780000	3	24260000.00	3.66	0.03
	Between stations	38060000	5	7611673.91	0.819	0.552
Centrales density	Between seasons	61770000	3	20590000.00	2.941	0.058
	Between stations	38990000	5	7798933.86	0.862	0.525
Pennate density	Between seasons	17131.09	3	5710.36	1.733	0.192
	Between stations	15000.91	5	3000.18	0.794	0.568
Dinoflagellate density	Between seasons	399691.6	3	133230.54	11.384	0
	Between stations	83012.89	5	16602.58	0.543	0.742
Cyanophyte density	Between seasons	18899.88	3	6299.96	2.036	0.141
	Between stations	12695.82	5	2539.16	0.671	0.65

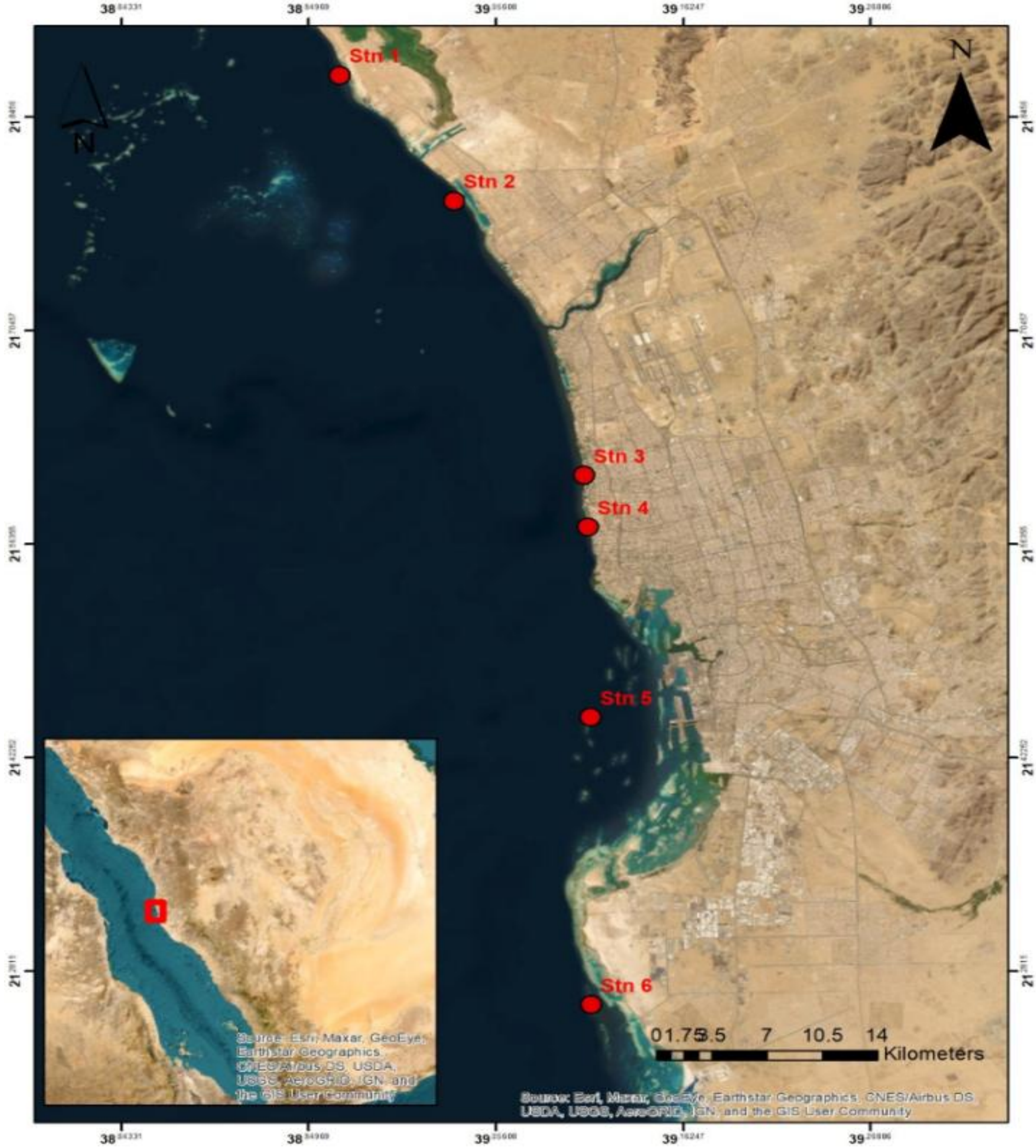

Fig. 1. Map showing various study stations in the coastal waters of Jeddah.

Nitrites (NO_2^-): Nitrites also exhibited minimal temporal differences with subtle spatial variations. During the summer season, there was a noteworthy occurrence of the lowest average nitrite values, measuring 0.05±0.01 µmol L^{-1} across the various stations. In contrast, the autumn season registered the highest average nitrite values, amounting to 0.17±0.14 µmol L^{-1}. (Fig. 3B) Notably, this increase in nitrite levels during autumn was accompanied by considerable spatial variation ($F = 4.95$, $p < 0.05$) (Table 1).

Ammonia (NH_3): In contrast to the other two nitrogen derivatives, ammonia exhibited notable temporal variations in the current study ($F = 4.73$, $p < 0.05$) (Table 1). The levels of ammonia displayed distinct fluctuations across different seasons. Specifically, the lowest average values for this inorganic nutrient were recorded during the summer season, with a concentration of 0.36±0.13 µmol L^{-1}. Conversely, the winter season presented the highest average ammonia values, reaching 0.71±0.27 µmol L^{-1} (Fig. 3c).

Phosphates (PO_4^{3-}): Phosphate ions, in the current study, exhibited a consistent lack of both temporal and spatial variations. Throughout the study period, their concentrations remained relatively stable, showing no discernible spatial or temporal trends. The observed phosphate levels consistently maintained lower values across the entirety of the study. The winter and spring seasons stood out for accounting for the lowest average phosphate values, measured at 0.13±0.03 µmol L^{-1} and 0.13±0.04 µmol L^{-1}, respectively. In contrast, the summer season recorded the highest average phosphate values, reaching 0.19±0.05 µmol L^{-1} (Fig. 3d).

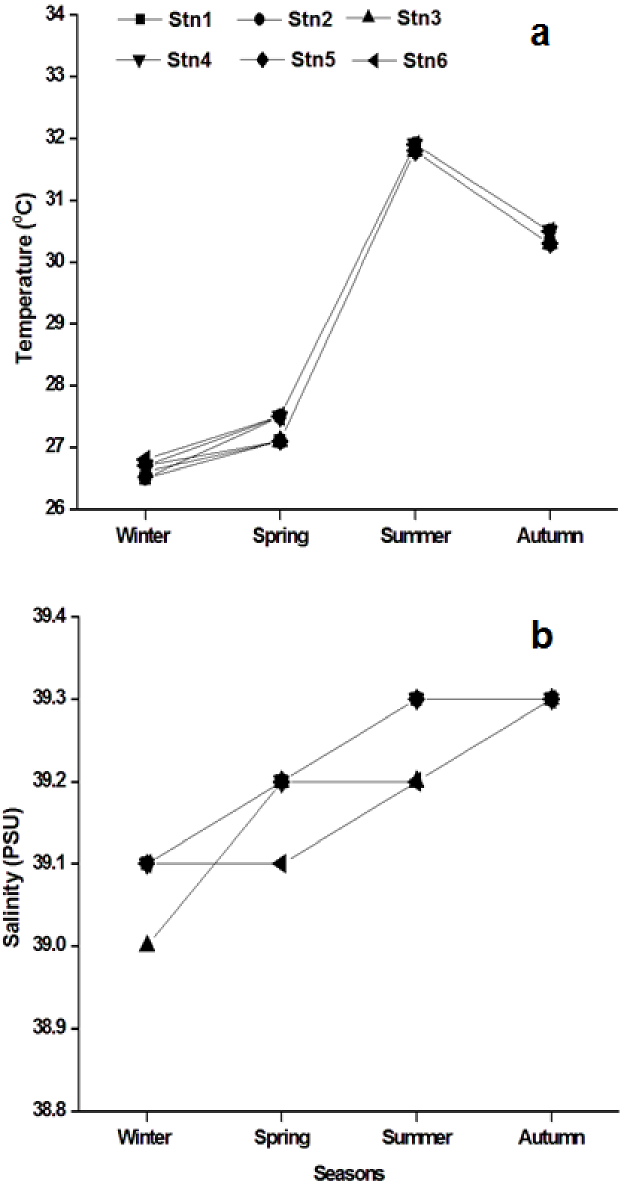

Fig. 2. The temperature (a) and salinity (b) obtained from the study stations during various seasons.

Silicates $(SiO_4)^{4-}$: The concentration of silicate in the current study showed significant variation among the sampled stations, as revealed by the results of the one-way ANOVA (F= 4.10, $p<0.05$) (Table 1). However, when assessed on a seasonal scale, silicate concentrations did not show any significant variations. On average, the lowest silicate values, measuring 1.55±0.49 µmol L^{-1}, were recorded during the winter period. Interestingly, the highest silicate value recorded throughout the entire study, reaching 2.38 µmol L^{-1}, was obtained from station 3 during the same winter period. Examining the seasonal averages, the highest station average values (1.94±0.33 µmol L^{-1}) occurred during the summer season of the study (Fig. 3e).

Phytoplankton biomass (Chlorophyll a): The phytoplankton biomass, quantified in terms of chlorophyll *a*, exhibited significant variations across different study seasons, as evidenced by results of the one-way ANOVA (F= 4.84, $p<0.05$) (Table 1). Notably, the average chlorophyll values during the summer season reached the highest level at 0.63±0.32 µg m^{-3}, representing the peak chlorophyll concentration for the entire study period in comparison to the other seasons. In contrast, the lowest chlorophyll values (0.21±0.12 µg m^{-3}) were observed during the spring phase of the study (Fig. 4). Specifically focusing on the summer season, the central stations, namely Station 3 and Station 4, recorded significantly higher chlorophyll values. Station 3 exhibited a chlorophyll concentration of 0.95 µg m^{-3}, while Station 4 recorded 0.92 µg m^{-3} during this period (Fig. 4).

Phytoplankton density

Total density: The study revealed a noteworthy variability in total phytoplankton density in the water column among different seasons, as indicated by a significant F-value of 3.66 ($p<0.05$) (Table 1). Notably, the summer season emerged with substantially higher phytoplankton densities compared to the other seasons. The average total density during the summer season reached 4287±5116 No × 10^3 cells m^{-3}. This elevated density was primarily attributed to the central study station 3, contributing a notable 14503.25 No × 10^3 cells m^{-3}.In contrast, the phytoplankton densities during the other seasons were considerably lower. Spring exhibited the lowest density, reporting 118.36±106 No × 10^3 cells m^{-3}. Following closely, the autumn season showed a density of 176±82 No × 10^3 cells m^{-3} (Fig. 5a).

Centric diatom density: The prevalence of centric diatoms was conspicuous within the overall phytoplankton density. The elevated total densities observed during the summer season were predominantly attributed to the robust proliferation of centric diatoms. Specifically, centric diatoms contributed a substantial 14444.81 No × 10^3 cells m^{-3}, constituting nearly 99.6% of the total phytoplankton density (14503.25 No × 10^3 cells m^{-3}) recorded at station 3 during summer (Fig. 5b). An examination of seasonal dynamics revealed that centric diatoms played a more prominent role during the winter (contributing 62-79%) and summer (contributing 57-99%) seasons compared to the other two seasons (F= 2.94, $p<0.05$) (Table 1). On average, the highest densities of centric diatoms, reaching 3852±5274 No × 10^3 cells m^{-3}, were recorded during the summer season. In contrast, the lowest densities, measuring 21.4±5.37 No × 10^3 cells m^{-3}, were observed during the autumn season (Fig. 5b).

Pennate diatom density: During the study period, pennate diatoms showed a less dominant presence, contributing between 1% to 37% across different seasons. Notably, they were entirely absent from certain stations, particularly during the summer seasons (Fig. 5c). Contrasting with centric diatoms, pennate diatoms did not show pronounced fluctuations across seasons or locations. The lowest average density, amounting to 8.54±9.86 No × 10^3 cells m^{-3}, was recorded during the summer season. In contrast, the highest density, reaching 78.31±109.52 No × 10^3 cells m^{-3}, was reported during the autumn season (Fig. 5c).

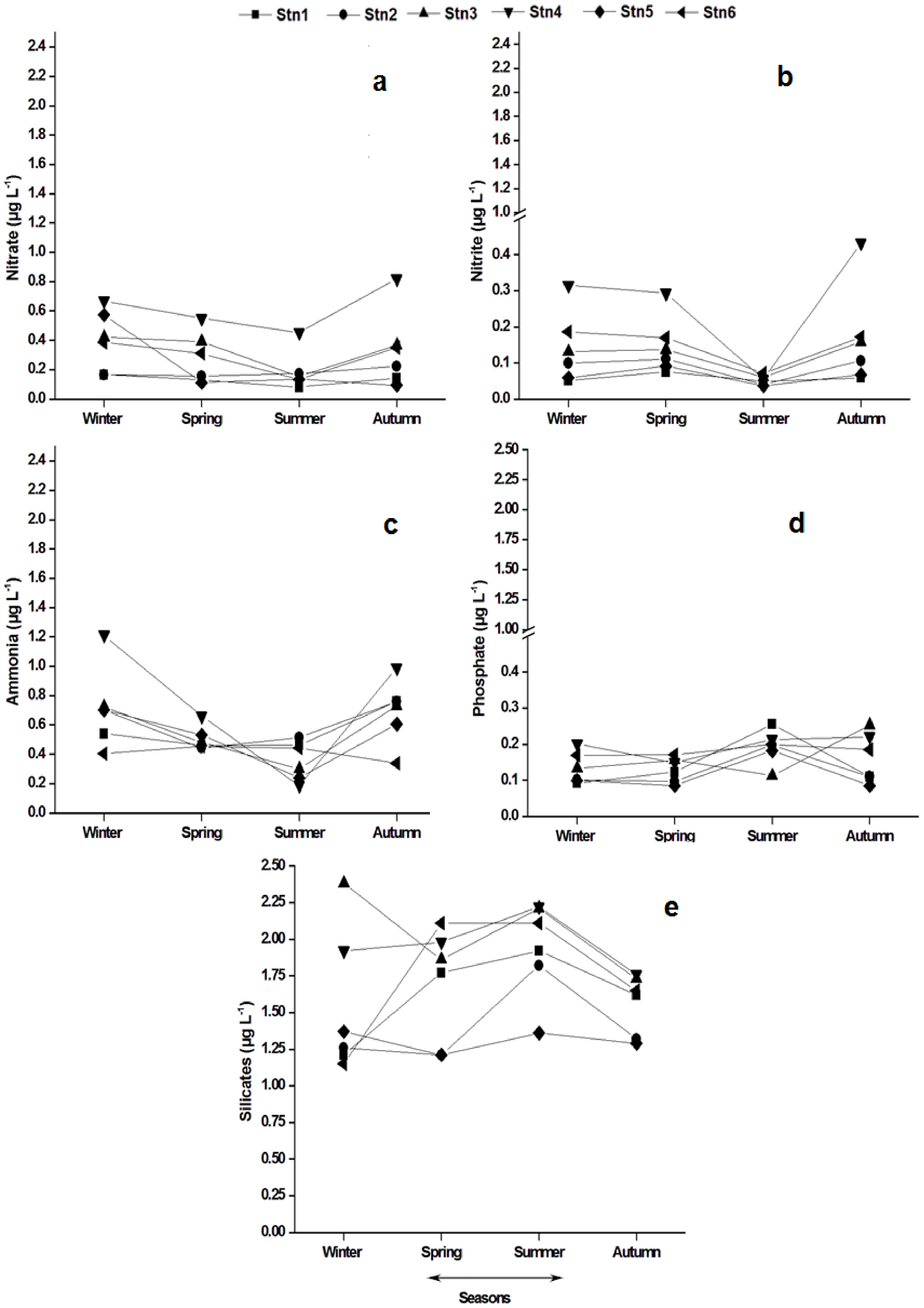

Fig. 3. Seasonal variability of inorganic nutrients obtained from the different study stations. Nitrates (a), Nitrites (b), Ammonia(c), Phosphates (d) and Silicates (e).

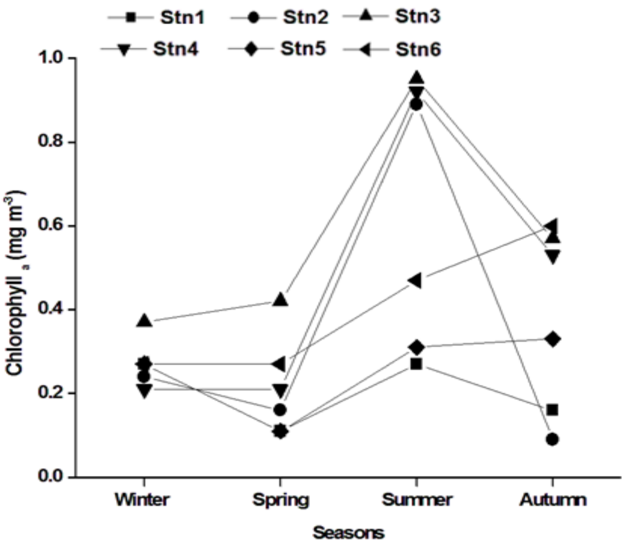

Fig. 4. Seasonal variability of phytoplankton biomass (Chlorophyll $_a$) obtained from various stations.

Dinoflagellate density: Dinoflagellates also exhibited lower abundances throughout the study, with their contributions ranging from the lowest of 6% at station 2 during winter to the highest of 54% at station 3 during summer. This variation among different seasons was statistically significant (F= 11.384, p<0.05) (Table 1), indicating a dynamic pattern in dinoflagellate abundance. Notably, during the autumn and spring seasons, dinoflagellates were more prominent compared to the other two seasons (Fig. 5d). The highest average density of dinoflagellates, reaching 354.28 ± 207.27 No × 10^3 cells m^{-3}, was reported during the summer season. In contrast, the lowest average density, measuring 38.56±25.66 No × 10^3 cells m^{-3}, was observed during the spring season (Fig. 5d).

Cyanophyte density: Cyanophytes emerged as the least dominant phytoplankton group in the current study, without any discernible seasonal or spatial variations. Except for a notable 65% contribution observed at station 2 during the autumn season, contributions from cyanophytes were generally negligible across other seasons and stations. The average density of cyanophytes during winter was the lowest, reported at 4.88 ± 5.96 No × 10^3 cells m^{-3}, indicating a minimal presence during this season. In contrast, the highest average density, reaching 72.21 ± 83.28 No × 10^3 cells m^{-3}, was reported during the summer season (Fig. 5e).

Phytoplankton diversity and species composition: Like the observed variations in abundances, the vertical phytoplankton diversity also exhibited seasonal fluctuations (F= 100.6, p<0.05). The study identified a total of 208 distinct phytoplankton species across various phytoplankton groups. Notably, the autumn season stood out with the highest species count, contributing 132 species to the overall diversity (Appendix 1). Throughout the study period, dinoflagellates emerged as the predominant group with 108 species, slightly outnumbering diatoms, which accounted for 99 species. Cyanophytes were less diverse, represented by only one species (Fig. 6a). Further classification within diatoms revealed that centric diatoms outnumbered pennate diatoms, with 66 and 33 species, respectively. Examining the temporal distribution, centric diatoms exhibited a consistent presence across all seasons, with a notable abundance during winter (43 species) and spring (38 species) (Fig. 6b). In contrast, pennate diatoms, though in lower numbers overall, displayed a uniform distribution, except for a decline in the summer season where only 2 species were observed. The dynamics of dinoflagellates showcased a seasonal pattern, with higher numbers observed during summer (67 species) and autumn (83 species) compared to winter and spring.

In the current study, among the diverse centric diatom genera identified, the genus *Chaetoceros* emerged as the dominant contributor to the overall distribution. Among the various centric diatom genera identified in the current study, the genus *Chaetoceros* emerged as the dominant player, significantly contributing to the overall distribution. A total of 23 different species falling under the genus *Chaetoceros* were recorded, underscoring its prevalence and diversity in the studied environment (Appendix 1). Following closely, the genus *Rhizosolenia* secured the second position in terms of abundance among centric diatoms, with a total of 10 species (Appendix 1). Additionally, other common genera such as *Guinardia* and *Hemiaulus* also made their presence known, each with four species. Within the realm of pennate diatoms, the genera *Pseudo-nitzschia* has asserted dominance, emerging as the primary contributor with a total of 7 distinct species identified in the current study. Following *Pseudo-nitzschia*, the genera *Pleurosigma* is notable for its contribution to pennate diatom diversity, with a total of 4 identified species. During our investigation, the prevalence of dinoflagellates was notably characterized by the substantial dominance of the *Tripos* genus, which boasted a remarkable diversity consisting of 37 distinct species (Appendix 1). Following closely behind, the genus *Protoperidinium* emerged as the second most influential contributor to dinoflagellate diversity, encompassing a noteworthy collection of 20 identified species. Additionally, our study revealed the significant presence of *Dinophysis*, which contributed to the dinoflagellate spectrum with 10 distinct species. Furthermore, the genera *Phalacroma* and *Prorocentrum* demonstrated their noteworthy contributions, each harboring 6 species. Throughout the entirety of our study, the representation of blue-green algae, also known as Cyanophyceae, was characterized by a singular species *Trichodesmium erythraeum*. The ascendancy of centric diatoms during the summer period in the overall vertical phytoplankton density was primarily attributed to the prolific growth of *Proboscia alata* (Brightwell) Sundström, 1986. This diatom species played a significant role in bolstering the overall abundance observed during this season.

In the current study, an examination of the Pearson's correlation coefficient was conducted to elucidate relationships between various biotic and abiotic parameters (Chlorophyll *a* and phytoplankton densities against Salinity, Temperature and various inorganic nutrients). The findings, presented in Table 2, revealed noteworthy associations among these factors. Specifically, chlorophyll levels displayed a highly positive correlation with temperature (r= 0.59, p<0.01), and exhibited significant positive relationships with phosphates (r= 0.48, p<0.05) and silicates (r= 0.51, p<0.05) (refer to Table 2). Moreover, a significant positive correlation was identified between the abundances of dinoflagellates and both temperature (r= 0.64, p<0.01) and salinity (r= 0.42, p<0.05) (Table 2). Conversely, pennate diatoms displayed a negative correlation with salinity (r= -0.47, p<0.05) and with phosphates (Table 2).

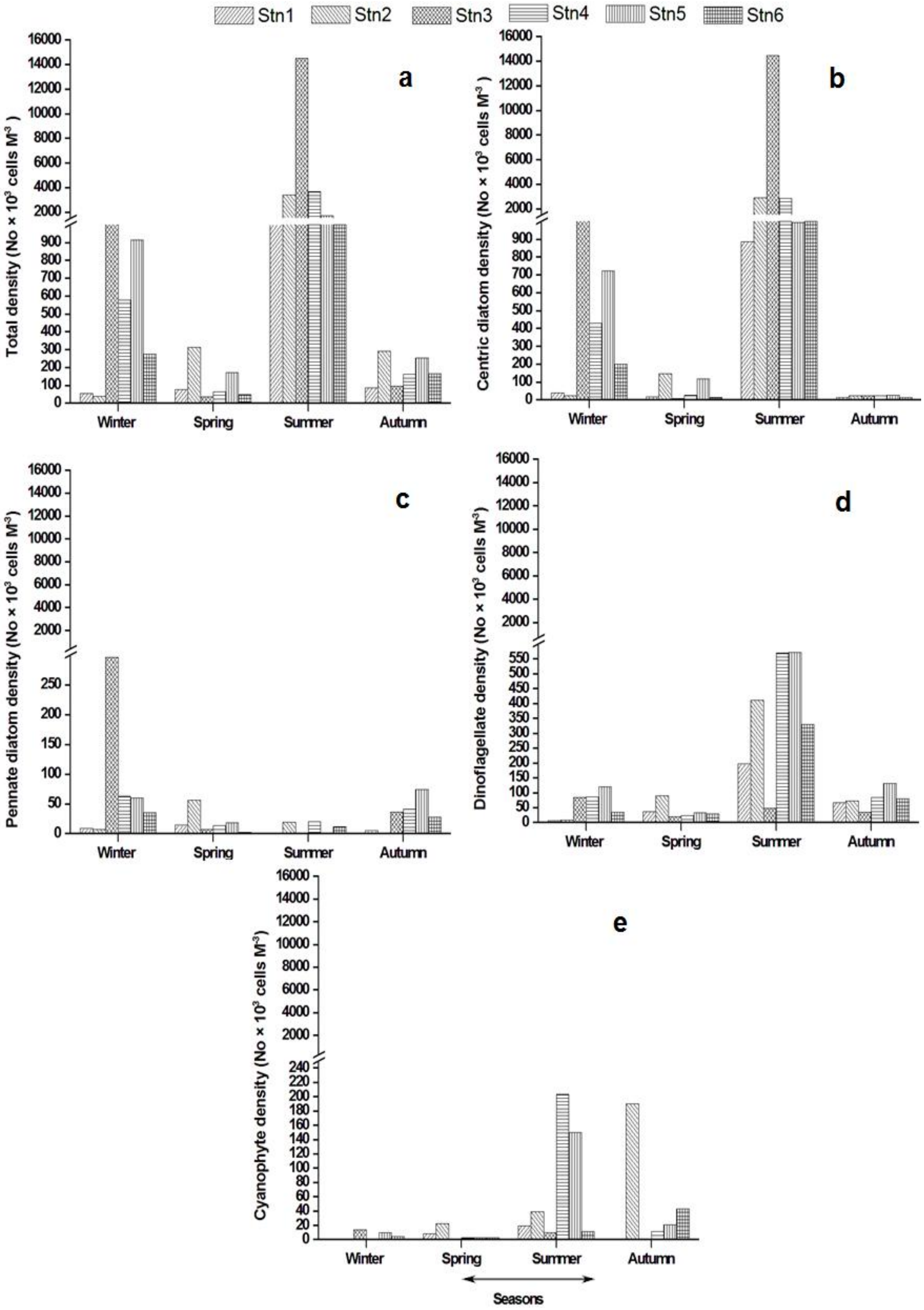

Fig. 5. Total vertical phytoplankton density (a) and the densities of different phytoplankton groups obtained from different study stations during the study period. centric diatoms (b), pennate diatoms (c), dinoflagellates (d) and cyanophytes (e).

Appendix 1. List of different phytoplankton species obtained during the study period. + indicates the presence, - indicates the absence of particular species.

Bacillariophyceae

Centric diatoms	**W**	**Sp**	**S**	**A**
Azpeitia africana (Janisch ex A.Schmidt) G.Fryxell & T.P.Watkins	-	-	-	+
Cerataulina bicornis (Ehrenberg) Hasle, 1985	-	-	+	-
Cerataulina dentata Hasle in Hasle & Syvertsen, 1980	+	+	-	-
Cerataulina pelagica (Cleve) Hendey, 1937	-	-	-	+
Chaetoceros aequatorialis Cleve, 1873	+	-	-	+
Chaetoceros affinis Lauder, 1864	+	+	-	-
Chaetoceros atlanticus Cleve, 1873	-	+	-	-
Chaetoceros coarctatus Lauder, 1864	+	+	-	-
Chaetoceros concavicornis Mangin, 1917	+	-	+	+
Chaetoceros constrictus Gran, 1897	-	+	-	-
Chaetoceros convolutes Castracane, 1886	+	+	-	-
Chaetoceros curvisetus Cleve, 1889	+	+	-	-
Chaetoceros danicus Cleve, 1889	-	-	+	-
Chaetoceros debilis Cleve, 1894	+	-	-	-
Chaetoceros decipiens Cleve, 1873	+	+	+	-
Chaetoceros diadema (Ehrenberg) Gran, 1897	-	-	+	-
Chaetoceros dichaeta Ehrenberg, 1844	+	-	-	-
Chaetoceros didymus Ehrenberg, 1845	+	+	-	-
Chaetoceros eibenii Grunow, 1882	+	-	-	-
Chaetoceros lorenzianus Grunow, 1863	-	+	-	-
Chaetoceros mitra (Bailey) Cleve, 1896	-	+	-	-
Chaetoceros neglectus Karsten, 1905	+	+	+	-
Chaetoceros peruvianus Brightwell, 1856	+	+	-	-
Chaetoceros pseudocurvisetum L. Mangin, 1910	+	-	+	-
Chaetoceros tenuissimus Meunier, 1913	-	-	-	+
Chaetoceros tetrastichon Cleve, 1897	+	+	-	-
Chaetoceros willei Gran, 1897	-	-	+	-
Climacodium frauenfeldianum Grunow, 1868	+	+	+	-
Corethron criophilum Castracane, 1886	-	+	-	-
Coscinodiscus marginatus Ehrenberg, 1844	+	-	-	+
Coscinodiscus radiatus Ehrenberg, 1840	+	-	-	+
Cyclotella sp.	+	-	-	+
Dactyliosolen fragilissimus (Bergon) Hasle, 1996	+	+	+	+
Dactyliosolen phuketensis (B.G.Sundström) G.R. Hasle, 1996	+	-	-	-
Ethmodiscus gazellae (C. Janisch ex Grunow) Hustedt, 1928	-	+	-	+
Ethmodiscus rex Wiseman & Hendey, 1953	+	+	-	+
Eucampia zodiacus Ehrenberg, 1839	+	+	-	-
Guinardia cylindrus (Cleve) Hasle, 1996	+	-	-	-
Guinardia delicatula (Cleve) Hasle, 1997	+	+	+	+
Guinardia flaccida (Castracane) H. Peragallo, 1892	+	+	+	+
Guinardia striata (Stolterfoth) Hasle, 1996	+	+	+	-
Hemiaulus hauckii Grunow ex Van Heurck, 1882	-	-	+	+
Hemiaulus indicus Karsten, 1907	-	+	+	+
Hemiaulus membranaceus Cleve	-	+	+	+
Hemiaulus sinensis Greville, 1865	-	+	+	+
Leptocylindrus danicus Cleve, 1889	+	+	-	+
Leptocylindrus minimus Gran, 1915	+	+	+	-
Melosira granulate (Ehrenberg) Ralfs, 1861	+	-	+	-
Planktoniella sol (C.G. Wallich) Schütt, 1892	+	+	-	-
Proboscia alata (Brightwell) Sundström, 1986	+	+	+	+
Pseudosolenia calcar-avis (Schultze) B.G. Sundström, 1986	+	+	+	+
Rhizosolenia acicularis B.G. Sundström, 1986	-	+	-	-

Appendix 1. (Cont'd.).

Bacillariophyceae				
Centric diatoms	**W**	**Sp**	**S**	**A**
Rhizosolenia acuminata (H. Peragallo) H. Peragallo, 1907	+	+	-	+
Rhizosolenia bergonii H. Peragallo, 1892	+	-	-	+
Rhizosolenia curvata Zacharias, 1905	+	-	-	+
Rhizosolenia formosa H. Peragallo, 1888	+	-	-	-
Rhizosolenia hebetata Bailey, 1856	-	-	+	+
Rhizosolenia hyaline Ostenfeld, 1901	-	-	+	-
Rhizosolenia imbricata Brightwell, 1858	+	+	+	+
Rhizosolenia robusta G. Norman ex Ralfs, 1861	+	+	-	-
Rhizosolenia setigera Brightwell, 1858	+	+	+	-
Rhizosolenia simplex Karsten, 1905	-	-	-	+
Rhizosolenia striata Greville, 1864	-	-	+	-
Rhizosolenia styliformis T. Brightwell, 1858	+	+	+	+
Skeletonema costatum (Greville) Cleve, 1873	+	-	-	+
Thalassiosira subtilis (Ostenfeld) Gran, 1900	-	+	+	+
Pennate diatoms				
Amphora sp.	+	-	-	-
Asterionella formosa Hassall, 1850	-	-	-	+
Asterionellopsis glacialis (Castracane) Round, 1990	-	+	-	-
Cylindrotheca Closterium (Ehrenberg) Reimann & J.C. Lewin, 1964	+	+	-	+
Entomoneis alata (Ehrenberg) Ehrenberg, 1845	-	-	-	+
Fragilaria cylindrus Grunow, 1883	-	-	-	+
Fragilaria striatula Lyngbye, 1819	-	-	-	+
Fragilariopsis sp.	-	-	-	+
Haslea trompii (Cleve) Simonsen, 1974	-	+	-	-
Haslea wawrikae (Hustedt) Simonsen, 1974	-	-	-	+
Licmophora abbreviate C. Agardh, 1831	-	+	-	-
Lioloma elongatum (Grunow) Hasle, 1997	+	+	-	-
Meuniera membranacea (Cleve) P.C. Silva, 1996	+	+	-	-
Navicula directa (W. Smith) Ralfs, 1861	+	-	-	+
Navicula distans (W. Smith) Ralfs, 1861	-	+	-	+
Navicula monilifera Cleve, 1895	-	-	+	-
Nitzschia longissima (Brébisson) Ralfs, 1861	+	-	-	+
Pleurosigma angulatum (Queckett) W. Smith, 1852	+	-	-	-
Pleurosigma directum Grunow, 1880	-	-	+	-
Pleurosigma elongatum W. Smith, 1852	+	-	-	+
Pleurosigma normanii Ralfs, 1861	+	-	-	-
Pseudonitzschia australis Frenguelli, 1939	-	+	-	-
Pseudo-nitzschia cuspidate (Hasle) Hasle, 1993	-	+	-	+
Pseudo-nitzschia delicatissima (Cleve) Heiden, 1928	+	+	-	+
Pseudo-nitzschia lineola (Cleve) Hasle, 1965	-	-	-	+
Pseudonitzschia seriata (Cleve) Peragallo & Peragallo, 1899	-	+	-	-
Pseudonitzschia turgidula (Hustedt) Hasle, 1993	-	-	-	+
Thalassionema bacillare (Heiden) Kolbe, 1955	-	+	-	-
Thalassionema frauenfeldii (Grunow) Tempère & Peragallo, 1910	+	+	-	-
Thalassionema javanicum (Grunow) Hasle in Hasle & Syvertsen, 1996	-	-	-	+
Thalassiothrix longissima Cleve & Grunow, 1880	-	+	-	+
Toxarium undulatum Bailey, 1854	+	+	-	+
Dinophyceae				
Alexandrium insuetum Balech, 1985	-	-	+	-
Alexandrium minutum Halim, 1960	-	+	-	+
Alexandrium tamarense (Lebour, 1925) Balech, 1995	-	+	+	-
Amphidinium sphenoides Wülff, 1916	+	-	+	+
Amphisolenia bidentata Schröder, 1900	-	-	+	+

Appendix 1. (Cont'd.).

Bacillariophyceae				
Centric diatoms	**W**	**Sp**	**S**	**A**
Ceratocorys armata (Schütt) Kofoid, 1910	+	+	+	+
Ceratocorys horrida Stein, 1883	-	+	-	-
Ceratocorys magna Kofoid, 1910	+	-	+	+
Ceratocorys reticulata H.W. Graham, 1942	-	-	-	+
Citharistes regius Stein, 1883	-	+	-	-
Corythodinium tesselatum (Stein) Loeblich Jr. & Loeblich III, 1966	-	-	+	+
Dinophysis caudata Saville-Kent, 1881	+	+	+	-
Dinophysis dens Pavillard, 1915	-	-	+	-
Dinophysis hastata Stein, 1883	-	-	+	+
Dinophysis miles Cleve, 1900	-	+	+	+
Dinophysis schuettii Murray & Whitting, 1899	-	-	+	-
Dinophysis tripos Gourret, 1883	-	-	-	+
Dinophysis uracantha Stein, 1883	-	+	-	+
Gonyaulax polygramma Stein, 1883	-	+	+	+
Gonyaulax scrippsae Kofoid, 1911	-	+	+	-
Gonyaulax spinifera (Claparède & Lachmann) Diesing, 1866	+	+	-	+
Histioneis depressa Schiller, 1928	-	-	+	+
Histioneis panda Kofoid & Michener, 1911	-	-	+	+
Noctiluca scintillans (Macartney) Kofoid & Swezy, 1921	-	-	+	+
Ornithocercus magnificus Stein, 1883	-	-	-	+
Ornithocercus steinii Schütt, 1900	-	-	-	+
Ornithocercus thurnii (Schmidt) Kofoid & Skogsberg	-	+	-	+
Oxytoxum gracile Schiller, 1937	-	-	-	+
Phalacroma circumsutum Karsten, 1907	-	-	-	+
Phalacroma cuneus F. Schütt, 1895	-	+	-	+
Phalacroma doryphorum Stein, 1883	-	-	-	+
Phalacroma favus Kofoid & Michener, 1911	-	-	-	+
Phalacroma favus Kofoid & Michener, 1911	-	-	-	+
Phalacroma mitra F. Schütt, 1895	-	-	-	+
Phalacroma rapa Jorgensen, 1923	-	-	-	+
Phalacroma rotundatum (Claparéde & Lachmann) Kofoid & Michener, 1911	-	-	-	+
Podolampas spinifera Okamura, 1912	-	-	-	+
Prorocentrum belizeanum M.A. Faust, 1993	-	-	-	+
Prorocentrum cordatum (Ostenfeld) J.D. Dodge, 1976	-	-	-	+
Prorocentrum gracile Schütt, 1895	-	+	+	-
Prorocentrum lima (Ehrenberg) F. Stein, 1878	-	-	-	+
Prorocentrum mexicanum Osorio-Tafall, 1942	-	-	-	+
Prorocentrum micans Ehrenberg, 1834	+	+	-	+
Protoperidinium bipes (Paulsen, 1904) Balech, 1974	-	-	+	+
Protoperidinium claudicans (Paulsen, 1907) Balech, 1974	-	-	+	-
Protoperidinium conicum (Gran, 1900) Balech, 1974 †	-	-	+	+
Protoperidinium crassipes (Kofoid, 1907) Balech, 1974	-	-	+	+
Protoperidinium curtipes (Jørgensen, 1912) Balech, 1974	+	+	+	-
Protoperidinium diabolum (Cleve, 1900) Balech, 1974	-	-	+	-
Protoperidinium divergens (Ehrenberg, 1840) Balech, 1974	-	+	+	+
Protoperidinium elegans (Cleve, 1900) Balech, 1974	+	-	+	+
Protoperidinium fatulipes (Kofoid, 1907) Balech, 1974	-	-	-	+
Protoperidinium grande (Kofoid, 1907) Balech, 1974	-	-	-	+
Protoperidinium inflatum (Okamura) Balech, 1974	-	-	-	+
Protoperidinium leonis (Pavillard, 1916) Balech, 1974	-	+	+	-
Protoperidinium oblongum (Aurivillius) Parke & Dodge, 1976	-	-	+	+
Protoperidinium oceanicum (VanHöffen, 1897) Balech, 1974	+	+	+	+
Protoperidinium ovum (Schiller, 1911) Balech, 1974	-	+	+	+

Appendix 1. (Cont'd.).

Bacillariophyceae				
Centric diatoms	**W**	**Sp**	**S**	**A**
Protoperidinium pallidum (Ostenfeld, 1899) Balech, 1973	-	+	+	-
Protoperidinium pellucidum Bergh, 1881	-	-	+	+
Protoperidinium pentagonum (Gran, 1902) Balech, 1974	+	+	+	-
Protoperidinium steinii (Jørgensen, 1899) Balech, 1974	+	+	+	+
Protoperidinium subpyriforme (P.-A. Dangeard, 1927) Balech, 1974	-	-	-	+
Pyrocystis lunula (Schütt) Schütt, 1896	+	-	+	+
Pyrocystis noctiluca Murray ex Haeckel, 1890	-	-	+	-
Pyrophacus horologium F. Stein, 1883	-	-	-	+
*Pyrophacus steinii** (Schiller) Wall & Dale, 1971	-	+	+	+
Schuettiella mitra (Schütt) Balech, 1988	-	+	-	-
*Scrippsiella trochoidea** (Stein) Loeblich III, 1976	-	+	-	+
Spiraulax kofoidii H.W. Graham, 1942	-	-	+	-
Tripos arietinus (Cleve) F. Gómez, 2013	-	-	-	+
Tripos belone (Cleve) F. Gómez 2013	+	-	+	+
Tripos biceps (Claparède & Lachmann) F. Gómez, 2013	-	+	+	+
Tripos brevis (Ostenfeld & Johannes Schmidt) F. Gómez, 2013	+	+	+	+
Tripos candelabrus (Ehrenberg) F. Gómez, 2013	+	+	+	+
Tripos carriensis (Gourret) F. Gómez, 2013	+	-	-	-
Tripos contortus (Gourret) F. Gómez, 2013	-	-	+	+
Tripos contrarius (Gourret) F. Gómez, 2013	+	-	+	+
Tripos declinatus (G. Karsten) F. Gómez, 2013	+	+	+	+
Tripos dens (Ostenfeld & Johannes Schmidt) F. Gómez, 2013	-	+	+	-
Tripos ehrenbergii (Kofoid) F. Gómez, 2013	-	-	+	-
Tripos euarcuatus (Jörgenen) F. Gómez, 2013	-	-	-	+
Tripos furca (Ehrenberg) F. Gómez, 2013	+	+	+	+
Tripos fusus (Ehrenberg) F. Gómez, 2013	+	+	-	+
Tripos geniculatus (Lemmermann) F. Gómez, 2013	-	-	-	+
Tripos gibberus (Gourret) F. Gómez, 2013	-	-	-	+
Tripos horridus (Cleve) F. Gómez, 2013	+	+	+	+
Tripos incisus (Karsten) F. Gómez, 2013	-	+	+	+
Tripos inflatus (Kofoid) F. Gómez, 2013	-	-	+	+
Tripos kofoidii (Jörgenen) F. Gómez, 2013	-	-	+	+
Tripos lineatus (Ehrenberg) F. Gómez, 2013	-	+	+	+
Tripos longipes (J.W. Bailey) F. Gómez, 2013	+	-	-	-
Tripos longissimus (Schröder) F. Gómez, 2013	+	-	+	-
Tripos lunula (Schimper ex Karsten) F. Gómez, 2013	+	-	+	+
Tripos macroceros (Ehrenberg) F. Gómez, 2013	-	-	+	+
Tripos massiliensis (Gourret) F. Gómez, 2013	+	-	+	-
Tripos muelleri Bory de Saint-Vincent, 1826	+	+	+	+
Tripos paradoxides (Cleve) F. Gómez, 2013	-	-	+	+
Tripos pentagonus (Gourret) F. Gómez, 2013	-	+	+	-
Tripos pulchellus (Schröder) F. Gómez, 2013	-	-	-	+
Tripos ranipes (Cleve) F. Gómez, 2013	-	-	+	-
Tripos reflexus (Cleve) F. Gómez, 2013	-	-	+	+
Tripos schrankii (Kofoid) F. Gómez, 2013	-	-	+	+
Tripos symmetricus (Pavillard) F. Gómez 2013	-	+	+	+
Tripos teres (Kofoid) F. Gómez, 2013	+	+	+	+
Tripos trichoceros (Ehrenberg) Gómez, 2013	+	+	+	+
Tripos vulture (Cleve) F. Gómez, 2013	+	-	-	+
Cyanophyceae				
Trichodesmium erythraeum Ehrenberg ex Gomont, 1892	+	+	+	+

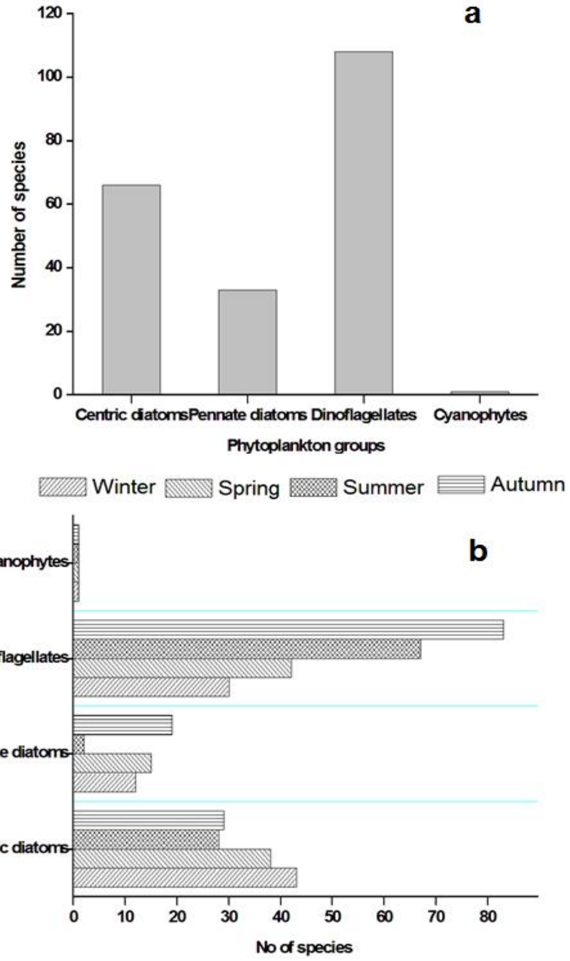

Fig. 6. Total number of species (a) and the seasonal variability in the species diversity (b) of different phytoplankton groups from the study area.

Discussion

The findings regarding the spatial distribution of temperature across the study stations indicate a certain degree of consistency within each season, suggesting a relatively homogeneous thermal environment. However, the temporal analysis revealed significant variations in temperature among different seasons, indicating a distinct seasonal pattern. These observed seasonal temperature fluctuations align with the typical climatic patterns in the Red Sea, where winter months experience cooler temperatures, and summer months are marked by warmer conditions (Morcos, 1970; Sofianos *et al*., 2002). The specific findings align closely with various studies conducted in the central red sea region (Al-Amri *et al*., 2020; El-Sherbiny *et al*., 2021; Touliabah *et al*., 2010). The Red Sea's unique hydrographic characteristics, influenced by its geographical location and oceanographic features, contribute to the distinct seasonal variations in temperature observed in this study, which happened in the central red sea region (Chaidez *et al*., 2017; Shaltout, 2019). The current study observed a noteworthy positive correlation between temperature and Chlorophyll, dinoflagellates, and cyanophytes. This suggests that ambient temperature plays a significant role in the growth of phytoplankton in the region. Similar patterns have been previously documented in studies conducted within the Jeddah region (Al-Aidaroos *et al*., 2019; Al-Amri *et al*., 2020; El-Sherbiny *et al*., 2021; Touliabah *et al*., 2010) and other areas of the Red Sea (Devassy *et al*., 2017: Kurten *et al*., 2015) A favourable temperature, coupled with a potential influx of nutrients, can alter the growth dynamics of phytoplankton, as observed in the present study. Specifically, a summer dominance of diatoms was reported in the central zones. Normally, the Red Sea displays a gradient in salinity values, with an increase towards the north Kurten *et al*., 2015; López-Sandoval *et al*., 2021). However, the current study, which primarily focused on the central Red Sea region, identified a uniform pattern of salinity distribution. This uniformity was found to have no significant influence on phytoplankton dynamics, indicating a minimal regional role played by salinity in the study area.

The majority of the periods and study stations exhibited the traditional oligotrophic nature of the Red Sea (Kurten *et al*., 2015, 2016; Pena-Garcia. *et al*., 2014; Wafar *et al*., 2016). However, the central Jeddah stations deviated from this trend, displaying comparatively higher values. This discrepancy in the central Jeddah stations may be primarily attributed to anthropogenic influences, specifically sewage disposal activities occurring in that region. This specific trend has been previously identified and documented in various research studies. (Al-Amri *et al*., 2020; Al-Farawati, 2010; Basaham *et al*., 2009; Fallatah *et al*., 2018; Pena-Garcia. *et al*., 2014). The absence of a significant correlation between nitrogen derivatives and the biomass or abundances of phytoplankton in the current study suggests that these nutrient salts may not be the limiting factor for primary production, at least in the coastal waters of the Red Sea. The present study observed a significant positive correlation between phosphates and chlorophyll *a*, highlighting the importance of this nutrient in the Red Sea's oligotrophic system. Traditionally, phosphates play a crucial role as a limiting factor for primary production in this ecosystem (Kurten *et al*., 2015; López-Sandoval *et al*., 2021). The uniformity in phosphate concentrations across various sampling locations, irrespective of both temporal and spatial variations, points to a consistent distribution of this nutrient within the study area. Silicate distribution played a significant role in shaping the distribution of both phytoplankton biomass and abundances, as evidenced by the significant positive correlations observed in the study. The availability of silicates can be attributed primarily to the close proximity of the study location to the land. This proximity suggests that land runoff, sewage waters, and aerosol deposits through winds are potential sources contributing to the presence of silicates in the studied area (Mudarris & Turkey, 2006).

Throughout our study, the study region displayed a lower phytoplankton biomass, which is a characteristic of the Red Sea ecosystem. (Brewin *et al*., 2013, 2015; Kheireddine *et al*., 2017; Racault. *et al*., 2015). This historical trend has been a notable aspect of the Red Sea's ecological dynamics. However, in contrast to this established pattern, our current study revealed an intriguing deviation a localized enrichment of chlorophyll specifically observed in central stations. The occurrence of a specific type of coastal higher phytoplankton biomass has been previously investigated, not only in the present region (Al-Amri *et al*., 2020; El-Sherbiny *et al*., 2021; Touliabah *et al*., 2010) but also in other coastal zones of the Red Sea (Acker *et al*., 2008; Devassy *et al*., 2017; Racault *et al*., 2015). This deviation signifies potential hotspots for heightened phytoplankton activity within the zone, challenging the conventional understanding of its lower phytoplankton biomass. The higher chlorophyll concentrations during the summer season, particularly in central stations, may be attributed to factors such as increased light availability and nutrient supply, promoting favourable conditions for phytoplankton growth (Al-Amri *et al*., 2020; El-Sherbiny *et al*., 2021). Furthermore, this observation suggests that the central zone has been receiving effluents from anthropogenic activities for the past two decades, and this trend is on-going. In some instances, as highlighted by Al-Aidaroos *et al*., (2019) this continuous influx of effluents can potentially lead to harmful algal blooms. During the summer season, the Red Sea experiences elevated temperatures and increased solar radiation, creating favourable conditions for phytoplankton growth. This is evident in the study's findings, where the average chlorophyll values reached their peak during the summer. A similar trend has been observed in the studies of Al-Amri *et al*., (2020) and Devassy *et al*., (2017), where they also reported a peak in chlorophyll levels during the summer from the coastal waters of the Red sea. Conversely, the lowest chlorophyll values were observed during the spring phase of the study. This could be attributed to factors such as reduced nutrient availability or transitional environmental conditions during the spring season.

The present study uncovered significant variability in the water column's total phytoplankton density across different seasons. Particularly noteworthy was the marked difference in phytoplankton densities during the summer season, which exhibited substantially higher values compared to other seasons. The prevalence of summer dominance has been previously observed in horizontal phytoplankton studies conducted by Devassy *et al*., (2017) in the coastal region of Alwajh, northern Red Sea. This trend is consistent with findings from the current study region by Al-Amri *et al*., (2020) and Touliabah *et al*., (2010). Due to the absence of other vertical phytoplankton distribution studies, the current study necessitated a comparison with horizontal phytoplankton studies conducted in the region. The sole study addressing vertical phytoplankton dynamics was conducted by Kurten *et al*., (2015). In their research, which involved phytoplankton studies from the entire Red sea on a south to north gradient, they collected samples from northern Jeddah, a location close to Station 2 in the current study. It appears that the findings from Kurten *et al*., (2015) study for the autumn season align with the results observed in the corresponding stations during the same season in the current study. The central study station, Station 3, played a pivotal role in contributing to the elevated phytoplankton density observed during the summer season. Emphasizing its significance as a hotspot for phytoplankton activity within the Red Sea ecosystem. Furthermore, the observed seasonal variations in phytoplankton density contribute to our broader understanding of the dynamic nature of the coastal waters of Jeddah, shedding light on the factors influencing phytoplankton abundance in this unique marine environment. The occurrence of localized phytoplankton proliferations is a well-documented phenomenon in the coastal waters of the Red Sea, and in certain instances, it can escalate to the stature of a bloom (Al-Aidaroos *et al*., 2019; Banguera-Hinestroza *et al*., 2016). This observation aligns with established patterns of phytoplankton dynamics in the Red Sea, where specific coastal areas may experience pronounced increases in phytoplankton abundance under favourable conditions (Al-Amri *et al*., 2020; Devassy *et al*., 2017; El-Sherbiny *et al*., 2021; Touliabah *et al*., 2010). These localized proliferations are indicative of the Red Sea's dynamic and complex ecosystem, where various factors such as nutrient availability, temperature, and water circulation patterns contribute to the spatial heterogeneity of phytoplankton distribution. The potential escalation to a bloom suggests that these coastal waters may occasionally witness an overwhelming and rapid increase in phytoplankton biomass, a phenomenon that can have significant ecological implications. A recent incident in central Jeddah, documented in the studies of Al-Aidaroos *et al*., (2019), involved the proliferation of a harmful diatom species, leading to a coastal bloom. Monitoring and comprehending the factors influencing the occurrence of these localized proliferations and blooms in the Red Sea are essential for both scientific understanding and effective coastal management. The findings of the current study highlight that phytoplankton proliferation occurs not only horizontally but also vertically within the water column. This underscores the significance of investigating the dynamics of phytoplankton throughout the water column.

The dynamic role of diatoms in the water column phytoplankton community is highlighted by its seasonal variation. Their proliferation is notably pronounced during the summer season, aligning well with previous studies conducted in the region (Al-Aidaroos *et al*., 2019; Al-Amri *et al*., 2020; El-Sherbiny *et al*., 2021; Touliabah *et al*., 2010). In recent times, there is a noticeable and prevailing trend in the coastal Red Sea regions, characterized by the dominance of diatoms during the summer. This phenomenon plays a significant role in contributing to the overall phytoplankton density, as highlighted by Devassy *et al*., (2017). It underscores the well-adapted nature of diatoms to the specific conditions prevalent in this marine environment. The findings of the study reaffirm the established understanding that the diatoms played a significant role in shaping the phytoplankton composition in the Red Sea.

The vertical diversity of phytoplankton too in the current study exhibited pronounced seasonal fluctuations. These observations provide valuable insights into the ecological dynamics and diversity of phytoplankton in this unique marine environment. The observed dominance of dinoflagellates over diatoms in terms of species diversity is consistent with previous observations in the Red Sea waters, reaffirming a recognized ecological characteristic of this marine environment. Additionally, the total number of species reported in the current study aligns well with findings from previous research in the region, indicating a certain degree of consistency in phytoplankton diversity over time (Al-Amri *et al*., 2020; Devassy *et al*., 2017; El-

Sherbiny *et al*., 2021; Halim, 1969, 1984; Ismael, 2015; Kurten *et al*., 2015). The dominance of the genera *Tripos* and *Protoperidinium* among dinoflagellates, along with the prominence of *Chaetoceros* and *Rhizosolenia* in diatoms, aligns with well-established patterns of phytoplankton composition in the Red Sea. (Al-Amri *et al*., 2020; Devassy *et al*., 2017; Dowidar, 1983; El-Sherbiny *et al*., 2021; Halim, 1969, 1984; Ismael, 2015; Kurten *et al*., 2015). This observation further indicates that the vertical phytoplankton density is like the horizontal distribution, suggesting a common distribution pattern in the current study region. These genera, including *Tripos* and *Protoperidinium* among dinoflagellates and *Chaetoceros* and *Rhizosolenia* among diatoms, have consistently been observed for their prevalence in the region. This persistence suggests a high degree of adaptation to the specific environmental conditions of the Red Sea, making them species that have successfully adapted to a hot, high-saline and oligotrophic ecosystem. In the context of a changing global scenario, with the world's oceans experiencing warming trends (Behrenfeld *et al*., 2016; Cheng *et al*., 2022), these species, known for their prevalence and adaptation to the specific environmental conditions of the Red Sea, may indeed be poised to dominate future oceans. The observed success of these species in a hot, high-saline ecosystem could position them as key players in responding to and thriving in the evolving conditions of a warmer world ocean. Continued research on the ecological roles and responses of *Tripos*, *Protoperidinium*, *Chaetoceros*, and *Rhizosolenia* can contribute to a comprehensive understanding of the factors influencing their presence and behaviour in the Red Sea. This knowledge can be crucial for shaping our understanding of how these species might respond to future global warming scenarios.

Furthermore, the current study reveals the unique prevalence of *Proboscia alata* (Brightwell) Sundström, 1986 during the summer season in the central Jeddah region. This dominance has been previously highlighted in the studies conducted by Devassy *et al*., (2017), suggesting that *Proboscia alata* (Brightwell) Sundström, 1986 is notably well-suited as a centric diatom in the coastal waters of the Red Sea. The consistency of its dominance underscores its adaptability and significance in this specific marine environment. The observation of *Proboscia alata*'s prevalence during the summer season suggests a specific temperature preference for its growth. This aligns with the findings of the current study, which revealed a significant positive correlation between temperature and total phytoplankton densities. The presence of the common cyanophyte *Trichodesmium erythraeum*, a regular representative of the Red Sea waters, is consistent with expectations. *Trichodesmium erythraeum* is known for its prevalence in the region and is recognized to proliferate, especially during certain seasons, notably the summer months (Devassy *et al*., 2017; Post *et al*., 2002). The lack of conspicuous dominance of *Trichodesmium erythraeum* observed during the current study may be ascribed to a multitude of factors, encompassing distinct environmental parameters, nutrient availability, and other ecological variables that intricately influence the proliferation and abundance of cyanophytes.

Table 2. Pearson's correlation coefficient between different paramters obtained during the study period.

	Correlations												
	Temperature	**Salinity**	**Nitrate**	**Nitrite**	**Ammonia**	**Phosphate**	**Silicate**	**Chlorophyll**	**Total density**	**Centrales**	**Pennales**	**Dinoflagellates**	**Cyanophytes**
Temperature	1												
Salinity	0.803**	1											
Nitrate	-0.243	-0.201	1										
Nitrite	-0.239	-0.103	0.807**	1									
Ammonia	-0.331	-0.203	0.530**	0.604**	1								
Phosphate	0.484*	0.354	0.341	0.324	0.003	1							
Silicate	0.278	-0.057	0.27	0.158	-0.04	0.481*	1						
Chlorophyll	0.598**	0.306	0.122	-0.086	-0.357	0.426*	0.510*	1					
Total density	0.422*	0.054	-0.15	-0.252	-0.347	-0.033	0.408*	0.666**	1				
Centrales	0.386	0.031	-0.149	-0.232	-0.325	-0.057	0.395	0.643**	0.998**	1			
Pennales	-0.306	-0.478*	0.272	0.127	0.281	-0.102	0.268	-0.026	-0.071	-0.084	1		
Dinoflagellates	0.644**	0.423*	-0.121	-0.358	-.437*	.409*	0.202	0.460*	0.19	0.125	-0.095	1	
Cyanophytes	0.488*	0.450*	-0.057	-0.255	-0.328	0.133	-0.007	0.209	0.106	0.052	-0.141	0.663**	1

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

An important aspect of coastal monitoring highlighted in the present study is the observation of harmful algal bloom-inducing dinoflagellates and diatoms (Appendix 1). Specifically, the pennate diatom *Pseudo-nitzschia delicatissima* (Cleve) Heiden, 1928, identified in the current study, is known for producing bloom-like abundances in the central Jeddah region (Al-Aidaroos *et al*., 2019). This diatom species possesses the potential to pose a threat to the marine ecosystem in the region by producing harmful chemicals, such as domoic acid (Hasle, 2002). Within the dinoflagellates, the identification of 5 *Alexandrium* species in the present study (Appendix 1) raises further serious concerns about the ecosystem health. The presence of these specific species within the dinoflagellate group can be alarming, as some *Alexandrium* species are known to produce saxitoxins that can adversely impact marine ecosystems and pose risks to both aquatic life and human health (Anderson *et al*., 1990). The dominance of the bloom-forming genus *Alexandrium* has been well-documented in the phytoplankton diversity of Al Wajh, a northern Red Sea coastal region ((Devassy *et al*., 2017). This further indicates the prevalence and dominance of these species in the Red Sea ecosystem. The consistent observation of *Alexandrium* in different regions of the Red Sea highlights the need for continued research and monitoring to better understand the dynamics of these bloom-forming genera and their potential impacts on the marine environment in the broader context of the Red Sea ecosystem. The current study provides a clear indication that the distribution of all these species occurs both horizontally and vertically. The observed horizontal and vertical distribution patterns suggest that these species can occupy various layers of the water column in the coastal ecosystem. Furthermore, the ability of these species to undergo cyst formation under unfavourable conditions allows them to deposit in sediments. This capability poses a continuous threat to coastal ecosystems, as these cysts can later dominate the ecosystem when favourable conditions return. The study underscores the importance of understanding the life cycle dynamics and ecological resilience of these species in managing and mitigating potential threats to coastal ecosystems. Indeed, the monitoring of these species should be comprehensive, considering not only surface horizontal monitoring but also considering the water column distribution. Understanding the vertical distribution of these species is crucial for a more accurate assessment of their ecological impact and potential threats to the coastal ecosystem. By incorporating both horizontal and vertical dimensions in monitoring efforts, researchers and environmental managers can gain a more holistic view of the distribution patterns and dynamics of these phytoplankton species. This approach enhances the ability to anticipate and respond to changes in the ecosystem, contributing to effective conservation and management strategies. Future studies could extensively investigate the recent additions of harmful algal bloom-causing species in coastal waters and their implications for coastal ecosystems. Such research could shed light on the ecological impacts of these species on marine biodiversity, fisheries, and human health, providing valuable insights for effective management and conservation strategies.

Conclusions

The present study marks a significant milestone in the understanding of vertical phytoplankton distribution within the coastal waters of Jeddah. Pioneering in its nature, this research sheds light on how phytoplankton is distributed vertically in relation to various physical and chemical factors. This novel investigation not only contributes to the broader knowledge of marine ecosystems in the region but also offers insights into the unique dynamics of phytoplankton in the coastal waters of Jeddah. The study uncovered substantial variations in vertical phytoplankton distribution, providing a comprehensive view of the intricate relationship between phytoplankton abundance and key environmental factors. By exploring the vertical dimension, the research highlighted the influence of physical parameters such as temperature, salinity, and nutrient concentrations on the spatial distribution of phytoplankton. The temporal aspect, reflecting the traditional behaviour of the Red Sea, was clearly echoed in the findings, underscoring the importance of considering seasonal variations in phytoplankton dynamics. Moreover, the study emphasized the existence of spatial differences throughout the research period. These observed variations in phytoplankton distribution not only contribute to our understanding of local marine ecosystems but also provide valuable information for environmental management and conservation efforts. The identification of spatial differences suggests the presence of localized environmental conditions that influence phytoplankton communities, further emphasizing the need for the understanding of ecosystem dynamics. The potential threat posed by the presence of various bloom-forming diatoms and dinoflagellates further emphasizes the importance of continuous coastal monitoring on both a horizontal and vertical basis. Monitoring the distribution patterns and abundance of these phytoplankton species across different layers of the water column is essential for a comprehensive understanding of their dynamics and potential impact on the coastal ecosystem. This information is crucial for early detection, assessment, and effective management strategies to mitigate the risks associated with harmful algal blooms and their consequences on marine environments.

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References

Acker, J., G. Leptoukh, S. Shen, T. Zhu and S. Kempler. 2008. Remotely sensed chlorophyll a observations of the northern Red Sea indicate seasonal variability and influence of coastal reefs. *J. Mar. Syst*., 69(3): 191-204. https://doi.org/10.1016/j.jmarsys.2005.12.006

Al-Aidaroos, A.M., R.P. Devassy and M.M. El-Sherbiny. 2019. Unusual dominance of harmful microalgae Pseudo-nitzschia delicatissima cf. (Cleve) Heiden in the coastal waters of Jeddah, central Red Sea. *Pak. J. Bot*., 51(2): 1-6. https://doi.org/10.30848/PJB2019-2(44)

Al-Amri, A.A., H.A. Qari and M.M. El-Sherbiny. 2020. Distribution and community structure of microphytoplankton in relation to increasing anthropogenic impact along coastal waters of Jeddah, the central Red Sea. *Oceanol. Hydrobiol. Stud.*, 49(2): 193-205. https://doi.org/10.1515/ohs-2020-0018.

Al-Farawati, R. 2010. Environmental conditions of the coastal waters of Southern Corinche, Jeddah, Eastern red sea: Physico-chemical approach. *Aust. J. Basic Appl. Sci.*, 4(8): 3324-3337.

Alsaaq. F. 2023. Assessing the Coral Reef Fish Biodiversity in the Al-Wajh Region of the Northern Red Sea, Saudi Arabia. *Pak. J. Zool.*, 1-12.https://dx.doi.org/10.17582/journal.pjz/20230801061958

Anderson, D.M., D.M. Kulis, J.J. Sullivan, S. Hall and C. Lee. 1990. Dynamics and physiology of saxitoxin production by the dinoflagellates *Alexandrium* spp. *Mar. Boil.*, 104: 511-524. https://doi.org/10.1007/BF01314358

Anderson., D.M., A.D. Cembella and G.M. Hallegraeff. 2012. Progress in understanding harmful algal blooms: Paradigm shifts and new technologies for research, monitoring, and management. *Ann. Rev. Mar. Sci.*, 4: 143-176. https://doi.org/10.1146/annurev-marine-120308-081121.

Banguera-Hinestroza, E., W. Eikrem, H. Mansour, I. Solberg, J. Cúrdia, K. Holtermann, B. Edvardsen and S. Kaartvedt. 2016. Seasonality and toxin production of Pyrodinium Bahamense in a Red Sea lagoon. *Harmful Algae* 55: 163-171 https://doi.org/10.1016/j.hal.2016.03.002

Basaham, A.S., A.E. Rifaat, M.H. El-Mamoney and M.A. El Sayed. 2009. Re-evaluation of the impact of sewage disposal on coastal sediments of the Southern Corniche, Jeddah, Saudi Arabia. *J. King Abdulaziz Univ. Mar. Sci.*, 20: 109-126.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier and E.S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. *Nature*, 444(7120): 752-755. https://doi.org/10.1038/nature05317

Behrenfeld, M.J., R.T. O'Malley, E.S. Boss, T.K. Westberry, J.R. Graff, K.H. Halsey, A.J. Milligan, D.A. Siegel and M.B. Brown. 2016. Revaluating ocean warming impacts on global phytoplankton. *Nat. Clim. Change*. 6(3): 323-330.https://doi.org/10.1038/nclimate2838

Brewin, R.J., D.E. Raitsos, G. Dall'Olmo, N. Zarokanellos, T. Jackson, M.F. Racault, E.S. Boss, S. Sathyendranath, B.H. Jones and I. Hoteit. 2015. Regional ocean-colour chlorophyll algorithms for the Red Sea. *Remote Sens. Environ.*, 165: 64-85. https://doi.org/10.1016/j.rse.2015.04.024

Brewin, R.J., D.E. Raitsos, Y. Pradhan and I. Hoteit. 2013. Comparison of chlorophyll in the Red Sea derived from MODIS-Aqua and in vivo fluorescence. *Remote Sens. Environ.*, 136: 218-224. https://doi.org/10.1016/j.rse.2013.04.018

Chaidez, V., D. Dreano, S. Agusti, C.M. Duarte and I. Hoteit. 2017. Decadal trends in Red Sea maximum surface temperature. *Sci. Rep.*, 7(1): 8144. https://doi.org/10.1038/s41598-017-08146-z

Cheng, L., K. von Schuckmann, J.P. Abraham, K.E. Trenberth, M.E. Mann, L. Zanna, M.H. England, J.D. Zika, J.T. Fasullo, Y. Yu, Y.Pan, J. Zhu, E.R. Newsom, B. Bronselaer and X. Lin. 2022. Past and future ocean warming. *Nat. Rev. Earth Environ.*, 3(11): 776-794. https://doi.org/10.1038/s43017-022-00345-1

Crain, C.M., B.S. Halpern, M.W. Beck and C.V. Kappel. 2009. Understanding and managing human threats to the coastal marine environment. *Ann. N.Y. Acad. Sci.*, 1162(1): 39-62. https://doi.org/10.1111/j.1749-6632.2009.04496.x

Cury, P., L. Shannon and Y.J. Shin. 2003. The functioning of marine ecosystems: A fisheries perspective. (Eds.): Sinclair, M., G. Valdimarsson. *Responsible Fisheries in the Marine Ecosystem*, FAO/CAB International, Rome, Italy/ Wallingford, UK (2003), p.

D'Angelo, C and J. Wiedenmann. 2014. Impacts of nutrient enrichment on coral reefs: new perspectives and implications for coastal management and reef survival. *Curr. Opin. Environ. Sustain.*, 7: 82-93. https://doi.org/10.1016/j.cosust.2013.11.029

Davidson, K., R.J. Gowen, P.J. Harrison, L.E. Fleming, P. Hoagland and G. Moschonas. 2014. Anthropogenic nutrients and harmful algae in coastal waters. *J. Environ Manage*, 146: 206-216.

Devassy, R.P., M.M. El-Sherbiny, A.M. Al-Sofyani and A.M. Al-Aidaroos. 2017. Spatial variation in the phytoplankton standing stock and diversity in relation to the prevailing environmental conditions along the Saudi Arabian coast of the northern Red Sea. *Mar. Biodivers.*, 47(4): 995-1008. https://doi.org/10.1007/s12526-017-0693-4

Dowidar, N.M. 1983. The genus Ceratium from the Red Sea. *J. Fac. Mar. Sci.*, 3: 5-37.

El-Sherbiny, M.M., M.A. Al-Harbi and A.J. Kumar. 2021. Spatio-temporal variation of microphytoplankton communities in Obhur Creek, the central Red Sea. *Oceanol. Hydrobiol. Stud.*, 50(1): 98-114. https://doi.org/10.2478/oandhs-2021-0010

Falkowski, P.G., R.T. Barber and V. Smetacek. 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science*, 281(5374): 200-206.

Fallatah, M.M., Y.N. Kavil, A.S. Ibrahim, M.I. Orif, Y.A. Shaban and R. Al Farawati. 2018. Hydrographic parameters and distribution of dissolved Cu, Ni, Zn and nutrients near Jeddah desalination plant. *Open Chem.*, 16(1): 246-257. https://doi.org/10.1515/chem-2018-0029.

Garmendia, M., Á. Borja, J., Franco and M. Revilla. 2013. Phytoplankton composition indicators for the assessment of eutrophication in marine waters: Present state and challenges within the European directives. *Mar. Pollut. Bull.*, 66(1-2): 7-16. https://doi.org/10.1016/j.marpolbul.2012.10.005

Halim, Y. 1969. Plankton of the Red Sea. *Oceanogr Mar. Biol. Ann. Rev.*, 7: 231-275.

Halim, Y. 1984. Plankton of the Red Sea and the Arabian Gulf. *Deep Sea Res. Part I Oceanogr. Res. Pap.*, 31(6-8): 969-982

Hallegraeff, G.M. 2014. Harmful algae and their toxins: progress, paradoxes and paradigm shifts. In: (Ed.): Rossini, G.P. Toxins and biologically active compounds from microalgae, 1st edn, vol 1. CRC Press-Taylor & Francis Group, Boca Raton, pp 3-20.

Hasle, G.R. 2002. Are most of the domoic acid-producing species of the diatom genus Pseudo-nitzschia cosmopolites?. *Harmfulalgae*, 1(2): 137-146. https://doi.org/10.1016/S1568-9883(02)00014-8

Heil, C.A. and A.L. Muni-Morgan. 2021. Florida's harmful algal bloom (HAB) problem: Escalating risks to human, environmental and economic health with climate change. *Front. Ecol. Environ.*, 9: 646080.

Ismael. A.A. 2015. Phytoplankton of the Red Sea. In: (Eds.): Najeeb, R., I.C.F. Stewart. The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin. Springer, Berlin, pp. 567-583.

Jakhar, P. 2013. Role of phytoplankton and zooplankton as health indicators of aquatic ecosystem: A review. *Int. J. Innov.*, 2(12): 489-500.

Kheireddine, M., M. Ouhssain, H. Claustre, J. Uitz, B. Gentili and B.H. Jones. 2017. Assessing pigment-based phytoplankton community distributions in the Red Sea. *Front. Mar. Sci.*, 4: 132. https://doi.org/10.3389/fmars.2017.00132

Klinker, J., Z. Reiss, C. Kropach, J. Levanon, H. Harpaz and Y. Shapiro. 1978 Nutrients and biomass distribution in the Gulf of Aqaba (Elat), Red Sea. *Mar. Biol.*, 45: 53-64. https://doi.org/10.1007/BF00388977

Kürten, B., A.M. Al-Aidaroos, S. Kürten, M.M. El-Sherbiny, R.P. Devassy, U. Struck, N. Zarokanellos, B.H. Jones, T. Hansen, G. Bruss and U. Sommer. 2016. Carbon and nitrogen stable isotope ratios of pelagic zooplankton elucidate ecohydrographic features in the oligotrophic Red Sea. Prog. Oceanogr., 140: 69-90. https://doi.org/10.1016/j.pocean.2015.11.003

Kürten, B., H.S. Khomayis, R. Devassy, S. Audritz, U. Sommer, U. Struck, M.M. El-Sherbiny and A.M. Al-Aidaroos. 2015. Ecohydrographic constraints on biodiversity and distribution of phytoplankton and zooplankton in coral reefs of the Red Sea, Saudi Arabia. *Mar. Ecol.*, 36(4): 1195-1214. https://doi.org/10.1111/maec.12224

LeGresley, M. and G. McDermott. 2010. Counting chamber methods for quantitative phytoplankton analysis haemocytometer, Palmer-Maloney cell and Sedgewick-Rafter cell. *Microscopic and molecular methods for quantitative phytoplankton analysis. UNESCO (IOC Manuals and Guides)*, 25-30.

López-Sandoval, D.C., C.M. Duarte and S. Agustí. 2021. Nutrient and temperature constraints on primary production and net phytoplankton growth in a tropical ecosystem. *Limnol. Oceanogr.*, 66(7): 2923-2935. https://doi.org/ 10.1002 /lno.11849

Makarewicz, J.C. 1993. Phytoplankton as indicators of environmental health. *Verh. Int. Ver. Theor. Angew. Limnol.*, 25(1): 363-365. https://doi.org/10.1080/03680770. 1992. 11900135

McQuatters-Gollop, A., A.J. Gilbert, L.D. Mee, J.E. Vermaat, Y. Artioli, C. Humborg and F. Wulff. 2009. How well do ecosystem indicators communicate the effects of anthropogenic eutrophication? *Estuar. Coast. Shelf Sci.*, 82(4): 583-596. https://doi.org/10.1016/j.ecss.2009.02.017

Meddeb, M., B. Grami, A. Chaalali, M. Haraldsson, N. Niquil, O. Pringault and A.S. Hlaili. 2018. Plankton food-web functioning in anthropogenically impacted coastal waters (SW Mediterranean Sea): An ecological network analysis. *Prog. Oceanogr.*, 162: 66-82. https://doi.org/10.1016/ j.pocean.2018.02.013

Morcos, S.A. 1970. Physical and chemical oceanography of the Red Sea. *Oceanogr. Mar. Biol. Annu. Rev.*, 8: 73-202

Mudarris, M.A. and A.J. Turkey. 2006. Sewage water quality and its dilution in the coastal waters of South Corniche, Jeddah, Red Sea. *J KAU: Mar Sci.*, 17(2): 11-128.

Paerl, H.W., K.L. Rossignol, S.N. Hall, B.L. Peierls and M.S. Wetz. 2010. Phytoplankton community indicators of short- and long-term ecological change in the anthropogenically and climatically impacted Neuse River Estuary, North Carolina, USA. *Estuar. Coast.*, 33: 485-497. https://doi.org/10.1007/s12237-009-9137-0

Paerl, H.W., L.M. Valdes-Weaver, A.R. Joyner and V. Winkelmann. 2007. Phytoplankton indicators of ecological change in the eutrophying Pamlico Sound system, North Carolina. *Ecol. Appl.*, 17(5): 88-101. https://doi.org/ 10.1890/05-0840.1

Parsons, T.R., Y. Maita and C.M. Lalli. 1984. A manual of chemical and biological methods for seawater analysis.

Pearman, J.K., S. Kürten, Y.V.B. Sarma, B.H. Jones and S. Carvalho. 2016. Biodiversity patterns of plankton assemblages at the extremes of the Red Sea. *FEMS Microbiol. Ecol.*, 92(3):fiw 002. https://doi.org/10.1093/femsec/fiw002

Pena-Garcia, D., N. Ladwig, A.J. Turki and M.S. Mudarris. 2014. Input and dispersion of nutrients from the Jeddah Metropolitan Area, Red Sea. *Mar. Pollut. Bull.*, 80(1): 41-51. https://doi.org/10.1016/j.marpolbul.2014.01.052

Post, A.F., Z. Dedej, R. Gottlieb, H. Li, D.N. Thomas, M. El-Absawi, A. El-Naggar, M. El-Gharabawi and U. Sommer. 2002. Spatial and temporal distribution of *Trichodesmium* spp. in the stratified Gulf of Aqaba, Red Sea. *Mar. Ecol. Prog. Ser.*, 239: 241-250. https://doi:10.3354/meps239241

Qurban, M.A., A.C. Balala, S. Kumar, P.S. Bhavya and M. Wafar. 2014. Primary production in the northern Red Sea. *J. Mar. Syst.*, 132: 75-82. https://doi.org/10.1016/j.jmarsys.2014.01.006

Racault, M.F., D.E. Raitsos, M.L. Berumen, R.J. Brewin, T. Platt, S. Sathyendranath and I. Hoteit. 2015. Phytoplankton phenology indices in coral reef ecosystems: Application to ocean-color observations in the Red Sea. *Remote Sens. Environ.*, 160: 222-234. https://doi.org/10.1016/j.rse.2015.01.019

Reiss, Z. and L. Hottinger. 1984. The Gulf of Aqaba. Ecological micropaleontology. Springer, Berlin

Reynolds, C.S. 2006. The ecology of phytoplankton. Cambridge University Press.

Rombouts, I., G. Beaugrand, L.F. Artigas, J.C. Dauvin, F. Gevaert, E. Goberville and R.R. Kirby. 2013. Evaluating marine ecosystem health: case studies of indicators using direct observations and modelling methods. *Ecol. Indic.*, 24: 353-365. https://doi.org/10.1016/j.ecolind.2012.07.001

Sathicq, M.B., N. Gómez, D.E., Bauera and J. Donadelli. 2017. Use of phytoplankton assemblages to assess the quality of coastal waters of a transitional ecosystem: Río de la Plata estuary. *Cont. Shelf Res.*, 150: 10-17. https://doi.org/1 0.1016/j.csr.2016.08.009

Shaltout, M. 2019. Recent sea surface temperature trends and future scenarios for the Red Sea. *Oceanologia*, 61(4): 484-504. https://doi.org/10.1016/j.oceano.2019.05.002

Shao, N.F., S.T. Yang, Y. Sun, Y., Gai C.S. Zhao, F. Wang, X. Yin and B. Dong. 2019. Assessing aquatic ecosystem health through the analysis of plankton biodiversity. *Mar. Fresh. Res.*, 70(5): 647-655. https://doi.org/10.1071/MF18342

Sofianos, S.S., W.E. Johns and S.P. Murray. 2002. Heat and freshwater budgets in the Red Sea from direct observations at Bab el Mandeb. *Deep Sea Res. Part II Top. Stud. Oceanogr.*, 49(7): 1323-1340. https://doi.org/10.1016/ S0967-0645(01)00164-3

Sommer, U. 2000. Scarcity of medium-sized phytoplankton in the northern Red Sea explained by strong bottom-up and weak top-down control. *Mari. Ecol. Progr. Ser.*, 197: 19-25. https://doi:10.3354/meps197019

Sournia, A. 1982. Form and function in marine phytoplankton. *Biol. Rev.*, 57(3): 347-394. https://doi.org/10.1111/j.1469-185X.1982.tb00702.x

Strickland, J.D and T.R. Parsons. 1972. A practical handbook of seawater analysis

Tam, J.C., J.S. Link, A.G. Rossberg, S.I. Rogers, P.S. Levin, M.J. Rochet and A. Rindorf. 2017. Towards ecosystem-based management: identifying operational food-web indicators for marine ecosystems. *ICES J. Mar. Sci.*, 74(7): 2040-2052. https://doi.org/10.1093/icesjms/fsw230

Taylor, F.J.R. 1976. Dinoflagellates from the International Indian Ocean Expedition. A material collected by the RV" Anton Bruun" 1963-1964. *Bibl. Bot.*, 132: 1-234.

Tett, P., C. Carreira, D.K. Mills, S. Van Leeuwen, J. Foden, E. Bresnan and R.J. Gowen. 2008. Use of a Phytoplankton Community Index to assess the health of coastal waters. *ICES J. Mar. Sci.*, 65(8): 1475-1482. https://doi.org/10.1093/ icesjms/fsn161

Tomas, C.R. (Ed.).1997. Identifying marine phytoplankton. Academic Press, Elsevier, Amsterdam (1997) (858 pp.)

Touliabah, H.E., W.S.A. El-Kheir, M.G. Kuchari and N.I.H. Abdulwassi. 2010. Phytoplankton composition at Jeddah Coast-Red Sea, Saudi Arabia in relation to some ecological factors. *J. King Abdulaziz Univ. Mar. Sci.*, 22(1): 115.

Wafar, M., M.A. Qurban, M. Ashraf, K.P. Manikandan, A.V. Flandez and A.C. Balala. 2016. Patterns of distribution of inorganic nutrients in Red Sea and their implications to primary production. *J. Mar. Syst.*, 156: 86-98. https://doi.org/ 10.1016/j.jmarsys.2015.12.003

Zhang, J., D. Gilbert, A.J. Gooday, L. Levin, S.W.A. Naqvi, J.J. Middelburg and A.K. Van der Plas. 2010. Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. *Biogeosciences*, 7(5): 1443-1467. https://doi.org/10.5194/bg-7-1443-2010