Indian Journal of Geo Marine Sciences
Vol. 52 (02), February 2023, pp. 101-113
DOI: 10.56042/ijms.v52i02.6926

Seasonal variation of diatom biodiversity with relation to environmental factors in Northern Arabian Sea

T Hamid, N Shoaib* & P J A Siddiqui

Centre of Excellence in Marine Biology, University of Karachi, Karachi – 75270, Pakistan

*[E-mail: nafisashoaib@gmail.com]

Received 16 January 2022; revised 17 January 2023

Diatoms are planktonic, microscopic and ubiquitous in distribution. In this study, the samples were collected in four seasons from two sites of the Northern Arabian Sea (Gadani shipbreaking area of the Baluchistan coast and Sandspit, Sind coast of Pakistan) for a period of one year. The seasonal distribution of diatom and variations in physico-chemical characteristics of seawater were examined from samples collected on board using Niskin bottles. Eighty five species of diatoms (pennate = 40; centric = 45) were recorded along the Gadani shipbreaking area of the Baluchistan coast of Pakistan. Similarly, from Sandspit, Sind coast of Pakistan seventy four species of diatoms (pennate = 35; centric = 39) were recorded. In Gadani, the highest number of species was recorded in North-East Monsoon (NEM), while in Sandspit, it was recorded in the South-West Monsoon (SWM). The dominant species of pennate diatoms such as *Navicula*, *Nitzschia* and *Pseudonitzchia* were similar in abundance at both the sites, while the dominant centric diatoms were diversified in both coastal sites. The present study indicates that the environmental factors such as temperature, dissolve oxygen, salinity, pH, nitrate, nitrite, phosphate, ammonia, and chlorophyll-*a* influences the diatom diversity and abundance, and any significant changes in the diversity of phytoplankton species indicate deterioration of the marine ecosystem.

[**Keywords**: Centric diatom, Gadani, Monsoon, Pennate diatom, Sind]

Introduction

Diatoms (Bacillariophyceae) are planktonic, unicellular microalgae with ubiquitous distribution. Phenotypically, these are present in two forms, *viz*. centric diatoms and pennate diatoms, and their structure is mainly composed of silica[1-4]. Diatoms are the autotrophic dominant phytoplankton found in a wide range of marine, freshwater, cold, warm, and moist habitats[5]. These are susceptible to alteration in their habitat, and therefore, diatom species are often used as biological indicators of aquatic ecosystems[6]. Monitoring of phytoplankton biomass is important as ecosystem monitoring solely based on chemical and physical analysis is often insufficient. The variation in the diatom composition can reveal the definite and the preceding situation of the aquatic environment. Diatoms depict water quality through alteration in the community composition, changes in sensitive species abundance and distribution[7]. They contribute approximately 45 % of primary productivity and represent 1 % of Earth's photosynthetic biomass[8]. Physico-chemical factors such as light, temperature, dissolved oxygen, salinity, pH, nutrients, hydrographic conditions, wind velocity, and seawater inflow into the estuaries induce diatom growth, composition and distribution[9-11].

The diatom's outer cell wall or frustule is made up of Silicon[1] hence, silicate act as a limiting factor for the growth of diatoms. Diatoms are predominant players in the functioning and regulation of Earth's biogeochemical cycles such as carbon, nitrogen and silicon. They are an environmentally significant group of phytoplankton community contributing twenty per cent of the world's carbon dioxide assimilation[12]. Studies have shown that nutrients such as silicon, nitrogen and phosphorus are essential for phytoplankton growth[13-15]. These are integrated into the phytoplankton cells as organic components for, *e.g.*, nucleic acid, proteins and for the development of cell wall. Discharge of inorganic silicon, phosphorus and nitrogen into the marine environments is mainly land-based and from the untreated municipal waste, sewage disposal, industrial pollution, and aquaculture farming[16-18]. The high nutrient loading into the marine environment causes eutrophication and proliferation of harmful algae in the form of algal blooms[19].

In the present study, seasonal biodiversity and richness of phytoplankton (diatom) in relation to physico-chemical parameters from the nearshore and offshore waters of the ship breaking industry (polluted site) and Sandspit (unpolluted site) is assessed. Changes in phytoplankton community (diatoms) structure may have essential implications in food web dynamics and nutrient cycling[20]. The present study will demonstrate the current data that aid in comprehending the marine ecological state of biodiversity and profusion of phytoplankton in the Gadani ship-breaking area and Sandspit. The study will help understand the seasonal phytoplankton abundance and biodiversity in the inshore and offshore waters of the Pakistan coast in relation to water parameters.

Materials and Methods

Study area

The sampling sites selected were Gadani ship-breaking (Baluchistan coast) and Sandspit (Sindh coast) for the analysis of diatoms (phytoplankton) and their variations with reference to seasons and physic-chemical parameters (Fig. 1). The Baluchistan coast stretches over 800 km, and the Sind coast is 250 km long. These areas are important for economically important fisheries and fishing ground that supports a thriving fishing industry, providing livelihoods for thousands of people and contributing significantly to the country's economy[21]. These coastal areas are also important shipping routes, providing access to international trade and facilitating the movement of goods and resources[22].

Methodology

The samples were collected in four seasons from these sites for a period of one year. For the diatom seasonal distribution studies in relation to environmental parameters, physico-chemical characteristics of seawater were determined from samples collected on board using Niskin bottles (1.7 litres) from 1 m depth. Seawater samples were fixed with Lugol's Iodine solution on board. The diatoms were analysed using an inverted microscope (Olympus, BX-51, Japan). Identification of diatoms was done following standard taxonomic literature[23]. Sea water temperature, salinity, and pH were recorded with a thermometer, refractometer (Atago), and pH meter (Hanna. Inc), respectively; while the Dissolve Oxygen (DO) is estimated using the Winkler's

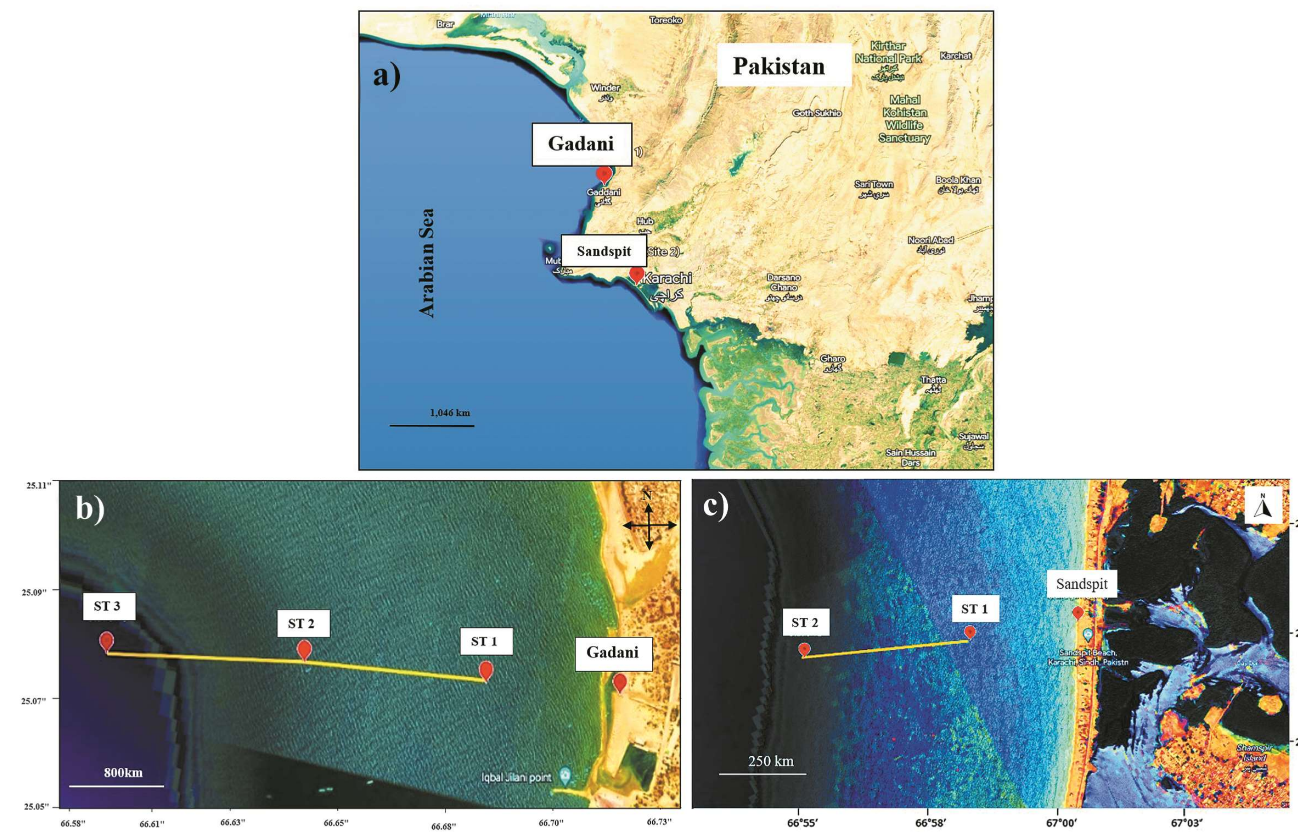

Fig. 1 — Coastland of Pakistan in the Arabian Sea. Baluchistan and Sindh coast are highlighted along with the station site and stations

method (Strickland & Parsons[24]). Chlorophyll-*a* (Chl-*a*) and nutrients were analysed following Strickland & Parsons[24]. The data was characterized in seasons as October – November (Autumn Inter-Monsoon - AIM), December – February (North-East Monsoon - NEM), March – April (Spring Inter Monsoon - SIM), and May to September (South-West Monsoon - SWM).

Statistical analysis

The species diversity indices such as Shannon Weiner diversity index (H'), Margalef's index of species richness (R), and Pielou's evenness index (J) were analysed through PRIMER 7.0. The correlation coefficient between physico-chemical parameters and abundance was examined using Past V4.03. The data represent in Cells/L.

Results

Environmental parameters

In Gadani, relatively high temperature, phosphate, and chl-*a* in SWM; high salinity, nitrite, nitrate, and ammonia in NEM; and high pH and DO in AIM were observed (Table 1) compared to other stations. While in Sandpit, relatively high temperature, ammonia, chl-*a* in SWM; high salinity, DO in AIM; high pH, phosphate, nitrite in SIM; and high nitrate was recorded in NEM (Table 2) compared to other stations of the study location.

Seasonal variations in diatoms

In the present study, 85 species of diatoms belonging to 15 centric and 17 pennate genera were recorded along the Gadani shipbreaking area on the Baluchistan coast of Pakistan (Table 3). From Sandspit, Sind coast of Pakistan, 74 diatom species were recorded in 16 centric and 10 pennate genera (Table 4). Variation in the diatom abundance and diversity is observed at both Gadani as well as Sandspit (Tables 3 & 4).

In Sandspit, the dominant centric diatom genera was *Cymatosira* (34 %) in AIM, while in NEM, the dominant genera were *Guinardia* (39 %) and *Melosira* (38 %). In SIM, the dominant genera were *Odentella* (26 %) and *Guinardia* (24 %), and in the SWM, the most abundant genera was *Coscinodiscus* (60 %) (Fig. 2). In Sandspit, the pennate diatoms were dominated by genera *Nitzschia* 67 % and 42 % in AIM and NEM, respectively and *Navicula (*34 %) in SIM and *Psuedonitzschia* (48 %) in SWM (Fig. 3). In Gadani, the centric diatoms were dominated by genera *Rhizosolenia* (61 %) and (31 %) in AIM and NEM, respectively, while in SIM, the abundant genera was *Cymatosira* (50 %) and during SWM *Melosira* (46 %) was the dominant genera (Fig. 4). Similarly, pennate diatoms in Gadani were dominated by *Nitzschia* (54 %) in AIM, *Psuedonitzschia* (52 %) in NEM, *Navicula* (64 %) in SIM and *Bacillaria* (70 %) in SWM (Fig. 5). The dominant species of pennate diatoms, such as *Navicula*, *Nitzschia* and *Pseudonitzchia* were similar in abundance at both the sites. In contrast, the dominant centric diatoms were found diversified at both studied sites.

Species diversity

In Gadani, the highest number of species was recorded in the NEM, while in Sandspit, it was recorded in the SWM. The maximum number of diatoms (Cells/L) was observed in NEM in both sites. Shannon diversity index (H') was high (2.8134) in Gadani during NEM, while it was high during SIM (3.1307) and SWM (3.1296) at Sandspit. Species Richness (SR) is found high in NEM in Gadani (4.7123), while in SWM (4.4492) at Sandspit.

Table 1 — Seasonal variation in physico-chemical parameters at Gadani

Gadani	Temp (°C)	Salinity (PSU)	pH	DO (mg/L)	NO_3- (ppm)	NO_2- (ppm)	PO_4^3 (ppm)	NH_3 (ppm)	Chl-*a* (µg/L)
AIM	26	34.5	8.45	10	9	0.2	2.5	2	0.343
NEM	21.33	38.67	8.23	7.89	10	0.2	3	2	0.528
SIM	26.5	35	7.9	8.07	9.95	0.1975	5	1.25	0.162
SWM	27.8	33.8	7.9	8.99	9.96	0.1998	3.8	1.9	1.752

Table 2 — Seasonal variation in physico-chemical parameters at Sandspit

Sandspit	Temp (°C)	Salinity (PSU)	pH	DO (mg/L)	NO_3- (ppm)	NO_2- (ppm)	PO_4^3 (ppm)	NH_3 (ppm)	Chl-*a* (µg/L)
AIM	24.5	38	8.2	9.95	9	0.3	3	2	0.67
NEM	21.67	36.67	8.07	8.07	10	0.3	3	2	0.39
SIM	22	32	8.4	8.85	9.95	0.45	4	1.5	0.19
SWM	29.2	36	7.98	7.56	9.98	0.26	2	2.1	0.86

Table 3 — Diversity of diatom species (Cells/L) in Gadani

S. No	Genera	S. No	Species	NEM	SIM	SWM	AIM
			Centric diatoms				
1	*Aulacoseria*	1	*Aulacoseria granulata*	0	0	60	0
2	*Cyclotella*	1	*Cyclotella* spp.	0	0	120	0
3	*Coscinodiscus*	1	*Coscinodiscus* spp.	1700	500	1880	540
4	*Cymatosira*	1	*Cymatosira lorenziana*	2340	4160	1560	660
		2	*Cymatosira acremonia*	0	0	0	520
5	*Chaetoceros*	1	*Chaetoceros decipiens*	60	0	60	0
		2	*Cheatoceros peruvianus*	60	0	0	0
		3	*Cheatoceros criopillus*	20	0	40	0
		4	*Chaetoceros atlanticus*	0	0	260	0
		5	*Cheatoceros lorenziana*	20	0	20	0
		6	*Chaetoceros aequatorialis*	0	20	360	0
		7	*Chaetoceros laciniosus*	0	20	0	0
		8	*Chaeoceros lauderi*	0	20	0	0
		9	*Chaetoceros coarctatus*	80	0	20	80
		10	*Chaetoceros danicus*	0	0	0	40
		11	*Chaetoceros affinis*	20	0	100	200
		12	*Cheatoceros* spp.	2460	20	160	460
6	*Eucamphia*	1	*Eucamphia* spp.	660	920	20	40
7	*Guinardia*	1	*Guinardia delicatula*	120	20	1800	0
		2	*Guinardia flaccida*	0	0	0	260
		3	*Guinardia striata*	260	60	0	20
8	*Hemiaulus*	1	*Hemiaulus sinensis*	140	0	0	0
9	*Leptocylindrus*	1	*Leptocylindrus danicens*	0	0	7300	0
10	*Melosira*	1	*Melosira arctica*	0	0	40	0
11	*Odontella*	1	*Odontella sinensis*	180	0	240	0
		2	*Odontella aurita*	0	20	20	0
		3	*Odontella mobiliensis*	0	300	40	0
		4	*Odontella longicruris*	0	100	0	0
12	*Planktoniella*	1	*Planktoniella sol (wallich) schutt.*	0	0	180	0
13	*Proboscia*	1	*Proboscia alata*	20	0	260	340
14	*Rhizosolenia*	1	*Rhizosolenia Setigera*	1320	80	380	4780
		2	*Rhizosolenia formosa*	20	660	0	20
		3	*Rhizosolenia imbricata*	1400	820	560	1600
		4	*Rhizosolenia hyalina*	40	0	0	120
		5	*Rhizosolenia borcalis*	40	0	0	0
		6	*Rhizosolenia robusta*	60	0	40	0
		7	*Rhizosolenia styliformis*	280	0	40	140
		8	*Rhizosolenia heimii*	80	0	0	0
		9	*Rhizosolenia curvata*	0	0	0	120
		10	*Rhizosolenia cressa*	60	120	0	60
		11	*Rhizosolenia pungens*	20	0	0	40
		12	*Rhizosolenia* spp.	0	0	0	240
		13	*Rhizosolenia alata*	0	40	0	0
15	*Thalassiosira*	1	*Thalassiosira* spp.	0	0	0	100
			Pennate diatoms				
1	*Amphora*	1	*Amphora* spp.	60	60	60	0
2	*Adoneis*	1	*Adoneis pacifica*	20	20	0	0

(*Contd.*)

Table 3 — Diversity of diatom species (Cells/L) in Gadani (*Contd.*)

S. No	Genera	S. No	Species	NEM	SIM	SWM	AIM
3	*Asterionellopsis*	1	*Asterionella formosa*	0	0	40	0
		2	*Asterionellopsis glacialis*	0	0	20	0
4	*Achnanthes*	1	*Achnanthes taeniata*	0	0	40	0
5	*Bacillaria*	1	*Bacillaria paxillifer*	0	0	8840	0
6	*Bleakeleya*	1	*Bleakeleya notata*	0	0	80	0
7	*Cylindrotheca*	1	*Cylindrotheca closterium*	0	20	0	0
8	*Haslea*	1	*Haslea wawrikae*	2140	0	0	0
9	*Hantzschia*	1	*Hantzschia amphioxys*	0	0	0	20
10	*Merdion*	1	*Merdion circulara*	1080	40	280	600
11	*Navicula*	1	*Navicula directa*	20	0	40	0
		2	*Navicula distans*	0	20	0	0
		3	*Navicula transitrans var derasa*	60	1420	320	0
		4	*Navicula Septentrionalis*	7900	100	460	200
12	*Nitzschia*	1	*Nitzschia longissima*	1020	0	160	0
		2	*Nitzschia acicularis*	0	0	80	0
		3	*Nitzchia Subpacifica*	1060	20	580	3240
		4	*Nitzschia* spp.	0	120	0	0
13	*Neodenticula*	1	*Neodenticula seminae*	240	600	560	2140
14	*Pleurosigma*	1	*Pleurosigma directa*	0	0	0	120
		2	*Pleurosigma normanii*	260	260	500	0
		3	*Pleurosigma directum*	80	40	40	0
15	*Pseudonitzschia*	1	*Pseudonitzschia* spp.	360	0	0	700
		2	*Pseudonitzschia heimii manguin*	300	0	0	0
		3	*Pseudonitzschia pungens*	60	0	0	980
		4	*Pseudonitzchia fraudulenta*	820	0	0	0
		5	*P.Pseudonitzschia delicatissima*	4960	20	0	0
		6	*Pseudonitzchia delicatissima*	5820	0	40	0
		7	*Pseudonitzchia seriata*	20	0	0	0
		8	*Pseudonitzchia lineola*	1820	0	40	0
		9	*Pseudonitzchia subcurvata*	140	0	0	0
		10	*Pseudonitzchia multiseries*	640	0	0	0
		11	*Pseudonitzchia turgidula*	20	0	0	0
		12	*Pseudonitzschia granii var granii*	40	0	0	0
		13	*Pseudonitzschia subpacifica*	140	0	0	0
		14	*Pseudonitzschia longissima*	20	0	0	0
16	*Striatella*	1	*Striatella unipunctata*	0	0	160	0
17	*Thalassionema*	1	*Thalassionema nitzschioides*	0	180	620	20
		2	*Thalassionema freuenfledii*	0	0	20	0
		3	*Thalassionema javanicum*	0	20	0	0

Evenness was high in AIM (0.73252) in Gadani, while it was high during SIM (0.84303) at Sandspit (Tables 5 & 6).

Correlation of diatoms with physico-chemical parameters

Pearson correlation coefficient was used to study the relationship among diatom communities with nutrients and other physico-chemical parameters. Diatom abundance was correlated positively with salinity in all stations, and with ammonia in station 1 & 3 at Gadani, whereas, it showed a negative correlation with all other parameters at Gadani (Table 7). In contrast, at Sandspit, diatom profusion was correlated positively with salinity, pH, nitrate, nitrite, phosphate and ammonia, while correlated negatively with temperature, DO, and chl-*a* in station 1. At station 2, diatom abundance was found correlated positively with pH, salinity, DO, nitrite,

Table 4 — Diversity of diatom species (Cells/L) in Sandspit

S. No	Genera	S. No	Species	NEM	SIM	SWM	AIM
			Centric diatoms				
1	*Bacteriastrum*	1	*Bacteriastrum delicatulum*	0	20	0	0
		2	*Bacteriastrum elongatum cleve*	0	100	0	0
2	*Coscinodiscus*	1	*Coscinodiscus* spp.	1440	240	2240	620
		2	*Coscinodiscus gigas*	0	0	1800	0
		3	*Coscinodiscus radiatus*	0	0	80	0
		4	*Coscinodiscus granii*	0	0	1680	0
		5	*Coscinodiscus Astesomphalus Ehrenberg*	0	0	480	0
3	*Chaetoceros*	1	*Chaetoceros affinis*	0	40	0	0
		2	*Cheatoceros criopillus*	40	0	0	0
		3	*Chaetoceros coarctatus*	0	20	0	0
		4	*Chaetoceros costatus*	20	0	0	180
		5	*Chaetoceros danicus*	0	20	0	0
		6	*Chaetoceros neglectus*	140	500	320	0
		7	*Cheatoceros* spp.	600	60	400	400
4	*Cymatosira*	1	*Cymatosira lorenziana*	70	0	0	0
5	*Eucampia*	1	*Eucampia zodiacus*	240	320	40	0
		2	*Eucampia cylindricornis*	0	0	20	0
6	*Guinardia*	1	*Guinardia delicatula*	9960	1120	60	180
		2	*Guinardia flaccida*	0	320	0	620
		3	*Guinardia striata*	20	0	0	0
7	*Hemiaulus*	1	*Hemiaulus sinensis*	0	0	0	220
8	*Leptocylindrus*	1	*Leptocylindrus danicens*	20	0	0	0
9	*Melosira*	1	*Melosira arctica*	7500	0	0	0
		2	Melosira nummuloides	2300	200	0	0
10	*Odontella*	1	*Odontella sinensis*	560	380	280	40
		2	*Odontella aurita*	140	920	100	0
		3	*Odontella mobiliensis*	0	260	40	0
11	*Planktoniella*	1	*Planktoniella sol (wallich) schutt.*	0	0	40	0
		2	*Pleurosigma normanii*	80	60	200	120
		3	*Pleurosigma directum*	60	60	140	0
		4	*Pleurosigma elongatum*	0	0	0	40
12	*Proboscia*	1	*Proboscia alata*	100	40	60	0
13	*Porosira*	1	*Porosira glacialis*	0	0	20	0
14	*Pseudoguinardia*	1	*Pseudoguinardia recta*	0	100	0	0
15	*Rhizosolenia*	1	*Rhizosolenia Setigera*	200	120	300	640
		2	*Rhizosolenia imbricata*	200	220	140	60
		3	*Rhizosolenia hyalina*	0	0	500	0
		4	*Rhizosolenia robusta*	100	20	0	0
		5	*Rhizosolenia styliformis*	20	0	0	60
16	*Thalassiosira*	1	*Thalassiosira* spp.	0	60	0	100
			Pennate diatoms				
1	*Amphora*	1	*Amphora* spp.	120	300	160	280
2	*Cylindrotheca*	1	*Cylindrotheca closterium*	2740	980	2100	1380
3	*Licmophora*	1	*Licmophora flabellata*	0	0	0	20
4	*Navicula*	1	*Navicula directa*	580	160	340	180
		2	*Navicula distans*	40	500	380	20
		3	*Navicula directum*	0	0	20	80

(*Contd.*)

Table 4 — Diversity of diatom species (Cells/L) in Sandspit (*Contd.*)

S. No	Genera	S. No	Species	NEM	SIM	SWM	AIM
		4	*Navicula transitrans var derasa*	0	40	120	20
		5	*Navicula Septentrionalis*	140	1740	40	200
		6	*Navicula vanhoeffenii*	120	0	0	0
5	*Nitzschia*	1	*Nitzschia longissima*	560	120	60	2060
		2	*Nitzschia acicularis*	440	0	0	60
		3	*Nitzchia Subpacifica*	0	0	140	0
		4	*Nitzchia turgidula*	60	0	0	300
		5	*Nitzschia multiseries*	0	0	1500	0
		6	*Nitzschia lorenziana*	0	0	0	140
		7	*Nitzschiz sigmoidea*	0	0	0	40
		8	*Nitzschia dissipata*	440	0	0	0
		9	*Nitzschia* spp.	100	160	260	420
6	*Pinnularia*	1	*Pinnularia diatom*	0	0	60	0
7	*Pleurosigma*	1	*Pleurosigma directa*	0	0	100	0
8	*Pseudonitzschia*	1	*Pseudonitzschia* spp.	0	20	0	0
		2	*Pseudo nitzschia australis*	0	40	0	0
		3	*Pseudonitzschia heimii manguin*	120	280	200	0
		4	*Pseudonitzchia fraudulenta*	200	440	160	0
		5	*P.Pseudonitzchia delicatissima*	20	600	840	0
		6	*Pseudonitzchia delicatissima*	0	520	280	40
		7	*Pseudonitzchia lineola*	0	0	1820	0
		8	*Pseudonitzchia turgidula*	0	80	460	40
		9	*Pseudonitzschia granii var granii*	0	0	200	0
		10	*Pseudonitzchia subpacifica*	0	0	160	0
		11	*Pseudonitzchia prolongatoides*	0	100	340	0
9	*Striatella*	1	*Striatella unipunctata*	0	480	0	0
10	*Thalassionema*	1	*Thalassionema nitzschioides*	80	1440	180	0
		2	*Thalassionema freuenfledii*	20	0	860	0

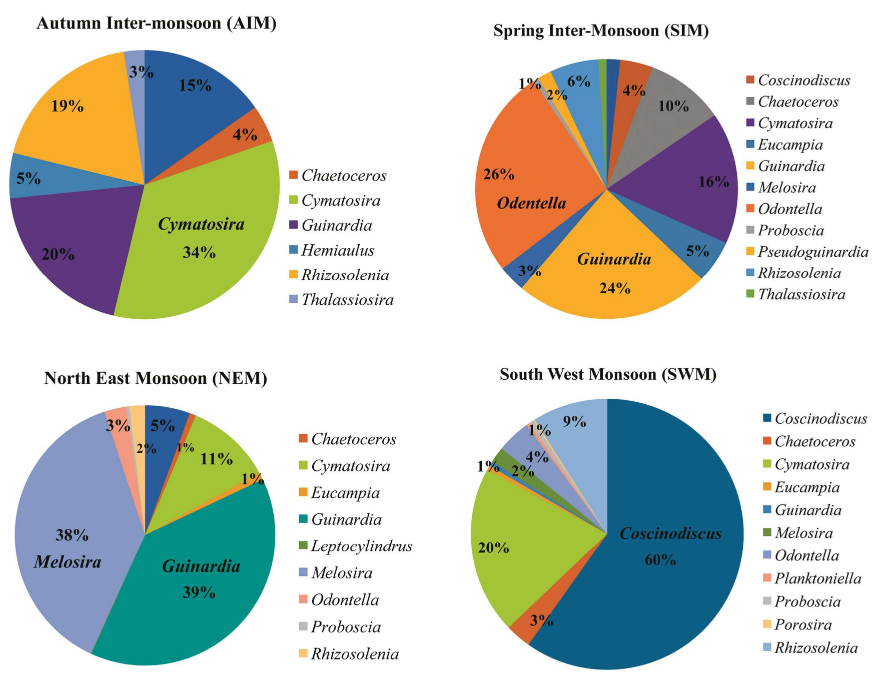

Fig. 2 — Seasonal variation of Centric Diatom in Sandspit

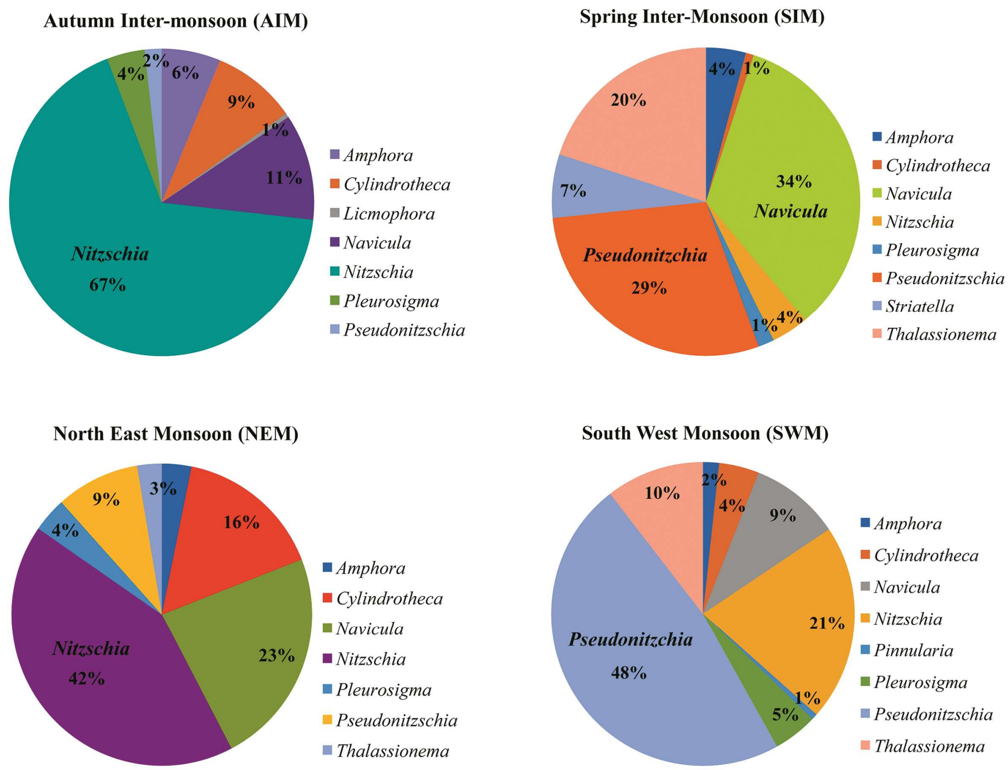

Fig. 3 — Seasonal variation of Pennate Diatom in Sandspit

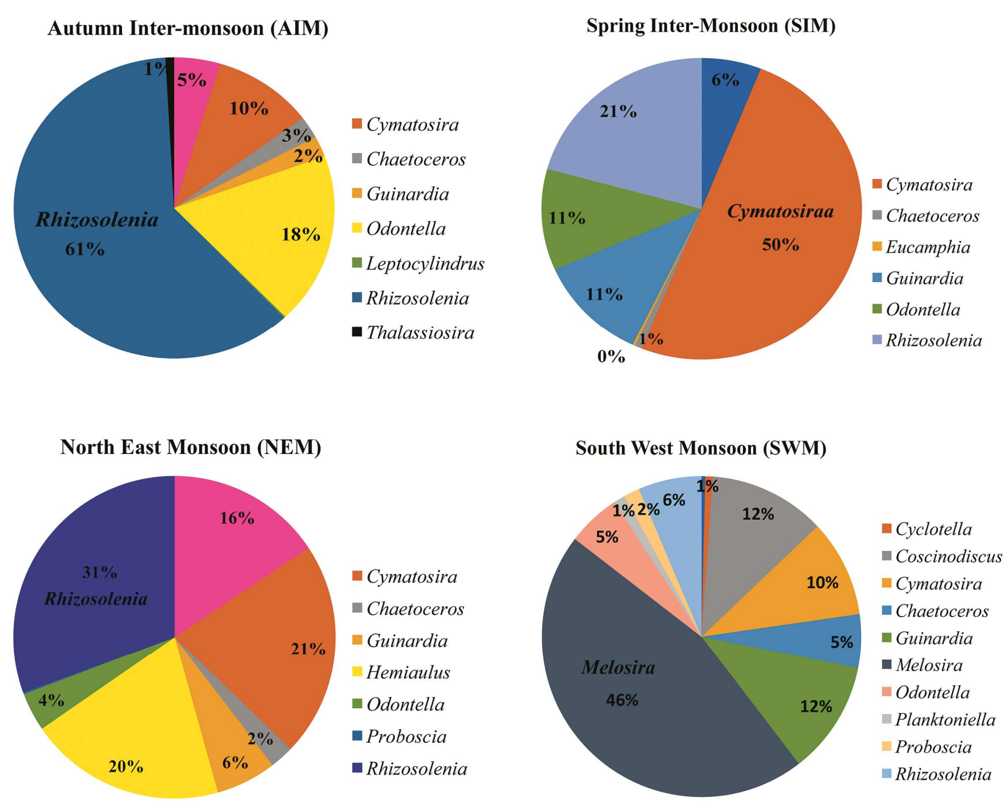

Fig. 4 — Seasonal variation of Centric diatom in Gadani

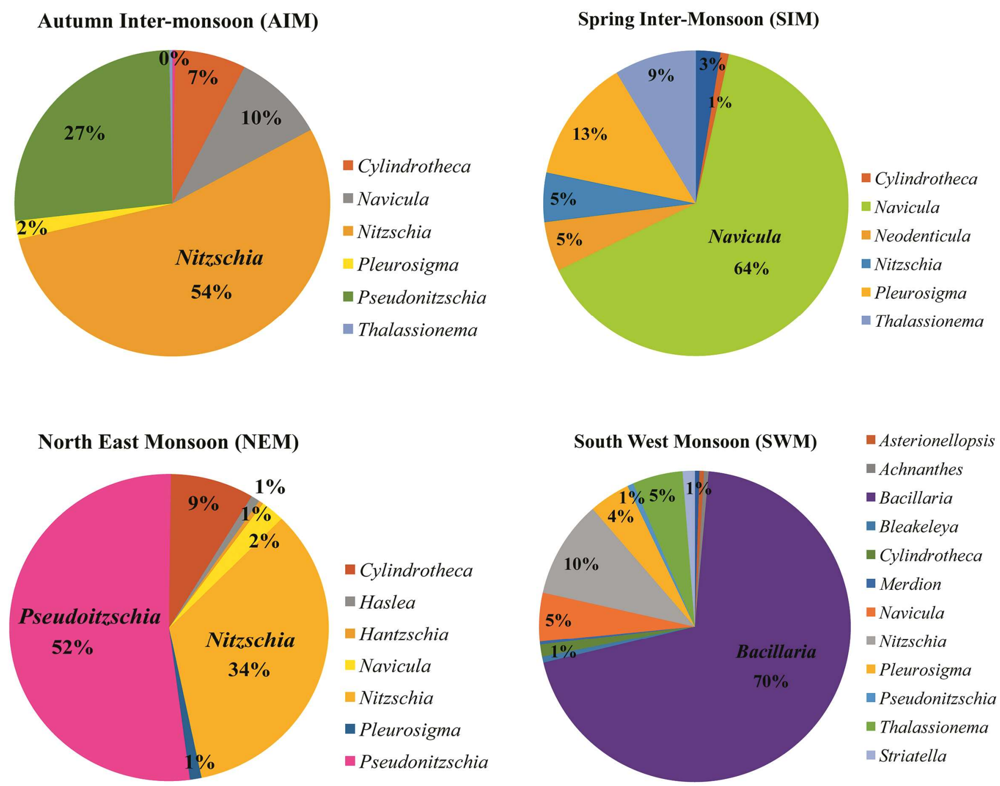

Fig. 5 — Seasonal variation of pennate diatom in Gadani

Table 5 — Seasonal diversity index of diatom at Gadani

Gadani	No. of species	Total no. of ind.cell/l	Margalef Species Richness	Pielou's Evenness Index	Shannon Diversity Index
NEM	51	40560	4.7123	0.71554	2.8134
SIM	32	10820	3.3372	0.6496	2.2514
SWM	46	28540	4.3864	0.62109	2.3779
AIM	30	18400	2.9531	0.73252	2.4914

Table 6 — Seasonal diversity index of diatom at Sandspit

Sandspit	No. of species.	Total no. of ind.cell/l	Margalef Species Richness	Pielou's Evenness Index	Shannon Diversity Index
NEM	37	29590	3.4968	0.60145	2.1713
SIM	41	13200	4.2159	0.84303	3.1307
SWM	45	19720	4.4492	0.82214	3.1296
AIM	29	8560	3.0923	0.78756	2.552

Table 7 — Pearson correlation of diatom in Gadani

Variables	Abundance			Temp °C	Salinity (PSU)	PH	DO (mg/L)	NO^{3-} (ppm)	NO^{2-} (ppm)	PO_4^{3} (ppm)	NH_3 (ppm)
	ST 1	ST 2	ST 3								
Temperature	-0.31	-0.39	-0.30								
Salinity	0.04	0.23	0.11	-0.17							
PH	-0.21	-0.19	-0.17	0.10	0.79						
DO	-0.30	-0.39	-0.32	0.06	0.48	0.84					
Nitrate (NO^{3-})	-0.20	-0.17	-0.19	0.08	0.83	0.99	0.81				
Nitrite (NO^{2-})	-0.21	-0.15	-0.21	0.08	0.85	0.95	0.76	0.99			
Phosphate (PO_4^{3})	-0.38	-0.18	-0.43	0.38	0.30	0.44	0.31	0.48	0.51		
Ammonia (NH_3)	0.05	-0.01	0.02	0.27	0.71	0.88	0.69	0.88	0.85	0.30	
Chlorophyll-*a*	-0.02	-0.18	-0.19	0.41	-0.21	0.02	0.36	0.03	0.07	0.15	0.16

Table 8 — Pearson correlation of diatom in Sandspit

Variables	Abundance		Temp °C	Salinity (PSU)	PH	DO (mg/L)	NO^{3-} (ppm)	NO^{2-} (ppm)	PO_4^3 (ppm)	NH_3 (ppm)
	ST 1	ST 2								
Temperature	-0.38	-0.03								
Salinity	0.00	0.14	0.16							
PH	0.49	0.54	-0.08	-0.11						
DO	-0.42	0.10	-0.11	-0.11	0.10					
Nitrate (NO^{3-})	0.08	-0.21	-0.02	0.42	-0.38	0.14				
Nitrite (NO^{2-})	0.37	0.38	-0.04	-0.05	0.38	0.09	0.48			
Phosphate (PO_4^3)	0.32	-0.29	-0.17	-0.30	0.45	-0.17	-0.10	0.29		
Ammonia (NH_3)	0.21	0.13	0.24	0.44	-0.13	0.01	0.54	0.06	-0.45	
Chlorophyll-*a*	-0.55	-0.48	0.47	0.12	-0.61	0.24	0.44	-0.08	-0.34	0.30

and ammonia, while negatively correlated with temperature, nitrate, phosphate and Chl-*a* (Table 8).

Discussion

The current study was carried out in the coastal area of the Baluchistan coast (Gadani) and Sindh (Sandspit) along the Northern Arabian Sea. The Arabian Sea has a unique oceanic basin, greatly dominated by the South-West Monsoon (SWM) and North-East Monsoon (NEM). Strong humid south-west airflow in summer (SWM) alternates with weaker, dry north-east airflow in winter (NEM)[25]. In SWM, the cooler waters rich with nutrients are brought into the photic zone due to upwelling, inducing a strong link between physical and biological activities. The water with rich nutrients influences the growth of phytoplankton, consequently increasing Chl-*a* and high gross primary productivity along the coastal area[26-28].

The phenomenon of upwelling in the coastal waters might be responsible for observed maximum abundance of phytoplankton at Gadani and Sandspit during SWM. The Chl-*a* values observed during this period at both the stations were also high compared to other seasons. Similar results were also reported by Siswanto *et al.*[27] from Bay of Bengal depicting direct linkage between chlorophyll content or phytoplankton with the nutrient availability. The elevated water temperature increases oxygen demand for organisms therefore, low dissolved oxygen retaining capability of water[29]. In the present study, elevated concentrations of dissolved oxygen were observed in the AIM of both study locations. However, the corresponding water temperature in AIM is relatively high compared to NEM (Gadani); and NEM and SIM (Sandspit). Further, to get better insight into the observed variations in DO, a more in-depth study is warranted including the effect of specific nutrient availability, phytoplankton species composition and abundance, incident sunlight and air-sea interaction in the region on the primary productivity and the dissolved oxygen concentration.

Salinity plays an essential role in maintaining the ecological activities of the marine environment. It is a key factor affecting the biodiversity of plankton and an increase in salinity may result in the loss of biodiversity[30]. The phytoplankton can tolerate broad salinity ranges, and various species withstand a wide range of salinity[31]. In Gadani and Sandspit, salinity is positively correlated with phytoplankton abundance. The pH is an essential factor in assessing water quality as it significantly influences the biogeochemical activity[32]. The pH value was 7.4 – 8.6 in the Gadani ship breaking area, whereas it was 7.7 – 8.6 in Sandspit, which is ideal for primary productivity[33].

The availability of nutrients in coastal waters is chiefly controlled by the circulation pattern of the ocean and from land run-off[33]. Cebrian & Valiela[34] reported that high productivity depends on nutrients brought by the rivers in coastal areas. The current study area along the coast also receive domestic and industrial wastes, primarily through Lyari and Malir Rivers and from small streams and drainages[35]. These also contribute to the productivity, abundance and species diversity of the region along with the coastal upwelling as observed in the correlation analysis (Tables 7 & 8).

The current study at Sandspit and Gadani reports variation in the diatom species richness (Gadani area: eighty-five species, and Sandspit: seventy-four species) at both stations. Similar variations in diatom species richness was reported by Khokhar *et al.*[36] from Manora Beach, Sindh, Pakistan. Moreover, Verlecar *et al.*[37] associated high-centric diatom species occurrence with increased nutrients and pollution. The coastal water of the Gadani shipbreaking area receives high organic pollution from shipbreaking industries. Similarly, coastal areas of Karachi also receive a high amount of organic pollution from Lyari and Malir rivers. Pollutants affect the water quality and alter water temperature, pH, electrical conductivity and light penetration in the ocean[38]. Phytoplankton is susceptible to anthropogenic substances; their growth and composition can alter due to changes in temperature, eutrophication and changes in the higher food web[39,40]. Numerous industrial discharges are extraordinarily alkaline or acidic in nature, affecting diatom densities, species richness, distribution and species composition, and mortality of juveniles of macroinvertebrates[41,42]. Hence, the reported variations in species richness can be attributed to nutrient enrichment from various sources, including pollution.

According to Fernández *et al*.[43], phytoplankton growth is limited by the accessible supply of nitrogen and phosphorus in water column. Excessive amounts of nutrients available in water may cause excessive growth of phytoplankton. Further, Hakkan *et al.*[44] reported that temperature and phosphorus have essential roles in phytoplankton growth due to their role in the photosynthetic process. The results of present study indicate that the relatively high temperature and phosphorus in Gadani can be related to high abundance and species number compared to Sandspit. Moreover, diatom species vary in composition with physical and ecological parameters, for example, dissolve oxygen, pH, nutrients and temperature. The significance of this relationship may differ significantly among diverse diatom species[45-47].

Phytoplankton are an indicator of water quality and any changes in the diversity of phytoplankton species may indicate pollution of the marine ecosystem[48]. Mawat *et al.*[49] reported high concentrations of phytoplankton and zooplankton in the Al-Arab River though the river is highly contaminated with household and industrial effluents. On the contrary, another study of the most polluted rivers in Latin America by Olguín *et al*.[50] showed strong inhibition of the phytoplankton populations due to pesticides as well as domestic and industrial waste. The shipbreaking area of Gadani is influenced by anthropogenic activities, adversely influencing the water quality of Gadani. The present study indicates that the prevailing environmental factors at selected study sites strongly influence the diatom diversity as well as abundance and the variations in the diversity of diatom species may indicate pollution-led deterioration of the water quality.

Acknowledgements

The authors are grateful to the Higher Education Commission (HEC) for providing funds to carry out research activities.

Conflict of Interest

The authors state that there is no conflict of interest.

Author Contributions

NS: Conceptualization, supervision, methodology, writing-reviewing and editing; TH: Data collection and analysis, software, and writing; PJAS: Conceptualizing and data collection.

References

1 Martin-Jezequel V, Hildebrand M & Brzezinski M A, Silicon metabolism in diatoms: Implications for growth, *J Phycol*, 36 (5) (2000) 821–840. https://doi.org/10.1046/j.1529-8817.2000.00019.x

2 Kuczynska P, Jemiola-Rzeminska M & Strzalka K, Photosynthetic pigments in diatoms, *Mar Drugs*, 13 (9) (2015) 5847-5881. https://doi.org/10.3390/md13095847

3 Khan-Bureau D A, Ector L, Morales E A, Wade E J & Lewis L A, Contrasting morphological and DNA barcoding methods for diatom (Bacillariophyta) identification from environmental samples in the Eight mile River in Connecticut, USA, *Nova Hedwig Beih*, 146 (2017) 279–302.

4 Tréguer P, Bowler C, Moriceau B, Dutkiewicz S, Gehlen M, *et al*., Influence of Diatom Diversity on the Ocean Biological Carbon Pump, *Nat Geosci*, 11 (1) (2018) 27-37. https://doi.org/10.1038/s41561-017-0028-x

5 Muruganantham P, Gopalakrishnan T, Chandrasekaran R & Jeyachandran S, Seasonal variations and diversity of planktonic diatoms of Muthupet and Aarukattuthurai, Southeast Coast of India, *Adv Nat Appl Sci*, 3 (2) (2012) 919-929.

6 Chellappa N T, Camara F R A & Rocha O, Phytoplankton community: Indicator of water quality in the Armando Ribeiro Goncalves reservoir and Pataxó channel, Rio Grande do Norte, Brazil, *Braz J Biol*, 69 (2009) 241-251. https://doi.org/10.1590/S1519-69842009000200003

7 Gharib S M, El-Sherif Z M, Abdel-Halim A M & Radwan A A, Phytoplankton and environmental variables as a water quality indicator for the beaches at Matrouh, south-eastern Mediterranean Sea, Egypt: An assessment, *Oceanologia*, 53 (3) (2011) 819–836. https://doi.org/10.5697/oc.53-3.819

8 Field C B, Behrenfeld M J, Randerson J T & Falkowski P G, Primary production of the biosphere: Integrating terrestrial and oceanic components *Science*, 281 (5374) (1998) 237–240. https://doi.org/10.1126/science.281.5374.237

9 Dwivedi B K & Pandey G C, Physico-chemical factors and algal diversity of two ponds (Girijakund and Maqubara Pond), Faizabad, India, *Pollut Res*, 21 (3) (2002) 361–370.

10 Parida A K & Das A B, Salt tolerance and salinity effects on plants: A review, *Ecotoxicol Environ Saf*, 60 (2005) 324–349. https://doi.org/10.1016/j.ecoenv.2004.06.010

11 Mariani P, Andersen K H, Visser A W, Barton A D & Kiørboe T, Control of plankton seasonal succession by adaptive grazing, *Limnol Oceanogr*, 58 (1) (2013) 173-184. https://doi.org/10.4319/lo.2013.58.1.0173

12 Moore C M, Mills M M, Arrigo K R, Berman-Frank I, Bopp L, *et al*., Processes and Patterns of Oceanic Nutrient Limitation, *Nat Geosci*, 6 (9) (2013) 701-710. https://doi.org/10.1038/ngeo1765

13 Fuhs G W, Phosphorus content and rate of growth in the diatoms *Cyclotella nana* and *Thalassiosira fluviatilis*, *J Phycol*, 5 (3) (1969) 312-321. https://doi.org/10.1111/j.1529-8817.1969.tb02620.x

14 Ho T Y, Quigg A, Finkel Z V, Milligan A J, Wyman K, *et al*., The elemental composition of some marine phytoplankton, *J Phycol*, 39 (5) (2003) 1145-1159. https://doi.org/10.1111/j.0022-3646.2003.03-090.x

15 Baines S B, Twining B S, Vogt S, Balch W M, Fisher N S, *et al*., Elemental composition of Equatorial Pacific diatoms exposed to additions of silicic acid and iron, *Deep Sea Res, Part II*, 58 (3-4) (2011) 512-523. https://doi.org/10.1016/j.dsr2.2010.08.003

16 Hydes D J & Wright P N, *SONUS: The Southern Nutrients Study 1995–1997*, Technical Report 7, (Southampton Oceanography Centre, Southampton, UK), pp. 130. https://nora.nerc.ac.uk/id/eprint/119118

17 Lui Y X, Yang T O, Yuan D X & Wu X Y, Study of municipal wastewater treatment with oyster shell as biological aerated filter medium, *Desalination*, 254 (2010) 149–153. https://doi.org/10.1016/j.desal.2009.12.003

18 Boopathy R, Bonvillain C, Fontenot Q & Kilgen M, Biological treatment of low-salinity shrimp aquaculture wastewater using sequencing batch reactor, *Int Biodeterior Biodegrad*, 59 (1) (2007) 16-19. https://doi.org/10.1016/j.ibiod.2006.05.003

19 Trainer V L, Cochlan W P, Erickson A, Bill B D, Cox F H, *et al*., Recent domoic acid closures of shellfish harvest areas in Washington State inland waterways, *Harmful Alga*, 6 (3) (2007) 449-459. https://doi.org/10.1016/j.hal.2006.12.001

20 Graham L E, Graham J M & Wilcox L W, *Alga*, 2nd edn, (Benjamin Cummings, San Francisco), 2009, pp. 616.

21 Qaimkhani A M, *The Marine Litter Action Plan-Status Report (Pakistan)*, (Government of Pakistan: Islamabad, Pakistan), 2018, pp. 36. http://www.sacep.org/pdf/Reports-Technical/2018.01.31-Pakistan-Marine-Litter-Action-Plan-Status-Report.pdf

22 Ishaq M, Azizullah A & Murad W, Environmental hazards and degradation of the coastal ecosystem of Pakistan: A review, *Mar Pollut Bull*, 165 (2021) 112-133. https://doi.org/10.1016/j.marpolbul.2021.112133

23 Tomas C R (ed), *Identifying marine phytoplankton*, 1st edn, (Academic Press, Elsevier, US), 1997, pp. 874. https://doi.org/10.1016/B978-0-12-693018-4.X5000-9

24 Strickland J D H & Parson T R, *A practical handbook of seawater analysis*, 2nd edn, (Fisheries Research Board of Canada, Ottawa, Canada), 1972, pp. 310. http://dx.doi.org/10.25607/OBP-1791

25 Burkill P H, Leakey R J G, Owens N J P & Mantoura R F C, Synechococcus and its importance to the microbial food web of the northwestern Indian Ocean, *Deep Sea Res*, *Part II*: *Top Stud Oceanogr*, 40 (3) (1993) 773-782. https://doi.org/10.1016/0967-0645(93)90057-T

26 Hashimoto S & Nagashima H, Seasonal variation in metabolic rate of plankton community in the inner part of Tokyo Bay, *J Oceanogr*, 79 (1) (2023) 1-10. https://doi.org/10.1007/s10872-023-00691-8

27 Siswanto E, Rahman Sarker M L, Peter B N, Takemura T, Horii T, *et al*., Variations of Phytoplankton Chlorophyll in the Bay of Bengal: Impact of Climate Changes and Nutrients from Different Sources, *Front Mar Sci*, 10 (2023) p. 1052286. https://doi.org/10.3389/fmars.2023.1052286

28 Habeebrehman H, Prabhakaran M P, Jacob J, Sabu P, Jayalakshmi K J, *et al*., Variability in biological responses influenced by upwelling events in the Eastern Arabian Sea, *J Mar Syst*, 74 (1-2) (2008) 545-560. https://doi.org/10.1016/j.jmarsys.2008.04.002

29 Hussain A, Sulehria A Q, Ejaz M & Maqbool A, Monthly variations in physico-chemical parameters of a flood plain reservoir on River Ravi near Balloki Headworks (Pakistan), *Biologia (Pakistan)*, 59 (2) (2013) 371-377.

30 Schallenberg M, Catherine J H & Carolyn W B, Consequences of climate-induced salinity increases on zooplankton abundance and diversity in coastal lakes, *Mar Ecol Prog Ser*, 251 (2003) 181-189. https://doi.org/10.3354/meps251181

31 Stenger-Kovács C, Béres V B, Buczkó K, Tapolczai K, Padisák J, *et al*., Diatom community response to inland water salinization: A review, *Hydrobiologia*, 850 (2023) 4627–4663. https://doi.org/10.1007/s10750-023-05167-w

32 Vase V K, Raman M, Sahay A K R K R S, Dash G & Rohit P, Dynamics of environmental variables during the incidence of algal bloom in the coastal waters of Gujarat along the northeastern Arabian Sea, *Environ Monit Assess*, 195 (10) (2023) p. 1238. https://doi.org/10.1007/s10661-023-11827-0

33 Abowei J F N, Salinity, dissolved oxygen, pH and surface water temperature conditions in Nkoro River, Niger Delta, Nigeria, *Adv J Food Sci Technol*, 2 (01) (2010) 36-40. https://maxwellsci.com/print/ajfst/v2-36-40.pdf

34 Cebrián J & Valiela I, Seasonal patterns in phytoplankton biomass in coastal ecosystems, *J Plankton Res*, 21 (3) (1999) 429-444. https://doi.org/10.1093/plankt/21.3.429

35 Karachi Development Authority, Karachi coastal recreation development plan, 1990-2000, (Master Plan and Environmental Control Department, Karachi Development Authority, Karachi) 1990.

36 Khokhar F N, Ahmad N, Ali A, Iqbal P, Jan B, *et al*., Spatio-Temporal Variations of Diatom Community in the Coastal Waters off Karachi, Northern Arabian Sea, *Thalassas: Int J Mar Sci*, 38 (1) (2022) 619-630. https://doi.org/10.1007/s41208-021-00389-y

37 Verlecar X N, Desai S R, Sarkar A & Dalal S D, Biological indicators in relation to coastal pollution along Karnataka coast, India, *Water Res*, 40 (17) (2006) 3304–3312. https://doi.org/10.1016/j.watres.2006.06.022

38 Alamgir A, Fatima N, Khan M A, Rehman M & Shaukat S S, A preliminary pollution appraisal of western backwater at Karachi Coastal area, *Appl Water Sci*, 9 (7) (2019) 1-6. https://doi.org/10.1007/s13201-019-1049-y

39 Di Pane J, Wiltshire K H, McLean M, Boersma M & Meunier C L, Environmentally induced functional shifts in

phytoplankton and their potential consequences for ecosystem functioning, *Glob Chang Biol*, 28 (8) (2022) 2804-2819. https://doi.org/10.1111/gcb.16098

40 Pitt K A, Welsh D T & Condon R H, Influence of jellyfish blooms on carbon, nitrogen and phosphorus cycling and plankton production, *Hydrobiologia*, 616 (1) (2008) 133–149. https://doi.org/10.1007/s10750-008-9584-9

41 Prins T C, Desmit X & Baretta-Bekker J G, Phytoplankton composition in Dutch coastal waters responds to changes in riverine nutrient loads, *J Sea Res*, 73 (2012) 49–62. https://doi.org/10.1016/j.seares.2012.06.009

42 Zhou Q, Wang S, Liu J, Hu X, Liu Y, *et al*., Geological evolution of offshore pollution and its long-term potential impacts on marine ecosystems, *Geosci Front*, 13 (05) (2022) p. 101427. https://doi.org/10.1016/j.gsf.2022.101427

43 Fernández-González C, Tarran G A, Schuback N, Woodward E M, Arístegui J, *et al*., Phytoplankton responses to changing temperature and nutrient availability are consistent across the tropical and subtropical Atlantic, *Commun Biol*, 5 (1) (2022) p. 1035. https://doi.org/10.1038/s42003-022-03971-z

44 Hakan T, Arnold G E & David E B, Filtration of green algae and cyanobacteria by Nile tilapia, *Oreochromis niloticus*, in the Partitioned Aquaculture Systems, *Aquaculture*, 215 (1) (2003) 93–101. https://doi.org/10.1016/S0044-8486(02) 00133-3

45 Khan F A & Ansari A A, Eutrophication: An ecological vision, *Bot Review*, 71 (4) (2005) 449-482. https://doi.org/10.1663/0006-8101(2005)071[0449:EAEV] 2.0.CO;2

46 Roelke D & Buyukates Y, Dynamics of phytoplankton succession coupled to species diversity as a system-level tool for study of Microcystis population dynamics in eutrophic lakes, *Limnol Oceanogr*, 47 (4) (2002) 1109-1118. https://doi.org/10.4319/lo.2002.47.4.1109

47 Harnstrom K, Indrani K & Godhe A, Phytoplankton species assemblages and their relationship to hydrographic factors - a study at the old port in Mangalore, coastal Arabian Sea, *Indian J Geo-Mar Sci*, 38 (2) (2009) 224. http://nopr.niscpr.res.in/handle/123456789/4673

48 Basavaraddi C C S, Prakasha P, Basavaraddi S S, Narayana J, Basavaraddi S B, *et al*., Applying Artificial Intelligence to Studies on Water Quality and Phytoplankton Diversity of Eachnur Tank, Tiptur, Tumkur-District, Karnataka, India, *Int J New Innov Eng Technol*, 17 (3) (2021) 38-51.

49 Mawat M & Hamdan A N, Review of Mathematical Surface Water's Hydrodynamic/Water Quality Models with Their Application on the Shatt Al Arab River Southern Iraq, *Euro J Eng Sci Tech*, 6 (1) (2023) 30-49. https://doi.org/10.33422/ejest.v6i1.1057

50 Olguín H F, Puig A, Loez C R, Salibián A, Topalián M L, *et al*., An integration of water physicochemistry, algal bioassays, phytoplankton, and zooplankton for ecotoxicological assessment in a highly polluted lowland river, *Water Air Soil Pollut*, 155 (2004) pp. 355-381. https://doi.org/10.1023/B:WATE.0000026538.51477.c2