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Seasonal variability of phytoplankton along some of the Red Sea harbors during 2019–2021

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ABSTRACT

Surface seawater and phytoplankton samples were collected from different stations covering the areas of six harbors in the Egyptian Red Sea during 2019–2021. The obtained results revealed 119 phytoplankton species, including 80 species of diatoms, 27 species of dinoflagellates, and six species of both cyanophytes and chlorophytes. Diatoms such as ***Proboscia alata*** var. ***gracillima, Chaetoceros curvisetus, Asterionellopsis glacialis***, and ***Licmophora flabellata*** produced the highest phytoplankton peak in most harbors. A relatively high phytoplankton population density was recorded at stations near Port Tawfiq Harbor, followed by Zaytiyat. This could be due to the relatively high impacts from various petroleum factories as well as the Sewage Treatment Company, which reflect the area's eutrophic conditions. In general, the highest phytoplankton population density was observed in February 2021, with average counts of 7112 units/L. This is primarily due to the diatom ***Licmophora flabellata***, which accounted for approximately 44% of all phytoplankton in Safaga Harbor waters. However, most of the phytoplankton species in the current study were unique to the Egyptian Red Sea region. On the other hand, several of the harmful species, such as the dinoflagellates ***Prorocentrum, Goniaulax***, and ***Dinophysis*** spp., as well as the C**yanobacterium *Oscillatoria*** sp., were found in low counts at some sites of the Egyptian harbors. The statistical analysis of the data indicated that dissolved nitrate (0.81-18.45µM) and ammonium (0.47-5.01µM) were the most effective factors controlling phytoplankton abundance. The multiple regression analysis was calculated to show the relationship between phytoplankton abundance and the most effective environmental factors. A regression equation was obtained and could be applied in the future to predict the total phytoplankton abundance in the coastal waters of the investigated Red Sea harbors.

INTRODUCTION

The Red Sea, one of the world's saltiest and warmest deep seas, is a semi-enclosed marginal sea about 2,000 km long and 300 km wide. The Red Sea has significant latitudinal gradients in physicochemical characteristics, with increasing temperature, nutrients, and decreasing salinity toward the south, owing primarily to the flow of water through the Bab el-Mandeb Strait and the Red Sea's thermohaline circulation (**Eladawy *et al*., 2017)**.

Phytoplankton is regarded as one of the most critical ocean players, accounting for roughly 50% of global primary production. They form the foundation of marine food webs, drive the chemical composition of the international atmosphere and thus influence the climate. The composition of phytoplankton species is naturally influenced by seasonal environmental changes and nutrient availability (**Käse and Geuer 2018**).

The majority of information on the Red Sea phytoplankton population is mainly obtained from the reviews of **Halim (1969)**, which listed approximately 209 species (125 dinoflagellates and 84 diatoms). Several researchers, including **Nassar and Hamed (2003); Deyab *et al*. (2004); Shams El-Din *et al*. (2005)**, and **Nassar (2007a)**, have studied the seasonal fluctuations of phytoplankton in the Gulf of Suez over the last 20 years. Several workers studied phytoplankton population density in the Gulf of Aqaba, including **Post *et al*. (2002)**; **Al-Najjar *et al.* (2007)**, and **Nassar (2007b)**. **El-Sherif and Abo El-Ezz (2000)** studied plankton distribution in the northern Red Sea and identified 41 diatom species, 53 dinoflagellates, 10 cyanophytes, and two chlorophytes. In the Halayib-Shalatin region of the Red Sea, **Abdel Rahman and Nassar (2005)** conducted a study on phytoplankton and zooplankton. According to **Madkour *et al*. (2010)**, diatoms (60 species) and dinoflagellates (116 species) represented the majority of the phytoplankton population in the Egyptian coastal waters of the Red Sea. In the northern part of the Red Sea, **Nassar *et al*. (2014)** identified roughly 145 species, with a clear dominance of diatoms (76.4%). In general, **Nassar and Khairy (2014)** described roughly 207 phytoplankton species that were identified and categorized by several workers in the Egyptian waters of the Red Sea. However, a guide to the photomicrographs for most of these phytoplankton species was provided by **Nassar and Khairy (2015)**.

Comparing the eastern coast of the Suez Gulf to its western coast and the northern Red Sea, **Nassar *et al*. (2015)** found that the total number of phytoplankton was comparatively low. About 389 species were identified by **Ismael (2015)** during an assessment of the Red Sea's phytoplankton distribution. About 129 diatoms, 152 dinoflagellates, and 2 cyanophytes were among the 283 phytoplankton species that **Devassy *et al.* (2017)** identified from the northern Red Sea. At Hurgada on the Red Sea coast, **Abbass *et al*. (2018)** published a checklist of 135 species, the majority of which were dinoflagellates (67 species) and diatoms (64 species). Recently, **Abu Faddan (2019)** and **El-Sheikh *et al*. (2023)** examined the seasonal dynamics of phytoplankton in Suez Bay (the northern part of the Suez Gulf). The phytoplankton community was characterized by 423 species dominated by diatoms.

The available literature on phytoplankton population dynamics at Egypt's various Red Sea harbors is limited, and information on phytoplankton in this area is lacking. The current study's motivation is to follow up on the impact of various activities on the spatial and temporal variations of phytoplankton in some northern Red Sea Egyptian harbors.

MATERIALS AND METHODS

1. Description of the selected harbors

Nineteen different stations were selected for investigation in the present study, covering about six different harbors (**Fig. 1)** along the two gulfs of the Red Sea during 2019–2021. The samples were collected from several sites at each port, and the averages of the obtained readings were taken. These harbors could be described as follows:

Port Tawfik Harbor is located in the northern part of the Suez Gulf, at the southern gate of the Suez Canal. It includes the northern coast until the Suez Canal entrance (32 34 E, 29 56 N). It has two basins, the first for shipping activity and the second for ship maintenance (El Tersana).

Zaytiyat Port is located on the eastern side of Suez-Port, on the northern side of the Suez Gulf, and at the southern entrance to the Suez Canal (32 31.8 E, 29 57.2 N). It has a long basin where the tankers can dock to upload and download the petroleum oil.

Nuwbia port is located on the western coast of the Aqaba Gulf, approximately 168 km north of Sharm El-Sheikh, and about 64 km south of Taba (34 39 E, 28 57 N).

Sharm El-Sheikh Port, which is located about 380 km south of Suez Governorate, is located on the tip of the triangle of the Sinai Peninsula, at the confluence of the Suez and Aqaba Gulfs in the South Sinai Governorate (34 17 E, 27 51.2 N).

Hurgada Harbor is located on the western coast of the Red Sea near the entrance to the Gulf of Suez, 370 km south of Suez. It's at 270° 13' 46" N and 330° 50' 34" E. It is highlighted by its location and global tourism service in the Red Sea region.

Safaga Harbor is located on the western coast of the Red Sea. It is located at 26° 44' 48" N, 33° 56' 51" E, about 60 km south of Hurgada City, and is protected from the eastern and northern sides by Safaga Island.

2. Hydro-chemical parameters

Water temperature was measured using a simple pocket thermometer graduated to 0.1^{o}C. The pH value of water samples was measured in *situ* using a pocket pH meter, model Orion 210. Samples for dissolved oxygen were determined by Winkler's method (**Strickland and Parsons, 1972**), and the dissolved inorganic nutrients (NO_3, NH_4, and PO_4) were determined spectrophotometrically in µM according to the methods described by **APHA (2005).**

3. Phytoplankton estimations

During September 2019, February 2020, September 2020, and February 2021, surface water samples were collected from various stations covering six Red Sea harbors (**Fig. 1**). The phytoplankton community structure and standing crop were determined by filtering a 50-liter water sample with 20 µm plankton net. Species identification was performed, and phytoplankton species were updated using taxonomic database sites such as algaebase.com (ab) and the World Register of Marine Species (WoRMS).

Fig.1. Different harbors of the investigated area of the Egyptian Red Sea.

4. Statistical analysis

The correlation matrices were applied between total phytoplankton counts and the hydro-chemical parameters at a 95% confidence limit. Multiple regressions were calculated for phytoplankton during the investigation period, using the program Statistica Version 5. Using Primer 5, a similarity index based on phytoplankton community structure was calculated between the stations of study area. The species diversity (H′) was calculated according to **Shannon-Weaver (1963).**

RESULTS AND DISCUSSION

1. Hydro-chemical characteristics

Water temperature influences phytoplankton bloom dynamics in shallow, productive coastal waters. Future global warming could become critical by altering bloom phenology and changing phytoplankton community structure, affecting the entire food web and ecosystem services (**Trombetta *et al*., 2019**). Seawater temperature affects phytoplankton indirectly through stratification and thus nutrient flux, as well as through community composition and metabolic rates (**Feng *et al*., 2021**). The current study found that seawater temperatures ranged from 16.23 ^{o}C at Safaga harbor in February 2020 to 33.5 ^{o}C at Sharm El-Sheikh harbor in September 2020.

pH may play a significant role in limiting the rate of primary production, growth, and total abundance of phytoplankton. The medium pH also influences the relative concentration of dissolved carbonate species, ultimately conditioning the isotopic composition of CO_2 (**Hinga, 2002**). In the present study, the pH values fluctuated within a narrow, limited range. The higher relative pH value was recorded at Zaytiyat Harbor in February 2020 (8.28), while the lower one (8.04) was found at Hurgada Harbor in February 2021. However, high pH levels are commonly observed in the late afternoon of sunny summer days after the photosynthesis process has consumed CO_2. Due to the end of the photosynthesis process in the evening, the pH level may drop significantly (**Ghobrani *et al*. 2014**). In this study, no correlation was found between seawater, pH values, and phytoplankton.

Marine phytoplankton species exhibit broad salinity tolerance, with many species capable of growing in a wide range of salinities (**Sergio *et al*., 2011**). The fact that salinity is a strong determinant of phytoplankton diversity, with species richness decreasing with increasing salinity and increasing with nutrient enrichment, emphasizes the importance of nutrient supply (**Chad and Gary, 2013**). In the current study, no clear relationship was found between water salinity and phytoplankton counts; salinity ranged from 42.91 $‰_o$ in the waters of Hurgada harbor in February 2021 to 40.25$‰_o$ at Zaytiyat harbor in September 2020.

Dissolved oxygen (DO) measures how much oxygen is dissolved in water and is thus available to living aquatic organisms. The amount of dissolved oxygen in a stream or lake can reveal a great deal about its quality (**Water Science School, 2018**). The concentrations of DO in the present study fluctuated between 8.24 mg/L at Zaytiyat Harbor in September 2020 and 6.8 mg/L at Nuwbia Harbor in September 2019. The highest DO value was linked to the relatively high occurrence of total phytoplankton, particularly the diatoms, *Proboscia alata* var. *gracillima* (Cleve) van Heurck (ab), *Chaetoceros curvisetus* Cleve (ab), and *Asterionellopsis glacialis* (Castracane) Round (ab) as well as *Oscillatoria simpliccissima* Gomont (WoRMS) of cyanophytes at Zaytiyat Port in September 2020. The results showed a positive correlation between DO and phytoplankton abundance (r = 0.219). However, the oxygen concentration in the Red Sea is relatively low due to the area's high salinity and high temperature (**Nassar 2007a)**, which is not supported by **Fahmy *et al*. (2016)** data for the Egyptian Red Sea coastal waters, which maintained high DO values and the presence of well-oxygenated seawaters.

2. Nutrients

Ammonium (NH_4^+) and nitrate (NO_3^-) are used in the production of fertilizers, fossil fuels, and explosives used in mine blasting and other anthropogenic activities (**Sparacino-Watkins *et al*., 2014**). However, the majority of phytoplankton species require nitrate and phosphate as macronutrients, and diatoms require silicate to build their frustules (**Barcelos *et al*., 2017**).

Table 1. The mean values of hydro-chemical parameters in surface waters of the Egyptian Red Sea harbors during 2019-2021.

Season	Harbors	Temp (^{0}C)	pH	Salinity ‰	DO (mg/L)	PO4 (µM)	NO3 (µM)	NH4 (µM)
Sep., 2019	Pw	28.6	8.25	41.95	7.28	0.746	2.15	3.79
	Zy	28.35	8.25	41.86	7.74	0.206	2.27	2.64
	Nw	27.9	8.17	40.62	6.80	0.265	1.60	1.82
	Sh	28.60	8.13	40.66	7.35	0.457	1.14	2.78
	Hg	28.70	8.18	40.69	7.19	0.155	0.98	1.21
	Sf	28.58	8.15	40.48	8.04	0.210	0.81	1.47
Feb., 2020	Pw	16.88	8.22	42.83	7.28	0.316	15.07	3.91
	Zy	16.73	8.28	42.87	7.29	0.234	14.40	5.01
	Nw	18.18	8.25	40.78	6.85	0.251	4.28	2.85
	Sh	17.88	8.22	40.63	7.13	0.211	2.79	1.16
	Hg	17.95	8.15	40.88	6.97	0.256	1.29	0.67
	Sf	16.23	8.18	40.69	7.13	0.231	4.05	0.62
Sept. 2020	Pw	29.43	8.21	41.71	8.00	0.569	4.94	2.26
	Zy	29.33	8.18	40.25	8.24	0.527	5.13	1.23
	Nw	28.23	8.23	40.75	6.90	0.532	1.31	1.25
	Sh	30.55	8.21	40.70	6.80	0.609	1.09	2.07
	Hg	27.93	8.18	40.56	6.82	0.257	1.00	2.59
	Sf	27.00	8.16	40.48	6.84	0.260	3.47	1.51
Feb. 2021	Pw	17.90	8.14	42.45	7.16	0.129	1.41	1.23
	Zy	17.55	8.13	42.35	7.44	0.124	2.14	1.71
	Nw	17.55	8.17	40.64	7.51	0.079	1.24	0.88
	Sh	21.43	8.18	40.75	7.45	0.126	1.36	0.47
	Hg	20.90	8.04	42.91	7.24	0.333	7.47	1.20
	Sf	21.28	8.15	40.40	7.50	0.263	18.45	1.67

Note: Pw = Port Tawfik; Zy = Zaytiyat; Nw =Nuwbia; Sh = Sharm El-Sheikh; Hg = Hurgada and Sf = Safaga.

Nitrogen, an essential nutrient, is a limiting factor in phytoplankton growth in the ocean. In oceanic and coastal ecosystems, dissolved nitrate is the most abundant type of nitrogen (**Zielinski *et al*., 2011**). The deep ocean generates a nitrogen supply through microbial activities such as denitrification in deep water (**Arrigo, 2005**). In the current study, dissolved nitrate reached a maximum of 18.45 µM at Safaga Harbor in February 2021, and a minimum of 0.81 µM was also observed in Safaga waters in September 2019. This highest nitrate value was associated with a high phytoplankton population density in February 2021 (average counts of 7112 units/L). This is primarily due to the diatom *Licmophora flabellata* (Greville) C. Agardh (ab), which alone accounted for approximately 44% of total phytoplankton in Safaga Harbor waters in February 2021. In general, the high nitrate concentrations in the present study enhanced phytoplankton growth. This was confirmed by the positive correlation between NO_3 and the total counts of phytoplankton (r = 0.77).

Ammonia (NH_3) is a common toxicant found in waste, fertilizers, and natural processes. Ammonium nitrogen is available in ionized (ammonium, NH_4^+) and unionized (ammonia, NH_3) forms. An increase in pH promotes the formation of the more toxic unionized form (NH_3), whereas a decrease promotes the formation of the ionized (NH_4^+) form (**Lease *et al*., 2003**). The toxicity of ammonia to aquatic life is also affected by temperature. Due to its nutrient properties, ammonia can also cause excessive plant growth (eutrophication). Algae and macrophytes absorb ammonia, lowering aqueous concentrations (**Yu *et al*., 2022**). In the current study, dissolved ammonia reached a maximum of 5.01 µM in February 2020 at Zaytiyat harbor and a minimum of 0.47 µM in the waters of Sharm El-Sheikh harbor in February 2021. The high levels of dissolved ammonia at Zaytiyat Harbor could be attributed to the effects of a sewage treatment company located near this area. According to **Fahmy *et al*. (2016)**, dissolved inorganic nitrogen concentration patterns were as follows: $NO_3 > NH_4 > NO_2$ and the Red Sea coastal waters are classified as oligotrophic to mesotrophic. The regression analysis of the current study revealed that nitrate was one of the most important factors controlling phytoplankton abundance, followed by dissolved ammonia.

The role of dissolved inorganic phosphorus (DIP) as an important nutrient for marine phytoplankton in oligotrophic environments emphasizes the importance of evaluating nutrient restriction at the taxon and single-cell level rather than inferring it from nutrient concentrations and ratios or bulk enzyme activities (**Mackey *et al*., 2007**). The primary source of phosphate for phytoplankton in marine waters is thought to be orthophosphate rather than dissolved organic phosphorus (DOP). Even though the concentration of dissolved organic phosphorus can be 5-10 times higher than that of dissolved inorganic phosphorus, microbial activity and phytoplankton growth are frequently considered P-limited during DIP depletion (**Fitzsimons *et al*., 2020**). In the present study, the highest concentration of dissolved phosphate (0.746 µM) was found in September 2019 at Port-Tawfik Harbor as a result of the impacts of sewage discharge near this area, while the lowest value (0.079 µM) was found in February 2021 in the waters of Nuwbia Harbor (**Table 1**).

3. Spatial and temporal variability of phytoplankton

Phytoplankton is an essential component of marine food webs, but both natural and anthropogenic environmental changes influence it. Most other aquatic organisms can survive because eukaryotic marine phytoplankton contributes significantly to major global processes (such as oxygen production, carbon fixation, CO_2 sequestration, and nutrient recycling). The most diverse and ecologically significant eukaryotic phytoplankton taxa in modern oceans are diatoms, dinoflagellates, haptophytes, and small prasinophytes, some of which regularly form massive blooms visible in satellite images (**Fabrice *et al*., 2022)**.

The obtained results revealed 119 phytoplankton species, including 80 species of diatoms, 27 species of dinoflagellates, and six species of both cyanophytes and chlorophytes. Diatoms such as *Proboscia alata* var. *gracillima, Chaetoceros curvisetus, Asterionellopsis glacialis,* and *Licmophora flabellata* produced the highest phytoplankton peak in most harbors. A relatively high phytoplankton population density was recorded at stations near Port Tawfiq Harbor, followed by Zaytiyat. This could be due to the relatively high impacts from various petroleum factories as well as the Sewage Treatment Company, which reflect the area's eutrophic conditions. According to **Nassar *et al*. (2014)**, these discharged materials may increase phytoplankton growth and flourish as long as they stay within the permitted limit for phytoplankton growth and prosperity. It has been reported that sewage discharge may increase phytoplankton productivity in areas since sewage is the primary source of nitrogen and phosphorus (**Burford *et al.*, 2012**). On the other hand, stations near the ports of Hurgada and Sharm El-Sheikh have recorded moderate phytoplankton counts **(Table 2 and Fig. 2)**. This is chiefly due to low nutrients, as indicated in the present study (**Table 1**), and reported by **Abdel Halim *et al*. (2007)** and **Dorgham *et al.* (2012)**, who stated that nitrogen, phosphorus, and reactive silicate concentrations were generally low in the oligotrophic to mesotrophic Gulf of Aqaba and the Egyptian Red Sea coastal waters. **Nassar *et al*. (2015)** reported that most of the eastern coast of the Suez Gulf is still healthy, relatively unpolluted, and an oligotrophic to mesotrophic area. **Malika *et al*. (2017**) concluded that the Red Sea is considered oligotrophic mainly due to the depletion of nutrients in the upper layer as the water transfers northward due to thermohaline forcing. Also, **Abbass *et al*. (2017, 2018**) indicated that the phytoplankton standing crop was relatively low at Hurgada, reflecting the oligotrophic conditions of this area. Generally, most of the previous studies agreed with and supported the current study.

In the current study, diatoms were the most prevalent group, accounting for approximately 72.44%, 59.2%, 81.9%, and 79% of total phytoplankton in September 2019, February 2020, September 2020, and February 2021, respectively, while the other algal groups were observed with low to moderately similar counts at the majority of the investigated sites during the study period. According to **Nassar *et al.* (2014)**, diatoms predominated in the Red Sea, accounting for roughly 76.4% of total abundance in the Red Sea's northwest region and roughly 67% of the eastern coast of the Suez Gulf (**Nassar *et al*., 2015**). Furthermore, **Nassar *et al*. (2016**) found 57 genera and 146 species at some sites in Egyptian Red Sea harbors. The diatoms were the most abundant and dominant group, accounting for roughly 81% of total phytoplankton abundance. However, they stated that the ports in the Gulf of Aqaba and those on the eastern coast of the Suez Gulf were the least productive, which supports and confirms the current study's findings.

Table 2. The mean counts of phytoplankton (unit/L) and their frequency percentage in the Egyptian Red Sea harbors during 2019-2021.

Harbors / Algal groups	Port-Tawfik	Zaytiyat	Nuwbia	Sharm El-Sheikh	Hurgada	Safaga	Average	Freq.%
September 19								
Bacillariophyceae	2320	1743	1889	909	1617	1525	**1667**	**72.44**
Cyanobacteria	220	100	119	104	0	195	**123**	**5.34**
Dinophyceae	840	662	438	256	692	179	**511**	**22.2**
Total Phytoplankton	**3380**	**2505**	**2446**	**1269**	**2309**	**1899**	**2301**	**100**
February 2020								
Bacillariophyceae	4418	2816	2032	1246	2327	1233	**2345**	**59.2**
Cyanobacteria	184	104	93	0	84	0	**77**	**1.94**
Dinophyceae	1609	1524	1704	1100	1861	1087	**1481**	**37.41**
Chlorophyceae	0	0	209	130	0	0	**57**	**1.43**
Total Phytoplankton	**6211**	**4444**	**4038**	**2476**	**4272**	**2320**	**3960**	**100**
September 2020								
Bacillariophyceae	7019	5893	2666	1450	4100	2854	**3997**	**81.9**
Cyanobacteria	319	584	257	162	0	211	**256**	**5.24**
Dinophyceae	1099	811	398	266	630	269	**579**	**11.86**
Chlorophyceae	0	107	114	73	0	0	**49**	**1**
Total Phytoplankton	**8437**	**7395**	**3435**	**1951**	**4730**	**3334**	**4880**	**100**
February 2021								
Bacillariophyceae	4332	5130	3743	3853	2235	14425	**5620**	**79.02**
Cyanobacteria	0	0	93	20	56	33	**33**	**0.46**
Dinophyceae	1538	1597	1899	969	1517	1019	**1423**	**20**
Chlorophyceae	53	0	0	45	117	0	**36**	**0.5**
Total Phytoplankton	**5923**	**6727**	**5735**	**4887**	**3925**	**15477**	**7112**	**100**

As a general trend, the highest phytoplankton population density was recorded in February 2021 (with an average count of 7112 units/L), followed by September 2020 (average count of 4880 units/L), and February 2020 (average count of 3960 units/L) (**Table 2 and Fig. 2**). This is primarily due to the diatom *Licmophora flabellata* (Greville) C. Agardh (ab), which alone accounted for approximately 48% of total diatoms and 44.7% of total phytoplankton in the waters of Safaga Harbor in February 2021. This was followed by the high prevalence of diatoms *Chaetoceros curvisetus* Cleve (ab) and *Lauderia borealis* Gran (ab) at Safaga in February 2021, as well as *Thalassionema nitzschioides* (Grunow) Mereschkowsky (ab) in the waters of Zaytiyat harbor and *Nitzschia longissima* (Brébisson) Ralfs (ab) in the waters of Sharm El Sheikh Port in February 2021 (**Table 3**).

Furthermore, diatoms such as *Proboscia alata* var. *gracillima* (Cleve) van Heurck (ab), *Chaetoceros curvisetus* Cleve (ab), and *Asterionellopsis glacialis* (Castracane) Round (ab) are responsible for phytoplankton flourishing in the waters of Port-Tawfiq and Zaytiyat ports during September 2020. Except for the high relative occurrence of *Oscillatoria simpliccissima* Gomont (WoRMS) of cyanophytes at Zaytiyat Port in September 2020, the other algal groups were observed with low to moderately similar counts at all sites during the investigation period. In this regard, **Schabhüttl *et al.* (2012)** found that diatoms performed better at lower temperatures in mixed communities, whereas Cyanobacteria responded more forcefully to rising temperatures. According to **Gittings *et al.* (2018)**, the northern Red Sea has a unique winter phytoplankton bloom, whereas the summer is associated with decreased vertical mixing and a decline in phytoplankton quantity. Furthermore, **Abu Faddan (2019)** and **El-Sheikh *et al.* (2023)** concluded that seasonal species diversity indicates that winter is the most prosperous season in the northern Suez Gulf, followed by summer.

Table 3. The mean counts of the common and dominant phytoplankton species (unit/L) in the Egyptian Red Sea harbors during 2019-2021.

Harbors / Algal groups	Port-Tawfik	Zaytiyat	Nuwbia	Sharm El-Sheikh	Hurgada	Safaga
September 2019						
Bacillariophyceae						
Chaetoceros tortissimus Gran (ab)	174	154	187	109	156	137
Proboscia alata var. *gracillima* (Cleve) van Heurck (ab)	210	211	109	100	214	150
February 2020						
Bacillariophyceae						
Proboscia alata var. *gracillima* (Cleve) van Heurck (ab)	2425	1200	426	276	450	161
Rhizosolenia imbricata Brightwell (ab)	265	278	144	104	178	154
Dinophyceae						
Tripos massiliensis (Gourret) F.Gómez (ab)	236	244	154	104	156	111
*Ceratium macroceros (*Ehrenberg) Vanhoffen (ab)	242	209	226	154	167	154
September 2020						
Bacillariophyceae						
Asterionellopsis glacialis (Castracane) Round (ab)	1450	821	357	215	513	287
Chaetoceros curvisetus Cleve (ab)	1183	900	307	207	539	292
Proboscia alata var. *gracillima* (Cleve) van Heurck (ab)	2238	2150	625	324	1461	900
Cyanophyceae						
Oscillatoria simpliccissima Gomont (WoRMS)	107	489	142	81	0	82
February 2021						
Bacillariophyceae						
Chaetoceros curvisetus Cleve (ab)	253	261	0	0	0	989
Rhizosolenia imbricata Brightwell (ab)	399	353	158	111	220	569
Thalassionema nitzschioides (Grunow) Mereschkowsky (ab)	352	1125	0	0	0	138
Skeletonema costatum (Greville) Cleve (ab)	0	444	0	0	0	0
Nitzschia longissima (Brébisson) Ralfs (ab)	111	42	160	992	72	82
Licmophora flabellata (Greville) C. Agardh (ab)	0	0	174	96	187	6917
Lauderia borealis Gran (ab)	0	0	214	0	0	683

On the other hand, the lowest occurrence of phytoplankton was observed in September 2019 (average counts of 2301 units/L), which was correlated with moderate counts of the previously dominant species. The data from **Nassar (2007a, b**) support this conclusion, where they stated that the highest phytoplankton counts were recorded during winter along the western coasts of the Suez and Aqaba Gulfs. Additionally, the northeastern side of the Red Sea was far more productive than the northwest (**Shams El-Din *et al*., 2005**). However, **Nassar (2000)** and **Nassar *et al*. (2014)** observed that the Red Sea displayed a distinctive trend in which autumn constituted the most productive season. Whereas, **Nassar *et al*. (2016)** revealed that the highest abundance of phytoplankton during winter was associated with the highest values of DO and nitrate in some Egyptian harbors along the Northern Red Sea during 2014–2015, which confirms and supports the data of the present study in 2019–2021.

In terms of species tolerance, **Mihnea (1985)** stated that the dominance of any species in polluted water for one season or more and accounting for approximately 10% of the entire community could be considered an indicator species. As a result, the dominant diatoms that were recorded near the different sites of Port-Tawfik Harbor and Zaytiyat in the current study, *Proboscia alata* var. *gracillima* (Cleve) van Heurck (ab), *Chaetoceros curvisetus* (Cleve) (ab), *Skeletonema costatum* (Greville) Cleve (ab), *Asterionellopsis glacialis* (Castracane) Round (ab), and the cyanophytes *Oscillatoria simpliccissima* Gomont (WoRMS) could be considered pollution-tolerant species. Such findings are consistent with those reported by **Nassar (2000, 2007a)** in the Gulf of Suez for *Oscillatoria simpliccissima* and *Skeletonema costatum* in Red Sea coastal waters (**El-Sherif and Abo El-Ezz, 2000**).

4. Species diversity

The current study's analysis of species diversity revealed that Nuwbia Harbor had a relatively high value of diversity (2.11), followed by Hurgada Harbor (2.0), where the majority of the recorded phytoplankton species were fairly distributed during the study period, indicating the absence of a distinct dominant species. While Safaga Harbor had the lowest diversity value (1.34), a diatom, namely *Licmophora flabellata*, thrived in its waters in February 2021, accounting for approximately 44.7% of total phytoplankton.

According to **Nassar (2000)**, the species diversity of phytoplankton decreases during periods of significant change in environmental factors. This could also be due to nutrient levels and availability. The high diversity improves community stability and productivity while making the system less vulnerable to invasions **(Nassar *et al.*, 2015)**. Changes in phytoplankton populations in domestic and industrially polluted environments, on the other hand, result in a decrease in the number of dominant species and species diversity, as well as an increase in the cell count of one or two resistant algae (**Rao and Mohanchand, 1988**). As a result, compared to other harbors in the study area, the harbors of Nuwbia and Hurgada may be considered stable sites.

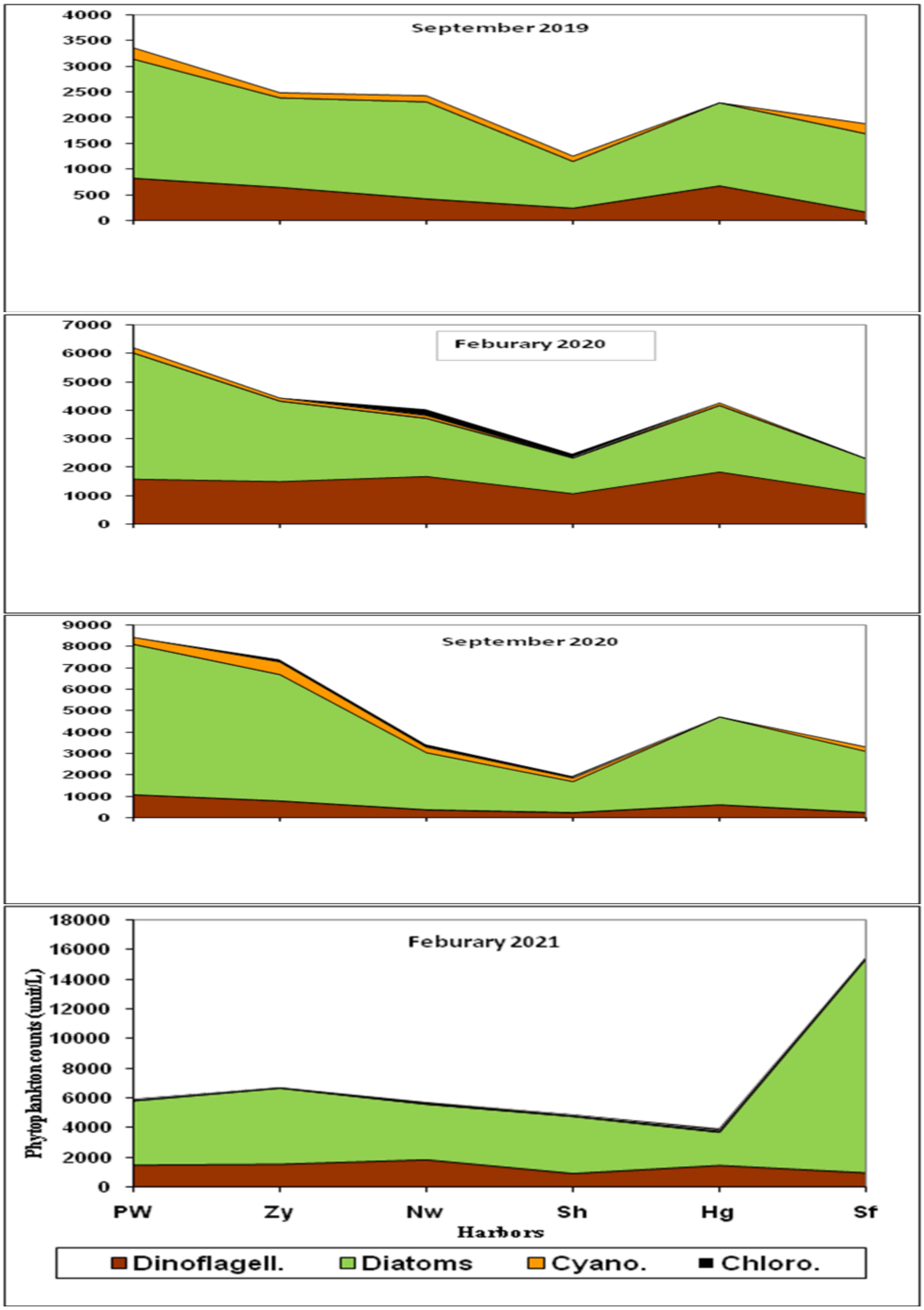

Fig. 2: Seasonal variations of phytoplankton (units/L) at the Egyptian Red Sea harbors during 2019–2021.

STATISTICAL ANALYSIS

Similarity index and multiple regressions

The similarity index (**Fig. 3**) revealed two groups with a similarity level of approximately 75% based on spatial and temporal fluctuations in phytoplankton counts. The first group includes the harbors of Zaytiyat, Port-Tawfik, and Hurgada, while the second includes Sharm El-Sheikh, Nuwbia, and Safaga. Each group is further divided into two clusters based on a similarity level of about 80–85%; one cluster represents two sites in the northern Suez Gulf (Port-Tawfik and Zaytiyat), and the other in the northern Red Sea (Hurgada Harbor). The second cluster consists of two locations in the Aqaba Gulf (Sharm El-Sheikh and Nuwbia) and one in the southwest of the Red Sea (Safaga Harbor). According to the dendrogram similarity, the species composition and abundance of phytoplankton at harbors in the Suez Gulf are very different from those in the Red Sea and the Gulf of Aqaba.

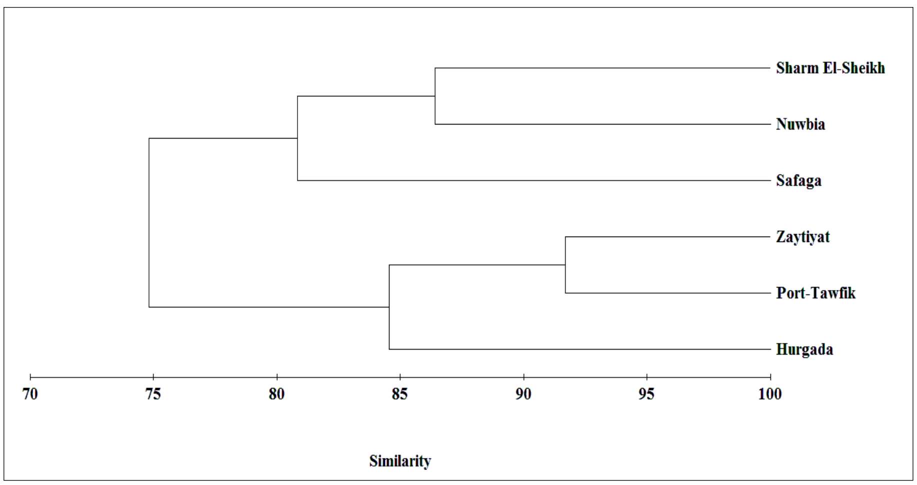

Fig. 3: Bray-Curtis plot of phytoplankton similarity between harbors

The statistical analysis of the data indicated that dissolved nitrate (0.81-18.45µM) and concentrations of ammonium (0.47- 5.01µM) were the most effective factors controlling phytoplankton abundance, followed by dissolved oxygen (6.80-8.24 mg/L) during the period of study. The multiple regression analysis was calculated to show the relationship between phytoplankton abundance and the most effective environmental factors. Total phytoplankton = -7454 + 0.77 NO_3 - 0.35 NH_4 + 0.219 DO (M.R. = 0.7599, N = 24, and $p < .05$), according to the obtained results. This regression equation could be applied in the future to predict the total phytoplankton abundance in the coastal waters of the investigated harbors of the Red Sea.

In conclusion, most of the phytoplankton species found in the current study were native to the Egyptian Red Sea region because they had already been recorded there by several other researchers. On the other hand, some low-count harmful species that don't harm the environment or the fish in the investigated harbors, such as the dinoflagellates *Prorocentrum*, *Goniaulax*, and *Dinophysis* spp., and the cyanophytes *Oscillatoria* sp., were found at some sites of Egyptian harbors. However, **Abu Faddan (2019)** and **El-Sheikh *et al*. (2023)** confirmed the existence of several harmful algal species in the northern Suez Gulf.

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