PRELIMINARY STUDIES ON DIVERSITY, OCCURRENCE AND ABUNDANCE OF PHYTOPLANKTON IN KALMAT KHOR, MAKRAN COAST BALOCHISTAN

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Abstract
Phytoplankton are foundation of marine food webs and are sensitive indicators of environmental variability. Phytoplankton are the primary biomass producer in marine ecosystems, providing ecological sustainability for aquatic life. Through photosynthesis, they produce nearly half of the Earth's organic matter, converting inorganic carbon into living biomass. This study documents the diversity, occurrence, and abundance of phytoplankton in Kalmat Khor, Makran coast, Balochistan, during October 2020–July 2021. Seasonal sampling revealed 92 species under 24 families, dominated by diatoms (Bacillariaceae, Chaetocerotaceae, Coscinodiscaceae, Rhizosoleniaceae) with dinoflagellate peaks of *Tripos* sp*., Protoperidinium* sp*., Dinophysis* sp*.,* during nutrient-enriched monsoon periods. Physico-chemical parameters showed variation with seasonal fluctuations, with higher salinity and transparency in winter and reduced dissolved oxygen and pH during summer. Diversity indices indicated a stable and highly diverse community (Shannon–Wiener $H' = 3.62–3.74$; Simpson's $1–D = 0.94–0.95$; Evenness $= 0.87–0.89$), with slight reductions in evenness during diatom blooms. These findings provide the first comprehensive baseline for Kalmat Khor, contributing to Pakistan's coastal biodiversity inventories and supporting conservation and management strategies for semi-enclosed lagoons along the Makran coast.

Keywords: Abundance, Balochistan, diversity, Kalmat Khor, occurrence, phytoplankton

Introduction

Phytoplankton are tiny photosynthetic organisms, and they are from the base of the aquatic food chain and responsible for almost half of the world's primary production (Falkowski et al., 2004; Behrenfeld et al., 2006). Their diversity, distribution and abundance are highly influenced by the environmental variables such as light, temperature, salinity, nutrient availability and hydrodynamic conditions (Cloern et al., 2014; Banerjee et al., 2023). Therefore, phytoplankton are widely used as bio-indicators of ecosystem health and climatic or anthropogenic activities (Paerland Paul, 2012; Hochfeld & Hinners, 2024). In tropical and subtropical marine ecosystems, particularly those influenced by monsoonal regimes, phytoplankton dynamics showed significant seasonal variability. The northern Indian Ocean is known as one of the most productive oceanic regions which are driven by intense upwelling during the southwest monsoon and stratification during the northeast monsoon (Prasanna Kumar et al., 2001; Shunmugapandi et al., 2022). These seasonal shifts result in alternating dominance of diatoms and dinoflagellates, with implications for biogeochemical cycling, carbon flux and potential fisheries productivity (Sarma et al., 2013; Suresh & Manjappa, 2024). Despite studies of phytoplankton ecology across the Indian Ocean region, Pakistani waters remain underexplored, particularly along the Balochistan/Makran coast. Phytoplankton have been investigated in several studies (Saifullah & Moazzam, 1978; Latif et al., 2013; Ali et al., 2013; Shahnaz et al., 2018; Khan, 2022; Bano et al., 2023). Kalmat Khor, a shallow coastal lagoon located along the Makran coast of Balochistan, represents a unique ecological niche. Tidal activities monsoonal inputs create unique environmental gradients that support diverse phytoplankton assemblages. However, no study has yet been conducted to document its planktonic biodiversity or assess its ecological dynamics. The ecosystems of coastal lagoons are particularly vulnerable to fluctuations brought on by changes in a variety of natural processes and human activities (Kwadzo et al., 2022; Zennaro et al., 2023). Additionally, their environments and ecosystems are more susceptible to the dual effects of land and sea, and are more affected by interactions between land, marine, and atmospheric processes. They are especially vulnerable to severe physical, ecological, and societal changes brought on by global climate change due to their location in the coastal landscape. Changes in the flushing regime, freshwater inputs, and water chemistry, as well as complete inundation and loss, with the accompanying loss of natural and human communities, are among the expected shifts in the physical and ecological characteristics of the lagoons impacted by global climate change. Changes in the climate influence the salinity, temperature, and other components of the Curonian Lagoon's water balance (Jakimavičius et al., 2018; Lopes et al., 2019). The study of phytoplankton abundance in the Kalmat Khor coastal lagoon has important environmental significance that extends further than species composition and seasonal variations. Phytoplankton are the base of the aquatic food web and the primary producers in coastal lagoon of ecosystems. Their elevated abundance indicates primary productivity is strong, which supports zooplankton, benthic invertebrates, fish larvae, and fish juvenile. This study revealed the role of Kalmat Khor as a productive nursery and feeding ground for higher trophic levels, as well as commercially important fish species. Phytoplankton abundance also reflects nutrient accessibility and biogeochemical processes within the lagoon. Variations in their density suggest vigorously nutrient cycling, mainly of nitrogen and phosphorus, which are necessary for supporting ecosystem yield. The lagoon may therefore function as both a nutrient sink and a source, influencing contiguous coastal waters. In addition, phytoplankton communities are receptive to changes in environmental conditions such as temperature, salinity, turbidity, and nutrient input. Their abundance can serve as a biological indicator of water quality and ecosystem health. Shifts in phytoplankton density may signal natural environmental fluctuations or rising anthropogenic pressures, such as organic enrichment and land-based runoff. Furthermore, phytoplankton plays a key role in carbon fixation and subtraction. Through photosynthesis, they

supply carbon cycling within the lagoon and assist to the transfer of organic carbon to sediments and higher trophic levels, emphasizing the lagoon's role in coastal carbon dynamics. Overall, the phytoplankton abundance observed in Kalmat Khor coastal lagoon underscores its ecological significance as a highly productive, dynamic, and sensitive ecosystem, providing vital ecological services and supporting coastal biodiversity and fisheries.

The aim of this research is to provide comprehensive data on the taxonomic diversity, abundance, and seasonal variation of phytoplankton in Kalmat Khor, along the Makran coast of Balochistan. As the first study of its kind in this specific area, it establishes a critical baseline for the region while examining how environmental factors influence seasonal distribution patterns. By highlighting the role of phytoplankton as primary producers and bioindicators of ecosystem health, these findings will contribute to regional biodiversity inventories and inform future conservation management strategies for the coastal ecosystems of Balochistan. Also, the study will move beyond a descriptive inventory and demonstrate a hypothesis-driven ecological framework. This study will clarify the analytical direction of the research and better highlight its scientific contribution.

Materials and Methods
Seasonal phytoplankton sampling was conducted from October 2020 to July 2021 at a fixed station in Kalmat Khor (25º24'47" N, 64 º03'49" E) Makran Coast Balochistan (Figure 1). Samples were collected by towing a Hydro-Bios net of mesh size 55 µm, in the subsurface (5 m) waters for 10 minutes at a constant speed of 0.5 m /s. A digital flow meter was used to measure the volume of water flowing through the net. Samples were preserved in 5% formaldehyde on boat. In laboratory, samples were divided into aliquots (sub-samples). A drop of plankton concentrated sample from the aliquot was kept on a cavity glass slide and identified the specimens by using an upright microscope (Nikon LABOPHOT-2) at (10x20 magnification). For identification of phytoplankton, literatures were followed by (Newell and Newell, 1977; Tomas, 1997; Castellani and Edwards, 2017; Minu and Muhamed Ashraf, 2022). Density of phytoplankton was calculated through Sedgewick Rafter Counting Chamber at 10x40 magnification power, by pouring 1 ml of concentrated samples on the grids of the cell. Phytoplankton density was measured at the lowest possible taxon level.

Statistical analysis
Density of phytoplankton was calculated through Sedgewick Rafter Counting Chamber at 10x40 magnification power, by pouring 1 ml of concentrated samples on the grids of the cell. Phytoplankton density was measured at the lowest possible taxon level. The final density of phytoplankton was counted by using the following formula:

$$\text{Number of organisms (m-3)} = (C \times V1) / (V2 \times V3)$$

where,
C= number of organisms counted,
V1 = Volume of concentrated sample (ml),
V2 = Volume of sample counted (ml),
V3= Volume of filtered water by the plankton net (m3)

By using the data on counting, Species richness (Df) was applied to determine the quantity of genera in the sample:

$$\text{Species richness, } Df = (S-1)/\ln(N)$$

where,
S = number of genera in a sample
N = total number of genera

Shannon-Wiener index (H) was used to evaluate the generic diversity in a sampling station. The following equation is used to calculate the Shannon-Wiener index:

$$\text{Shannon-Wiener index, } H = -\Sigma\, Pi \times \ln(Pi) \text{ and } Pi = n/N$$

where,
n = total number of individuals in a sample
N = total number of individuals

One-way ANOVA and Pearson's correlation were used to test seasonal differences between physicochemical parameters and families of phytoplankton. Principal Component Analysis (PCA) was used to explore relationships between phytoplankton assemblages and environmental parameters (temperature, salinity, pH, dissolved oxygen, transparency) by R 4.4.1 software.
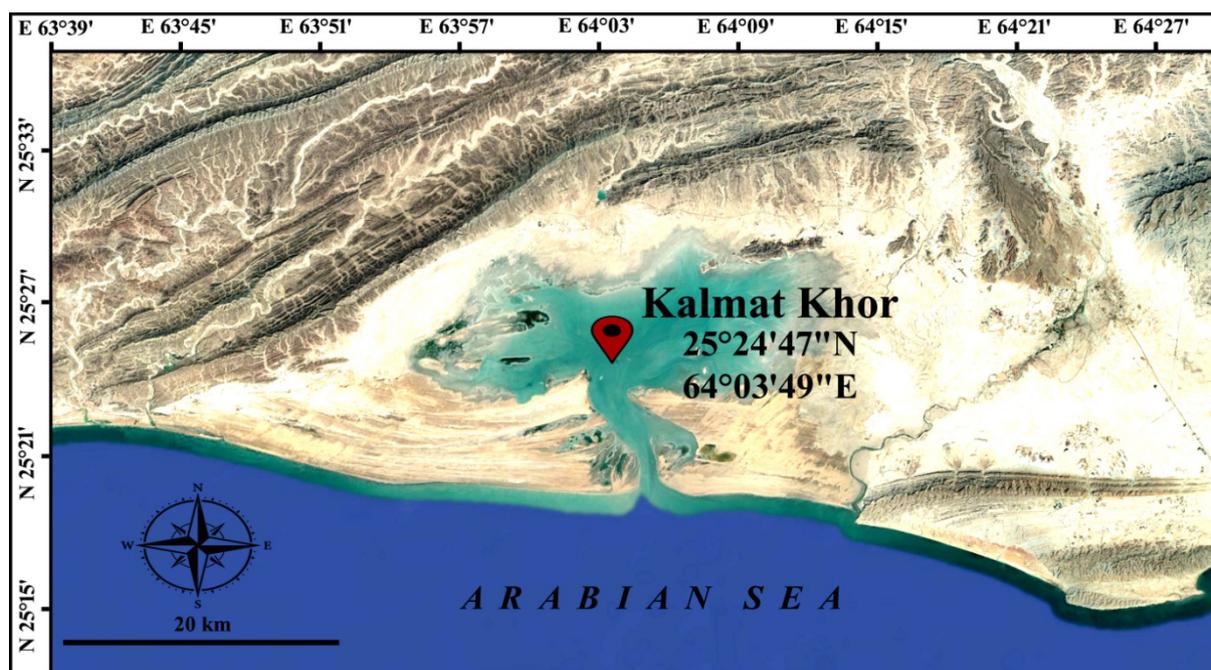
Figure 1. Study area of Kalmat Khor (25°24'47"N, 64°03'49"E), Makran Coast Balochistan

Results and Discussion

Table 1 shows Physico-chemical parameters from KalmatKhorwere taken simultaneously on boat during plankton sampling in the period of October 2020 to July 2021. Highest water temperature 31 °C was recorded in July and lowest 21 °C in January. Salinity fluctuated between 37‰ and 40‰, with the highest values recorded during winter months (January and March). pH remained relatively stable, ranging from 7.9 to 8.6, with slightly lower values in July. Dissolved oxygen (DO) levels varied between 7.0 and 8.0 mg/l, with the lowest

concentration in July. Transparency ranged from 65 cm to 120 cm, with highest range of clarity observed in January.

Species composition of Phytoplankton at Kalmat Khor
A total of 24 families comprising 92 species of phytoplankton were identified from Kalmat Khor during five (05) monsoonal seasons (Pre monsoon, intermediate I, monsoon, intermediate II and post-monsoon) (Table 2). Bacillariophyceae recorded as the dominant family of the diatom assemblage, while Chaetocerotaceae, Coscinodiscaceae, Rhizosoleniaceae and Leptocylindraceae found consistently across seasons. Families of dinoflagellates, i.e. Ceratiaceae, Protoperidiniaceae and Gonyaulacaceae were present throughout the seasons but contributed less to overall richness. Phytoplankton were found diverse with consistent occurrence of *Biddulphia, Chaetoceros, Coscinodiscus* and *Protoperidinium* in Pre monsoon season. Large centric diatoms (*Ditylum brightwellii* and *Odontella regia*) were recorded as abundant group during present study. Diversity in Intermediate I season remained high, but several taxa (*Nitzschia socialis, Tripos horridus*) showed reduced frequency. Dinoflagellates (*Dinophysis rotundata*) appeared sporadically. In Monsoon season, composition of phytoplankton species shifted markedly, with dominance of *Nitzschia ventricosa*, *Cylindrotheca closterium* and *Chaetoceros diversus*. Several Tripos species were recorded in blooms, reflecting nutrient enrichment during monsoon mixing. Phytoplankton community became stabilized in Intermediate II season with the presence of *Pleurosigmae longatum*, *Odontella regia* and *Cyclotella* spp. Dinoflagellates were found less frequent in Intermediate II season as compared to monsoon. Post-monsoon assemblages were recorded as diverse with the presence of *Chaetoceros, Coscinodiscus* and *Protoperidinium*. Species such as *Ditylum brightwellii* and *Lauderia annulata* were consistently present, indicating resilience of diatom communities.

Figures 2 show Relative abundance (%) of phytoplankton families identified in Kalmat Khor was shown in Figure 02. The seasonal percentage analysis revealed that the phytoplankton assemblage at Kalmat Khor was consistently dominated by Bacillariaceae, contributing between 9.1% and 12.8% across all seasons, with its peak during the monsoon season. Ceratiaceae (*Tripos* spp.) also showed strong seasonal presence, accounting for 9.8% to 17.1%, with highest contributions during Intermediate I and Monsoon, reflecting its affinity for nutrient-rich, turbulent conditions. Coscinodiscaceae maintained a stable and prominent role throughout the year, ranging from 9.8% to 17.1%, peaking in Intermediate II. Families such as Dinophysaceae, Hemiaulaceae and Chaetocerotaceae contributed moderately (typically 6.4% to 12.2%), indicating their resilience across hydrological transitions. In contrast, families like Hyalodiscaceae, Thalassiosiraceae and Stephanodiscaceae remained low in abundance, often below 4.3%, suggesting limited ecological dominance or seasonal specialization. Protoperidiniaceae and Peridiniaceae showed marked seasonal variability, with Protoperidiniaceae peaking at 9.1% during Pre monsoon and Intermediate II and dropping to zero during the monsoon.Diversity indices calculated for Kalmat Khor, phytoplankton assemblages reveal consistently high diversity across seasons. Shannon–Wiener values (H′ = 3.62–3.74) and Simpson's diversity (1–D = 0.94–0.95) indicated a stable, diverse community structure. Evenness values (0.87–0.89) suggested relatively balanced species distributions, with slight reductions during monsoon due to diatom dominance. These results align with Northern Arabian Sea phytoplankton dynamics, where monsoon upwelling enhances richness but reduces evenness through diatom blooms (Table 3).

Table 1. Seasonal variation in the Physico-chemical parameters recorded at Kalmat Khor during October 2020 to July 2021.

Seasons	Tide (m) /Time	Water temperature	Salinity	pH	Dissolved oxygen	Transparency
Inter-monsoon II (October)	1.81/ 14:07 p.m.	31 °C	37 ‰	8.0	7.4 mg/l	80 cm
Post-monsoon (December)	1.99/ 12:51 p.m.	20 °C	38 ‰	8.1	8 mg/l	70 cm
Pre-monsoon (January)	0.88/ 12:46 p.m.	21 °C	40 ‰	8.1	7.8 mg/l	120 cm
Intermediate I (April)	2.23/ 9:36 a.m.	29 °C	38 ‰	8.0	7.5 mg/l	80 cm
Monsoon (July)	2.49/ 13:28 p.m.	32 °C	37 ‰	7.9	7 mg/l	80 cm

Table 2. Taxonomic list of phytoplankton species collected from KalmatKhor during October 2020 to September 2021.

Family	Species	Intermediate II	Post-monsoon	Pre-monsoon	Intermediate I	Monsoon
Biddulphiaceae	*Biddulphia* sp.	+	+	+	+	-
Bacillariaceae	*Nitzschia socialis* Gregory, 1857	-	-	-	+	+
	Nitzschia linearis W.Smith, 1853	+	-	+	-	+
	Nitzschia ventricosa Kitton, 1873	+	-	-	-	+
	Nitzschia insignis Gregory, 1857	-	+	+	+	-
	Nitzschia sp. I	-	-	+	+	-
	Nitzschia sp. II	+	+	-	-	+
	Bacillaria sp. I	-	+	+	+	-
	Bacillaria sp. II	+	+	-	-	+
	Cylindrotheca closterium (Ehrenberg) Reimann & J.C.Lewin, 1964	-	+	+	+	+
	Cylindrotheca sp.	+	+	-	-	+
	Pseudonitzschia sp.	-	-	+	+	+
Bellerocheaceae	*Bellerochea* sp. I	-	+	+	+	+
	Bellerochea sp. II	-	+	-	+	-
Ceratiaceae	*Tripos brevis* (Ostenfeld & Johannes Schmidt) F.Gómez, 2013	-	-	+	+	+
	Tripos furca (Ehrenberg) F.Gómez, 2013	+	-	-	-	+
	Tripos fusus (Ehrenberg) F.Gómez, 2013	-	+	+	+	+
	Tripos falcatus (Kofoid) F.Gómez, 2013	+	-	+	+	+
	Tripos longirostrum(Gourret) Hallegraeff & Huisman, 2020	+	+	-	-	+
	Tripos horridus (Cleve) F.Gómez, 2013	-	+	+	+	-
	Tripos trichoceros (Ehrenberg) Gómez, 2013	-	-	-	+	+
	Tripos sp. I	-	+	+	+	-
	Tripos sp. II	-	+	+	+	+

Chaetocerotaceae	*Chaetoceros diversus* Cleve, 1873	-	+	+	+	+
	Chaetoceros costatus Pavillard, 1911	-	+	-	+	+
	*Chaetoceros decipiens*Cleve, 1873	-	+	+	+	-
	Chaetoceros brevis F.Schütt, 1895	+	-	-	-	+
	Chaetoceros sp. I	+	-	+	+	-
	Chaetoceros sp. II	+	+	-	-	+
Coscinodiscaceae	*Coscinodiscus lineatus* Ehrenberg, 1841	-	+	+	+	-
	Coscinodiscus marginatus Ehrenberg, 1844	+	+	+	-	-
	Coscinodiscus radiates Ehrenberg, 1840	+	-	+	-	+
	Coscinodiscopsis jonesiana (Greville) E.A.Sar & I.Sunesen, 2008	-	+	-	+	+
	Coscinodiscus sp. I	+	-	+	+	-
	Coscinodiscus sp. II	-	+	-	+	+
Dinophyceae	*Dinophysis miles* Cleve, 1900	-	+	-	+	+
	Dinophysis caudata Saville-Kent, 1881	-	+	+	-	+
	Dinophysis sp.	-	-	+	+	+
Hemidiscaceae	*Actinoptychus octonarius* (Ehrenberg) Kützing, 1844	+	-	+	-	+
	Actinocyclus sp. 1	+	-	-	-	-
	Actinocyclus sp. II	+	-	-	-	+
	Hemidiscus sp. I	+	+	-	+	-
	Hemidiscus sp. II	+	+	+	+	-
Hemiaulaceae	*Hemiaulus membranaceus* Cleve	-	+	+	+	+
	Cerataulina sp. 1	-	-	+	+	+
	Cerataulina sp II	+	+	+	+	+
	Cerataulina sp III	+	+	+	+	+
	Eucampia zoodiacus Ehrenberg	+	-	+	-	-
	Eucampia sp.	+	-	+	-	-
Hyalodiscaceae	*Podosira stelligera* (Bailey) A. Mann, 1907	-	-	-	+	-
Gonyaulacaceae	*Gonyaulax* sp.	-	+	-	+	-
Lauderiaceae	*Lauderia annulata* Cleve, 1873	+	+	+	-	+
	Lauderia sp. I	+	+	+	-	+
	Lauderia sp. II	+	+	+	-	+
Triceratiaceae	*Triceratium brightwellii* T.West, 1860	+	+	+	-	+
Lithodesmiaceae	*Ditylum* sp.	+	+	+	+	+
Leptocylindraceae	*Leptocylindrus minimus* Gran, 1915	+	-	+	+	+
	Leptocylindrus danicus Cleve, 1889	-	+	-	-	+
	Leptocylindricus sp.	-	+	-	-	+
Naviculaceae	*Navicula* sp I	-	-	-	-	+
	Navicula sp II	-	+	-	-	+
Oxyphysaceae	*Phalacroma rotundatum* (Claparéde &Lachmann) Kofoid & J.R.Michener, 1911	+	+	+	+	-
Pleurosigmataceae	*Pleurosigmae longatum* W.Smith, 1852	-	+	-	+	+
	Pleurosigma sp. I	+	+	+	+	-
Protoperidiniaceae	*Protoperidinium depressum* (Bailey, 1854) Balech, 1974	+	+	+	+	-
	Protoperidinium oceanicum (VanHöffen, 1897) Balech, 1974	+	-	+	+	-

	Protoperidinium conicum (Gran) Balech, 1974	+	-	+	+	-
	Protoperidinium sp. 1	+	+	+	+	-
	Protoperidinium sp. 1I	+	+	+	+	-
	Protoperidinium antarcticum (Schimper ex Karsten) Balech, 1974	+	-	+	+	-
Peridiniaceae	*Peridinium* sp	+	+	+	+	-
Rhizosoleniaceae	*Rhizosolenia fragilissima f. fragilissima* Bergon, 1903	+	+	+	+	-
	Dactyliosolen sp. I	+	+	+	+	-
	Dactyliosolen sp. II	+	+	+	+	-
	Rhizosolenia cylindrus Cleve, 1897	+	+	+	-	-
	Guinardia sp.	+	+	-	-	-
Rhopalodiaceae	*Pyxidicula sp* O'Meara, 1877	+	-	-	+	-
Stephanodiscaceae	*Cyclotella* sp. I	+	-	-	+	-
	Cyclotella sp. II	+	+	-	-	-
	Cyclotella sp. III	+	+	+	+	-
Triceratiaceae	*Hobaniella longicruris*(Greville) P.A. Sims & D.M. Williams in Sims et al., 2018	+	+	+	+	-
	Odontella regia (Schultze) Simonsen, 1974	+	-	+	-	-
	Odontella mobilensis (J. W. Bailey) Grunow, 1884	+	+	+	+	-
	*Odontella*s p. I	+	+	-	+	-
	Odontella sp. II	+	+	-	+	-
	Trieres mobiliensis(J.W.Bailey) Ashworth &E.C.Theriot in Ashworth, Nakov&E.C.Theiriot, 2013	+	+	+	+	-
	Cerataulus granulatus (Roper) P.A. Sims & D.M. Williams, 2018	+	-	+	-	+
Thalassiosiraceae	*Planktoniella* sp. I	+	-	-	+	-
	Planktoniella sp.II	+	-	+	-	-
	Thalassiosira eccentrica (Ehrenberg) Cleve, 1904	+	+	+	+	-

Table 3. Seasonal variation in phytoplankton diversity indices at Kalmat Khor during October 2020 to July 2021.

Season	Species Richness	Shannon–Wiener Diversity Index	Simpson's Diversity Index	Evenness
Pre-monsoon	52	3.62	0.94	0.89
Intermediate I	55	3.68	0.95	0.89
Monsoon	61	3.74	0.95	0.88
Intermediate II	59	3.7	0.95	0.88
Post-monsoon	57	3.66	0.94	0.87
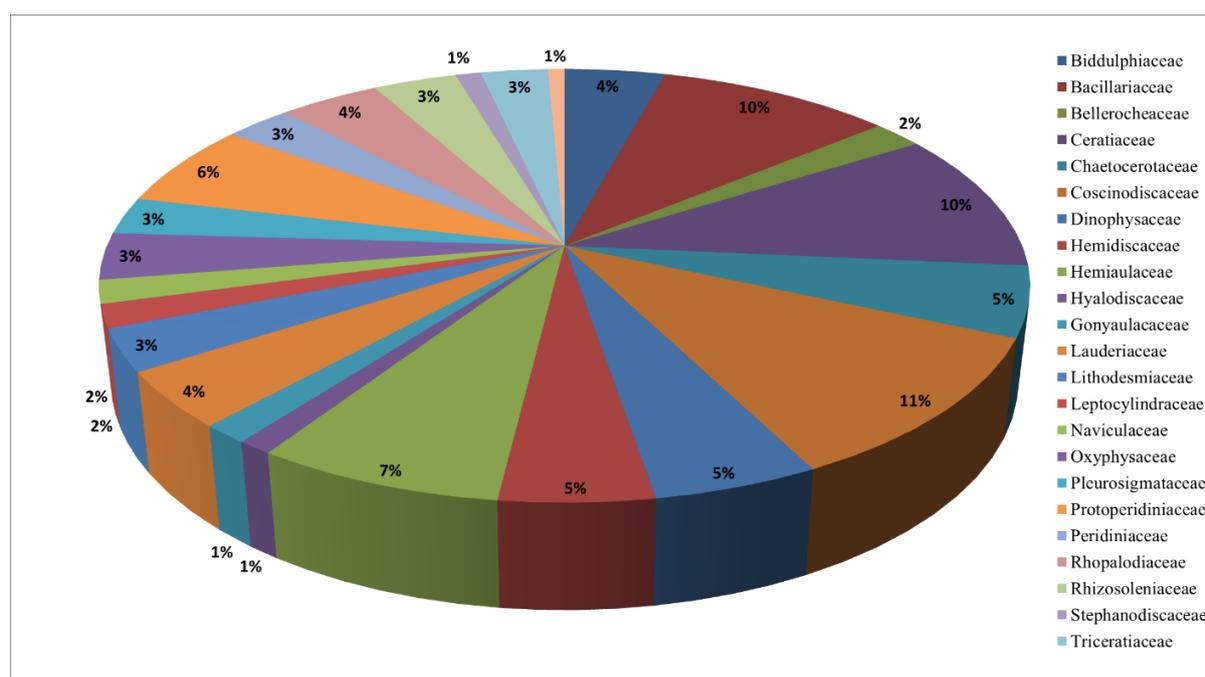
Figure 2. Relative abundance (%) of phytoplankton families identified in Kalmat Khor from October 2020 to September 2021.

ANOVA revealed that only two diatom families, Hemiaulaceae ($p = 0.015$) and Stephanodiscaceae ($p = 0.047$), exhibited statistically significant seasonal variation, both peaking in cooler, oxygen-rich seasons. Most of the families including Bacillariaceae, Ceratiaceae (*Tripos* spp.), Gonyaulacaceae, and Naviculaceae, did not show significant seasonal differences ($p > 0.05$). Dinoflagellate families such as Gonyaulacaceae and Lauderiaceae were positively associated with temperature and negatively with dissolved oxygen, consistent with post-monsoon stratified conditions, but their seasonal variation was not statistically significant. Diatom families including Bacillariaceae, Coscinodiscaceae, and Rhizosoleniaceae correlated positively with dissolved oxygen, reflecting their prevalence in cooler, mixed waters (Table 4).

Table 4. One-way ANOVA results showing seasonal variation in phytoplankton families, where significant differences are marked with * ($p < 0.05$), while ns indicates non-significant variation.

| Family	P_value	Significance	Ecological Interpretation
Biddulphiaceae	0.638	ns	No seasonal variation found; opportunistic distribution
Bacillariaceae	0.638	ns	Stable across seasons; favors oxygen-rich cooler waters but not statistically significant
Bellerocheaceae	1.000	ns	Very low abundance; no seasonal pattern
Ceratiaceae (Tripos spp.)	0.519	ns	Warm-season dinoflagellate, but variation not significant
Chaetocerotaceae	0.182	ns	Very low or negligible seasonal tendency, but not significant

Coscinodiscaceae	0.559	ns	Associated with dissolved oxygen; no seasonal difference
Dinophysaceae	0.559	ns	Opportunistic dinoflagellate; no seasonal signal
Hemidiscaceae	0.559	ns	Transitional diatom; no significant seasonal variation
Hemiaulaceae	0.015	*	Significant seasonal variation; peaks in cooler, oxygen-rich waters
Hyalodiscaceae	1.000	ns	No seasonal variation found
Gonyaulacaceae	0.559	ns	Linked to warm stratified waters; not statistically significant
Lauderiaceae	0.559	ns	Warm-season dinoflagellate; no significant seasonal difference
Lithodesmiaceae	0.182	ns	Transitional; no significant seasonal variation
Leptocylindraceae	0.450	ns	Weak seasonal tendency; not significant
Naviculaceae	0.420	ns	Transitional diatom; no significant seasonal variation
Oxyphysaceae	0.559	ns	Rare occurrence; no significant seasonal difference
Pleurosigmataceae	1.000	ns	Monsoon-associated; no significant seasonal difference
Protoperidiniaceae	0.638	ns	Chemical sensitivity; no seasonal variation
Peridiniaceae	1.000	ns	No seasonal variation
Rhizosoleniaceae	0.718	ns	Oxygen-linked diatom; no significant seasonal variation
Rhopalodiaceae	0.559	ns	Transitional diatom group; no significant seasonal variation
Stephanodiscaceae	0.047	*	Significant seasonal variation; peaks during mixing periods
Triceratiaceae	1.000	ns	Monsoon preference; not significant
Thalassiosiraceae	0.638	ns	Cooler-water diatom; no significant seasonal variation

Correlation analyses revealed distinct family-level responses to environmental gradients. Warmer waters were negatively correlated with dissolved oxygen but positively associated with dinoflagellate families such as Gonyaulacaceae and Lauderiaceae, highlighting their dominance in post-monsoon stratified conditions. In contrast, oxygen-rich cooler waters favored diatom families including Bacillariaceae and Coscinodiscaceae. Salinity and transparency were positively linked, but negatively correlated with Pleurosigmataceae, Triceratiaceae, and Peridiniaceae, indicating that these families thrive in lower-salinity, turbid monsoon waters. pH showed moderate positive associations with Hemiaulaceae and Protoperidiniaceae.

In PCA analysis, PC1 represents the primary seasonal gradient, as the seasonal samples (Pre monsoon, Monsoon, Postmonsoon, Intermediate I) are clearly separated along this axis. This matches the PCA outcome, where PC1 explained the largest proportion of variance (42.6%) and distinguished diatom-dominated cooler seasons (Thalassiosiraceae, Bacillariaceae, Rhizosoleniaceae) from dinoflagellate-rich warmer seasons (Ceratiaceae, Gonyaulacaceae,

Protoperidiniaceae). As the PC1 isseasonal structuring axis,showed the community structure was found influenced by temperature, salinity, and transparency gradients. PC2 shows proportion of variance with (13.4%). Families such as Naviculaceae, Pleurosigmataceae, and Leptocylindraceae align with this axis, showing sensitivity to pH and dissolved oxygen (Figure 3).
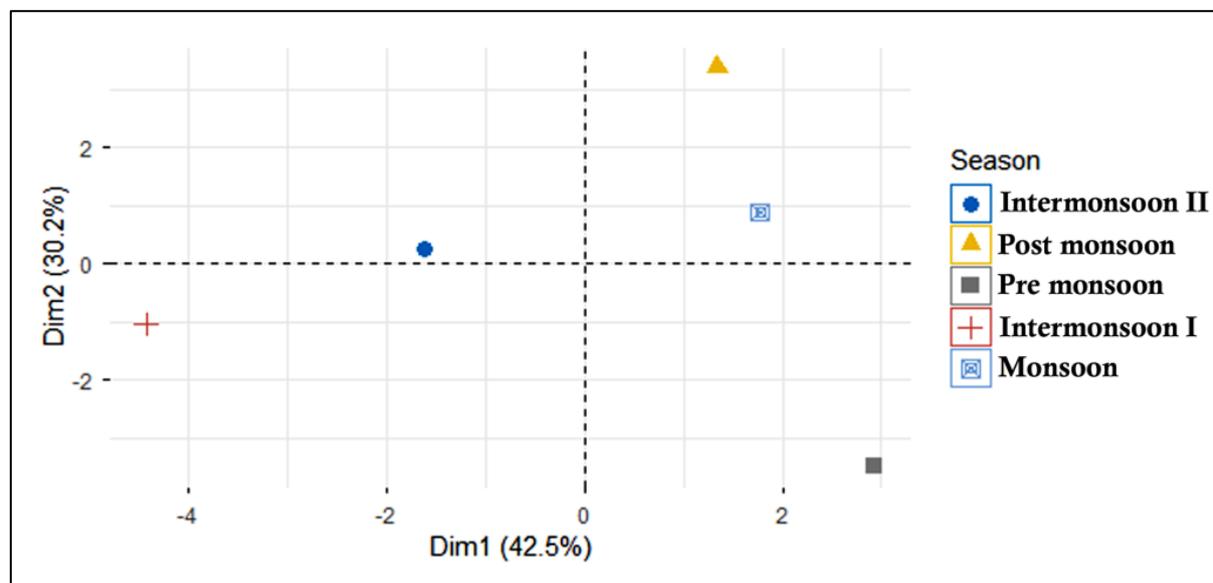
Figure 3. Principal component analysis of phytoplankton community structure across seasons from Kalmat Khor during October 2020 to July 2021.

The seasonal succession of phytoplankton in Kalmat coastal waters, characterized by persistent diatom dominance and opportunistic dinoflagellate peaks during the monsoon, underscores the profound impact of monsoonal hydrodynamics on coastal productivity.Our findings are consistent with regional studies along Pakistan's Arabian Sea coast and align with global patterns in monsoon-driven and upwelling ecosystems.

Diatom dominance (*Chaetocerotaceae, Coscinodiscaceae, Rhizosoleniaceae*) across seasons were found parallels to the observations from MianiHor Lagoon, where Latif et al. (2013) reported elevated diatom productivity during the southwest monsoon. Khokhar et al. (2020) similarly documented seasonal shifts at Manora Island and Mubarak Village, with taxa such as *Nitzschia* and *Cylindrotheca* proliferating during monsoon enrichment. Siddiqui et al. (2008) emphasized the resilience of centric diatoms (*Coscinodiscus, Ditylum*) in post-monsoon phases along Karachi's coast, mirroring our results. Comparable seasonal succession has been reported in other monsoon-influenced systems. In the Bay of Bengal, Madhupratap et al. (1996) and Gomes et al. (2000) documented diatom dominance during monsoon mixing, followed by dinoflagellate proliferation in stratified waters. Along the Indian west coast, Sawant and Madhupratap (1996) observed similar diatom and dinoflagellate alternations. In the South China Sea, Chen et al. (2009) and Doan-Nhu et al. (2010) reported monsoon-driven shifts, with diatoms thriving during nutrient pulses and dinoflagellates dominating in post-stratification phases. In the Persian Gulf, Al-Yamani et al. (2004) highlighted seasonal diatom blooms linked to monsoon currents. Globally, Margalef's (1978) successional model provides a theoretical framework that matches our observed transitions. Mediterranean studies (Estrada et al., 1985; Vidussi et al., 2001) and upwelling systems off Peru and Chile (Thomas, 1970; Iriarte &

González, 2004) similarly reported diatom dominance during nutrient-rich phases, followed by dinoflagellate opportunism. In temperate estuaries like Chesapeake Bay, Harding et al. (2002) documented seasonal diatom peaks and dinoflagellate blooms, reinforcing the universality of these patterns.

Therefore, our findings confirm that monsoonal hydrodynamics are the primary driver of phytoplankton succession in Kalmat Khor. Diatoms dominate during nutrient-rich seasons, while dinoflagellates exploit stratified conditions. The resilience of centric diatoms in post-monsoon periods supports their ecological importance in sustaining productivity. These results extend regional knowledge of Pakistan coastal ecosystems and prove Kalmat Khor as a global framework of monsoon- and mixing-driven phytoplankton dynamics.

This study demonstrates that phytoplankton assemblages in Kalmat Khor coastal waters are strongly structured by monsoonal hydrodynamics, with diatoms dominating across all seasons and dinoflagellates appearing opportunistically during nutrient phases. The observed succession pattern in pre-monsoon stability, monsoon enrichment and post-monsoon remarkable resilience with regional and global trends, provides the adaptability of coastal phytoplankton communities to fluctuating environmental conditions. These findings highlight the ecological importance of diatoms in sustaining productivity and emphasize the need for continued biodiversity monitoring to support conservation and management of Pakistani coastal ecosystems.The data and results will be a substantialaddition to the knowledge of phytoplankton assemblage, species diversity and seasonal variation an important geographical location of Makran coast.

Ethical approval
This article does not contain any studies involving human subjects.

Informed consent
Not available.

Data availability statement
No data additional to the sources cited were used for the research described in the article.

Conflicts of interest
The authors declare that there are no conflicts of interest.

Contribution of authors
Quratulan AHMED: Taxonomic analysis, identification and corresponding to the expert for confirmation of species, writing - original draft preparation
Qadeer Mohammad ALI: Conceptualization, sampling and data collection, paper review

Shumaila MUBARAK: Writing- original draft preparation and literature searching

Levent BAT: Writing - review and editing

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