



Biological indicators as tools for monitoring water quality of a hot spot area on the Egyptian Mediterranean Coast

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Abstract

El-Mex Bay is a semi-sheltered coastal embayment located west of Alexandria, the Egyptian Mediterranean Sea. It is considered as a hot spot area receiving industrial, agricultural, and domestic wastes from the adjacent Lake Mariut through El-Umum Drain. To evaluate the water quality of the bay, phytoplankton and macroalgae as biological tools were investigated seasonally concerning physicochemical parameters from 2018 to 2019. The results indicated that the Bay harbored a diversified phytoplankton community (162 species), comprising 99 freshwater forms, 38 marine, 22 euryhaline, and only 3 brackish forms. The total average phytoplankton abundance was 419,414 unit/L. Few species were responsible for the main bulk of phytoplankton namely *Merismopedia tenuissima*, *Cylindrotheca closterium*, *Cyclotella* sp., *Skeletonema costatum*, *Scenedesmus quadricauda*, *Scenedesmus bijugus*, and *Tetradesmus dimorphus*. During the study period, El-Mex Bay was affected by the presence of 13 harmful and/or toxic algal species, among which the mediophyte species *Skeletonema costatum* was responsible for the peak occurring during autumn (2018). The results of the recorded nutrients indicated that the Bay is highly loaded, where NH_4 , NO_2 , NO_3 , PO_4 , and SiO_4 attained 141.68 μM , 25.61 μM , 151.16 μM , 10.73 μM , and 232.86 μM , respectively. The macroalgal flora was represented only by the two opportunistic species (*Ulva fasciata* and *Ulva intestinalis*). Both species could survive in freshwater conditions exhibiting very broad salinity tolerance (6.51–38.41‰) and a high level of nitrogenous compounds. Those results revealed that El-Mex Bay suffers from pollution and deterioration of water quality.

Keywords Biological tools · Physicochemical parameters · El-Mex Bay · Mediterranean Sea

Introduction

The world's coastal areas are of great ecological and economic importance. These areas represent natural resources, biological diversity, and a high potential for all kinds of commercial and industrial activities. They have naturally higher nutrient values than the open sea, due to inflows from land, more shallow and complex topography, higher water temperatures, and restricted water exchange (Bonsdorff et al. 2002). High population pressure due to tourism and other human activities such as fisheries and aquaculture, shipping,

oil, and gas industries are leading to drastic consequences (El-Saeedy 2007; Masria et al. 2014), among which water quality degradation is the worst (El-Saeedy 2007). Pollution and eutrophication of water are major concerns on the coasts of most countries due to the discharge of several land-based effluents consisting of industrial, domestic, and agricultural wastes, non-point discharges, and discharges from shipping vessels (De Jong et al. 2002; GESAMP 1993; Masria et al. 2014). This nutrient over-enrichment impacted the aquatic ecosystems causing the degradation of water quality (Okbah et al. 2017). Marine systems eutrophication is well explained on both global and regional levels as in Jørgensen and Richardson (1996), Cloern (2001), Boesch (2002), de Jonge et al. (2002), and Wassmann and Olli (2005).

In the strict sense, eutrophication is a phenomenon that has been occurring for thousands of years. It is the process of the addition of nutrients to water bodies, leading to changes in the primary production and community composition (Shaw et al. 2003; Callisto et al. 2005). However, many adverse effects on human health have been arisen associated

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with changes in the energy flow of aquatic food webs (Smith et al. 2006; Howarth 2008; Rabalais et al. 2009), as well as economic losses (Wilson and Carpenter 1999) including the decrease in industrial and recreation uses (Le et al. 2010), losses in seafood production, and the presence of toxic phytoplankton species (Howarth 2008; Rabalais et al. 2009; Ngatia et al. 2019). The largest eutrophication-related problem in coastal areas is the excessive algal growth that can be toxic or cause serious degradation in the ecology of water bodies (Anderson et al. 2002; Bonsdorff et al. 2002).

Likewise, the Mediterranean coastal areas suffer from degradation of water quality, and many hot spot areas are designated there. That is due to receiving huge volumes of wastewaters every year which are loaded by variable amounts and types of pollutants, in addition to the nitrogenous and phosphorous compounds which cause in turn a high level of eutrophication. This importunate problem extended to the Egyptian Mediterranean coast, resulting in elementary changes in the structure of planktonic and benthic communities and sometimes caused fish mortality. The level of eutrophication varied along the Egyptian coast according to the variations in volume and contents of discharged wastes (Dorgham 2011). Over $183 \times 10^6 \text{ m}^3$ of untreated domestic sewage and wastewater are annually discharged into the sea through several sewers from different sources to the coast (Dorgham 2011).

El-Mex Bay, west of Alexandria, is one of the most important coastal embayment and industrial zones along the Mediterranean Sea. It is an essential fishery ground as well as a recreational area. It has been identified as one of several hot spots on the northern coast of Egypt (Khalil 1987; EEAA 2009) for its continuous increase in population, development, and environmental degradation in the last decades (Shobier et al. 2011; Abdel Ghani et al. 2013). Consequently, the bay suffers from eutrophication which was first recorded in 1985 (Dorgham 2011), with deteriorated ecological and biological conditions causing the flourish of some organisms responsible for the heavy blooms which sometimes become a regular event. Labib (1997) reported three algal blooms (9.53 , 4.4 , and 0.41×10^6 , cells/liter) during July, September and October (1993), respectively, while Mikhail (2008) recorded a red tide in May (225.5×10^6 , cells/liter). Both events were mainly caused by *Skeletonema costatum* accompanied by water discoloration, covering most of the stations of El-Mex Bay. However, intensive attention was paid to investigate physical and chemical characteristics of El-Mex Bay (e.g., Emara et al. 1984, 1992; Dorgham et al. 1987; Said et al. 1991; Nessim 1994; Nessim et al. 2010; Shreadah et al. 2014; Abo-Taleb et al. 2015 and Okbah et al. 2017). Nevertheless, the previous work on the biological characteristics concerning phytoplankton standing crop as well as macroalgae was rather limited (Dorgham et al. 1987; Labib 1997; Gharib 1998; Hussein and Gharib 2012).

Pollution and/or eutrophication are still major problems in El Mex Bay, with no real signs of reduced concentrations of nutrients. In this work, we evaluate the present status (April 2018– February 2019) of El-Mex Bay based on the community structure of the phytoplankton and seaweeds as biological tools concerning the physicochemical parameters. The aim is to identify gaps in the current knowledge and to provide the information necessary to control and manage El-Mex Bay as one of the hot spot areas of the Egyptian marine ecosystems successfully.

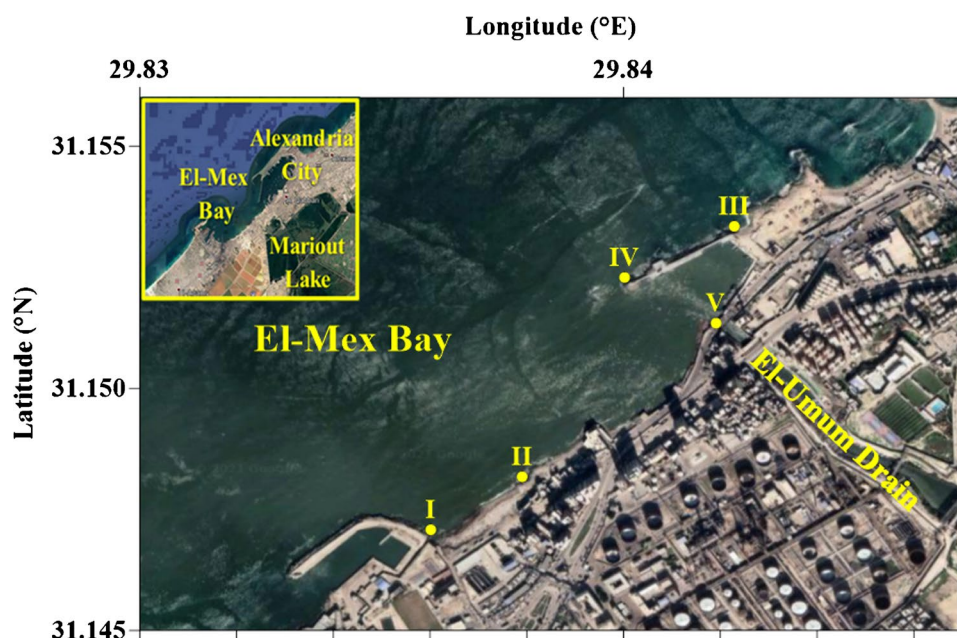
Materials and methods

The sampling of biological parameters (Phytoplankton and macroalgae) and the ambient seawater were performed seasonally from April (spring, 2018) to February (winter, 2019), covering five sites in El-Mex Bay (St. I, II, III, IV and V) (Fig. 1).

Water analysis

At each site, 1 L of seawater was collected in a polyethylene bottle for chemical analysis. Surface water temperature was measured immediately in situ using a thermometer graduated to 0.1°C . The pH-value of water samples was measured in situ using Bench type (JENWAY, 3505 Electrochemistry Analyzer pH-meter) of ± 0.01 unit accuracy after necessary precautions in the sampling and standardization processes. Salinity was measured using the salinometer model (YSI556MPS). Dissolved oxygen was fixed in situ and measured according to the common Winkler method applied by Grasshoff (1976). The concentrations of chlorophyll-a were calculated according to Strickland and Parsons (1968). Ammonium ($\text{NH}_4\text{-N}$) sample was fixed in situ and was determined, using the indophenol blue technique according to Intergovernmental Oceanographic Commission (IOC 1983), while for determination of the other nutrient salts, water samples were filtered immediately using GF/C filter. The dissolved inorganic nitrogen forms ($\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$) were determined according to Strickland and Parsons (1968). Dissolved inorganic phosphorous ($\text{PO}_4\text{-P}$) was carried out according to Murphy and Riley (1962), which is then modified by Grasshoff et al. (1983). Silicate ($\text{SiO}_4\text{-Si}$) was determined by the molybdo-silicate method (Grasshoff 1964). The determination of TP and TN was carried out according to the technique described by Valderrama (1981) and modified by Koroleff (1983). The developed colors of these nutrient salts were measured spectrophotometrically using a spectrophotometer (Shimadzu UV-150-02) and the concentrations of two replicas of each nutrient salt were expressed as μM .

Fig. 1 The study area and sampling sites during 2018–2019



Biological parameters

Phytoplankton collection

A polyethylene bottle of a capacity of 1 L was fixed immediately by adding formalin (4%) for phytoplankton analysis. Estimation of the phytoplankton count was carried out by sedimentation method (Utermöhl 1958), using a binocular microscope. The results of phytoplankton count are the means of two replicas and were expressed as unit per liter (The unit comprised cells, colonies, and filaments). The identification and classification of algal taxa followed Heurk (1896), Peragallo and Peragallo (1897–1908), Lebour (1925), Cupp (1943), Hendey (1964), Sournia (1968, 1986), Dodge (1982), and Mizuno (1990). The taxonomic position of phytoplankton species was updated according to the site of AlgaeBase (Guiry and Guiry 2020).

Collection of seaweeds

Qualitative sampling Sampling of seaweeds in El-Mex Bay was done at the same five sites mentioned before from April (spring, 2018) to February (winter, 2019). Healthy specimens were collected and were washed with seawater in situ to remove the adhered sediments and impurities, then were put in labeled polyethylene bags for further identification. In the laboratory, quick rinsing of the algae with tap water was carried out on the same day to get rid of the remaining impurities and epiphytes. Identification of the two recorded species was performed according to Aleem (1993).

Quantitative sampling Samplings were conducted for the investigation of biological parameters of seaweeds which are namely species assemblages, species composition, cover %, and biomass, by applying ten replicated quadrates with 25 subdivisions and an area of 0.25 m², which were randomly taken from the littoral zone of each station at 0.5–1.0 m depth. Seaweed cover % for each subdivision in each quadrate was estimated in the field according to Saito and Atobe (1970) and Wong et al., (2012). Biomass (g fw/m²) was calculated according to Scanlan et al, (2007).

Statistical analysis

The principal component analysis was performed between the different groups of phytoplankton, harmful algae, and the physicochemical parameters. The similarity index between the sites of El-Mex Bay, based on phytoplankton community structure and their ambient water quality, was calculated by using the program Minitab 14. The species diversity (H') was calculated according to Shannon and Weaver (1963).

For the recorded seaweeds, principal component analysis was applied between cover%, wet biomass of *Ulva fasciata* and *Ulva intestinalis*, and the physicochemical parameters of El-Mex Bay during the years 2018 and 2019.

Results

The results of the physicochemical parameters and that of the biological studies are shown in Tables 1–6 and Figs. 1–8.

Table 1 The range, average, and standard deviation of the physicochemical parameters of El-Mex Bay during (2018–2019)

Physico-chemical parameters	Site I	Site II	Site III	Site IV	Site V
Temperature (°C)	14.00–31.50 25.10 ± 7.92	16.00–31.10 25.50 ± 6.86	17.00–32.00 25.30 ± 6.4	18.00–32.00 25.5 ± 5.97	16.00–32.00 25.1 ± 6.66
pH	7.73–7.90 7.83 ± 0.08	7.64–7.99 7.78 ± 0.15	7.58–7.82 7.70 ± 0.10	7.66–8.26 7.97 ± 0.25	7.62–7.92 7.78 ± 0.15
Salinity (‰)	6.51–23.63 15.27 ± 8.16	8.8–22.91 16.04 ± 6.75	7.68–30.15 22.33 ± 9.99	30.55–38.44 35.50 ± 3.47	7.77–21.46 15.39 ± 6.35
Dissolved oxygen (mg. L ⁻¹)	3.51–9.71 5.97 ± 2.68	4.21–8.42 5.70 ± 1.86	3.10–9.81 5.48 ± 3.03	5.88–12.72 8.37 ± 3.07	3.34–10.79 6.30 ± 3.20
Chl. a (µg/l)	6.74–28.59 17.67 ± 15.45	8.11–21.27 14.69 ± 9.31	0.84–13.09 6.97 ± 8.66	1.82–5.77 3.80 ± 2.79	3.61–21.50 12.56 ± 12.65
Ammonium (NH ₄) (µM)	88.43–141.68 122.06 ± 24.76	82.75–139.12 121.28 ± 26.50	48.02–140.47 95.88 ± 44.89	9.32–60.26 33.41 ± 27.59	55.83–138.40 101.03 ± 36.16
Nitrite (NO ₂) (µM)	5.57–25.36 15.98 ± 10.33	2.23–21.05 14.69 ± 8.51	4.74–25.61 12.78 ± 9.16	2.16–7.92 4.70 ± 2.72	6.6–17.61 13.25 ± 4.72
Nitrate (NO ₃) (µM)	5.63–68.31 31.04 ± 26.73	3.06–49.09 31.57 ± 19.86	1.48–151.16 58.41 ± 66.35	2.0–39.18 17.77–17.23	5.4–42.97 27.88–18.08
Total N (µM)	117.82–235.34 169.80 ± 54.61	130.16–207.2 167.53 ± 39.31	77.59–317.23 167.68 ± 103.75	17.87–107.36 56.24 ± 38.91	80.62–194.15 143.23 ± 53.43
PO ₄ (µM)	0.73–9.01 4.21 ± 3.70	0.57–10.73 4.37 ± 4.54	0.95–4.14 2.22 ± 1.38	0.03–1.59 0.88 ± 0.64	1.39–3.36 2.55 ± 0.84
Total P (µM)	2.07–14.88 6.96 ± 5.60	2.35–14.88 7.94 ± 5.90	2.18–5.32 4.27 ± 1.45	0.96–5.41 2.45 ± 2.01	1.46–7.83 4.16 ± 2.70
Si (µM)	79.28–220.94 124.42 ± 65.50	76.02–232.86 132.38 ± 71.35	32.94–147.23 87.35 ± 46.98	3.92–170.38 60.62 ± 75.55	24.93–207.23 110.75 ± 82.93

Physicochemical parameters

The results of the physicochemical parameters of sea-water samples collected from El Mex Bay during (2018–2019) are shown in Table 1. Surface water temperature in El-Mex Bay ranged from 14 °C at Site I during winter (2019) to 32 °C at Site III, IV, and V during summer (2018). The normal thermal cycle was clear in the study area, showing the highest temperature during summer (31.40 °C) against the lowest (16.20 °C) during winter (2019). The pH values were close to each other and lied on the alkaline side (7.58–8.26), with slight temporal and spatial variations. The readings of salinity were generally low at all sites, except for Site IV (30.55–38.44‰). On the temporal scale, the salinity showed the lowest value (13.68‰) during winter (2019). The content of dissolved oxygen varied spatially and temporally, attaining a maximum of 12.72 mg/L at Site IV during autumn (2018) and recording the highest average (10.29 mg/L) during this season. Levels of Chl-a in El-Mex Bay water showed great variations ranging from 0.84 (Site III) to 28.59 (Site I) µg/L, with the highest average of 17.67 µg/L at the latter site, while the seasonal highest average was recorded during winter (18.04 µg/L) (Table 1).

As far as the nutrients are concerned, a distinguishable high ammonium content was observed at all sites during the four seasons, ranging from 9.32 µM at Site IV during summer (2018) to 141.68 µM at Site I during winter (2019). Regarding nitrite, it reached a maximum value of 25.61 µM at Site III during winter (2019) against a minimum of 2.16 µM at Site IV during autumn (2018). The nitrate content was particularly high during winter (2019), attaining a maximum of 151.6 µM (Site III), with an average of 58.41 µM at this site. Total nitrogen content ranged between 17.87 µM at Site IV during autumn (2018) and 317.23 µM at Site III during winter (2019), with notably the lowest average at Site IV (56.24 µM). Reactive phosphate contents ranged between 0.03 µM at Site IV during summer (2018) and 10.73 µM at Site II during autumn (2018), with the lowest average concentration (0.88 µM) at Site IV. The concentration of TP varied from 0.96 µM at Site IV during spring to 14.88 µM at Site I and II during autumn. The concentration of silicate fluctuated between 3.92 µM at Site IV during autumn (2018) and 232.86 µM at Site II during the same season. There is a general trend of increase in the nutrients contents compared with the previous studies, except for that of Okbah et al. (2017) which was comparable to the present study (Table 2).

Table 2 Long-term study of environmental parameters in El-Mex Bay on the long-term scale

After Dorgham (2011)											
	Dorgham et al. (1987)	Labib (1997)	Soliman and Gharib (1998)	Dorgham (1997)	EEAA (2003)	EEAA (2004)	EEAA (2005)	Nessim et al., (2010)	Shreadah et al., (2014)	Okbah et al. 2017	Present study
Study period	1982–1983	1993	1995	1996	2003	2004	2005	2007–2008	2010–2011	2012–2013	2018–2019
Salinity	5.2–38.44	20–39.8	3.68–38.5	0.6–39.6	-	-	-	7.93 – 32.30	28.2 – 32.3	7.1 – 8.7	6.5 – 38.4
Dissolved oxygen (mg L ⁻¹)	-	1.6–9.8	0.23–8.2	2.6–9.6	-	-	-	1.96 – 5.63	4.95 – 6.4	0.00 – 3.2	3.1 – 12.7
Nitrite (μM)								6.0 – 12.5	4.5 – 7.7	0.1 – 10.0	2.2 – 25.6
Nitrate (μM)	6.3–21.0	2.0–16.6	4.81–58.0	0.0–71.0	2.37–12.6	3.97–11.5	5.23 – 6.0	13.3 – 28.9	6.21 – 13.1	0.1 – 66.7	1.5 – 151.2
Ammonia (μM)	5.78–34.6	2.5–65.8	0.0–132.1	2.13–127.8	1.5–19.6	1.95–5.1	3.29–9.4	31.7 – 174.4	70.4–118.7	4.2 – 219.1	9.3 – 141.7
Total Nitrogen (μM)	-	-	-	-	-	-	-		77.2 – 86.3	99.3 – 335.1	17.9 – 317.2
Phosphate (μM)	4.2–19.43	0.6 – 4.4	0.28–17.2	0.32 – 48.0	0.07–3.31	0.37–1.7	0.09–3.5	2.9 – 12.6	1.9 – 7.0	7.0 – 17.4	0.03 – 10.7
Total Phosphorus (μM)	-	-	-	-	-	-	-		-	2.1 – 7.0	3.1 – 14.9
Silicate (μM)	-	-	11.4–159.8	-	2.1 – 35.2	-	-	36.3 – 149.2	16.8 – 48.6	31.7 – 78.9	19.1– 232.7
Chl- <i>a</i> (μg L ⁻¹)	16.25–53.3	1.5 – 28.0	-	0.2–16.3	3.25 – 50.0	8.33–25.2	1.62 – 15.9	-	62.1 – 128.1	4.7 – 37.6	1.8 – 28.6

Biological studies

Community composition

El-Mex Bay was found to be a discrete area of high phytoplankton diversity (162 species), comprising 99 freshwater forms, 38 marine, 22 euryhaline, and only 3 brackish forms. The bay was represented by nine algal groups namely Bacillariophyceae (40 species), Chlorophyceae (31 species), Cyanophyceae (23 species), Euglenophyceae (21 species), Dinophyceae (13 species), Mediophyceae (11 species), Trebouxiophyceae (10 species), Cosinodiscophyceae (9 species), and Conjugatophyceae (4 species) (Table 3). The average total count of phytoplankton amounted to 419,414 unit/L (Table 3). The Mediophyceae was the dominant group forming (43.22%) of the total count, followed by Cyanophyceae (25.12%) and Chlorophyceae (16.95%), Trebouxiophyceae (7.45%), Bacillariophyceae (4.35%) while Euglenophyceae, Cosinodiscophyceae, Dinophyceae, and Conjugatophyceae formed collectively (2.92%).

The phytoplankton diversity displayed low variations, where Site IV was the lowest diversified (96 species), while Site V was the most diversified (112 species), with only five species restricted to this site (*Dinophysis caudata*, *Navicula anglica*, *Navicula rhynchocephala*, *Nitzschia linearis*, and *Protoperdinium divergens*). On the other hand, there were no perceptible seasonal variations in phytoplankton diversity (92–103 species). Among the recorded species, the third was perennial (58 species) (occurring during the four seasons), against a large number occurring during one season (68 species). The rest number of the species was observed either for three or two seasons.

Phytoplankton community

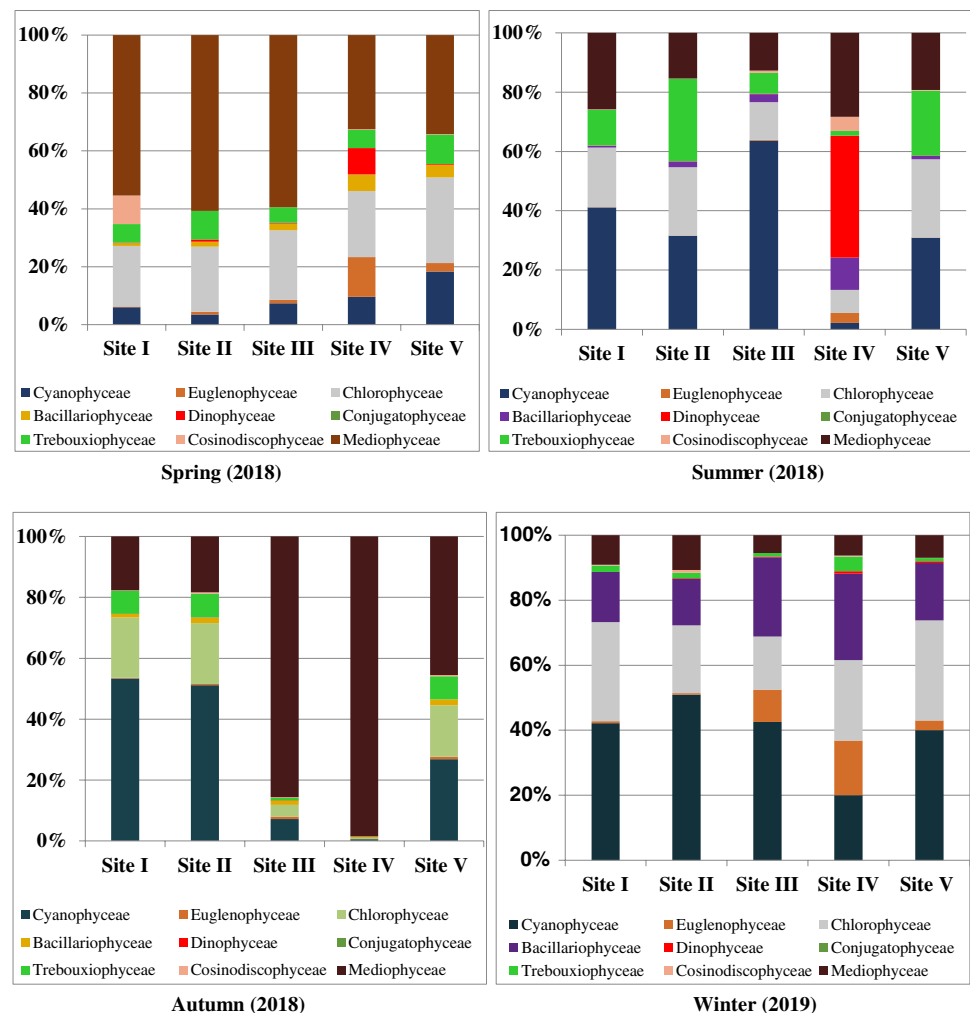
The relative abundance of the algal groups showed great variations. During spring (2018), the Mediophyceae prevailed at all sites, with the highest contribution at Site II (60.76%) against the lowest at Site IV and V (32.50 and 34.26%), respectively, forming numerically an average of 52.83% of the main bulk during this season. During summer, the three groups Cyanophyceae, Chlorophyceae, and Mediophyceae co-shared the dominance at all sites, except for Site IV, where the dinoflagellates co-dominated with the bacillariophytes and mediophytes showing a pronouncedly high percentage (41.08%). The autumn showed a distinguishable peak, where the mediophytes formed numerically the highest percentage (68.06%). This was due to its absolute dominance at Site III (85.61%) and Site IV (98.56%). During winter, the cyanophytes dominated at all sites, except for Site IV where it retrograded to 20.02% and co-shared with the bacillariophytes (26.59%), chlorophytes (24.74%), and Euglenophytes (16.82%). On the other hand, cosinodiscophytes and conjugatophytes appeared at a negligible rate during the study (Fig. 2).

Standing crop

The total abundance of phytoplankton was relatively high in the current study of El-Mex Bay (average of 419,414 unit/L) as compared with the previous studies, except for Dorgham (1997) which showed an exclusively high total count, followed by Gharib (1998) (Table 3). The total phytoplankton showed the highest count during autumn (2018), with an average of 664,319 unit/L, followed by summer (424,425 unit/L), spring (319,950 unit/L), and winter (268,964 unit/L), while on the spatial scale, the total count showed little variations (392,379–448,745 unit/L) (Table 4). However,

Table 3 The community structure and count of phytoplankton in El-Mex Bay on the long-term scale

	Dorgham et al. (1987)	El-Sherif (1989)	Gharib (1998)	Dorgham (1997)	Present study
Study period	1982–1983	1988	1995	1996	2018–2019
Bacillariophyceae	119.00	83.00	83.00	41.00	40.00
Cosinodiscophyceae					9.00
Mediophyceae					11.00
Dinoflagellates	50.00	5.00	17.00	14.00	13.00
Chlorophyceae	26.00	41.00	30.00	-	31.00
Trebouxiophyceae					10.00
Cyanophyceae	11.00	26.00	20.00	-	23.00
Euglenophyceae	4.00	4.00	8.00	-	21.00
Freshwater forms	-	-	-	11.00	-
Conjugatophyceae	-	-	-	-	4.00
Total sp. no	210.00	159.00	158.00	66.00	162.00
Total count ($\times 10^6$ unit L ⁻¹)	0.04	0.10	0.94	31.40	0.42

Fig. 2 The relative abundance of phytoplankton groups in El-Mex Bay during 2018–2019**Table 4** Total count of phytoplankton (Cells/L) in El-Mex Bay during 2018–2019

	Site I	Site II	Site III	Site IV	Site V	Average for seasons
Spring 2018	462,679 ± 303,601	384,656 ± 167,066	395,159 ± 162,176	102,768 ± 23,024	254,488 ± 103,892	319,950
Summer 2018	562,150 ± 142,737	597,156 ± 290,380	329,786 ± 69,614	112,697 ± 88,198	520,337 ± 27,183	424,425
Autumn 2018	444,950 ± 88,098	347,656 ± 19,642	593,847 ± 164,567	1,374,228 ± 256,374	560,915 ± 221,970	664,319
Winter 2019	325,202 ± 28,606	356,360 ± 4981	327,211 ± 98,520	102,275 ± 34,119	233,776 ± 6189	268,964
Average for stations	448,745	421,457	411,500	422,992	392,379	

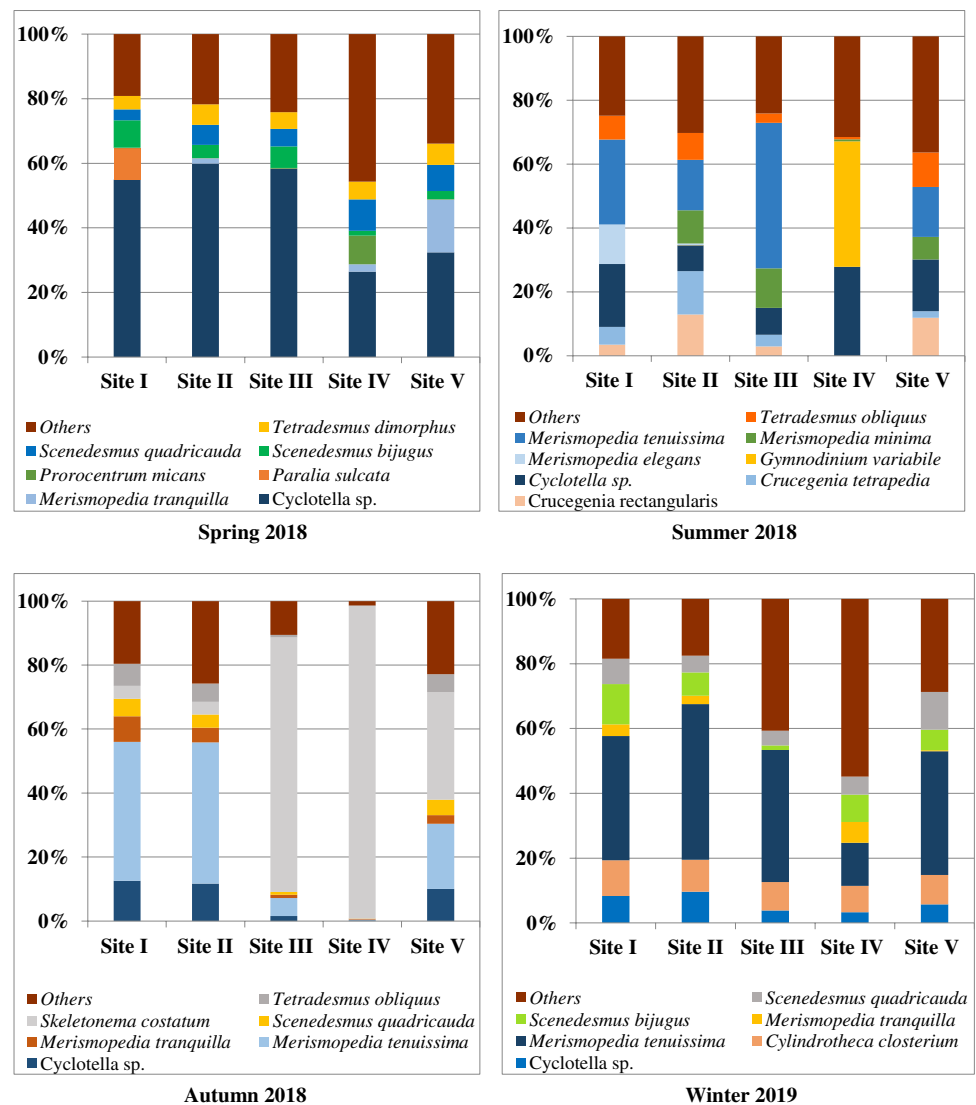
few species were responsible for the main bulk of phytoplankton, which are namely the cyanophyte *Merismopedia tenuissima*, the bacillariophyte *Cylindrotheca closterium*, the two mediophytes *Cyclotella* sp., *Skeletonema costatum*, and the three chlorophytes *Scenedesmus quadricauda*, *Scenedesmus bijugus*, and *Tetradesmus dimorphus*.

The high phytoplankton count (664,319 unit/L) during autumn was due to the exclusively high count of Site IV (1,374,228 unit/L) followed by Site III (593,847 unit/L). The mediophyte species *Skeletonema costatum* was responsible for the peak of autumn and dominated absolutely at Site IV (97.63%), while it contributed by 79.58% to the total count

at Site III. The summer was the second season in rank. The cyanophyte *Merismopedia tenuissima* was the leader species at all sites, except for Site IV where it was completely absent giving the rank to *Cyclotella* sp. (27.86%) and the dinoflagellate *Gymnodinium variable* (39.22%) (Fig. 3).

During spring *Cyclotella* sp. recorded the highest count at Site I, II, and III (54.92%, 59.90% and 58.31%) and co-dominated with the green algae *Scenedesmus* spp. forming collectively (16.05, 16.61, and 17.26%), respectively. The two sites (IV and V) followed the same pattern, but in addition to these species, the dinoflagellate *Prorocentrum micans* co-dominated at Site IV (8.81%), while *Merismopedia*

Fig. 3 The dominant species of phytoplankton in El-Mex Bay during spring, summer, autumn, and winter (2018–2019)



tranquilla ranked in the second-order (16.35%) at Site V (Fig. 3).

The winter season sustained the lowest count (268,964 unit/L) during the study. *Merismopedia* spp. were dominant, attaining the highest percentage (50.62%) at Site II against their lowest percentage (19.75%) at Site IV. The mediophyte *Cyclotella* sp. and the diatomate *Cylindrotheca closterium* contributed with (3.32–9.60%) and (8.12–11.10%) to the total count, respectively, while *Scenedesmus* spp. co-shared at all the sites (Fig. 3).

During the study period, 13 harmful and /or toxic algal species were recorded throughout the Bay, among which seven species belong to the Cyanophyceae (*Anabaenopsis circularis*, *Merismopedia tenuissima*, *Microcystis aeruginosa*, *Kamptonomia formosum*, *Oscillatoria limnetica*, *Oscillatoria tenuis*, and *Planktothrix agar-dhii*), in addition to two bacillariophytes (*Cylindrotheca*

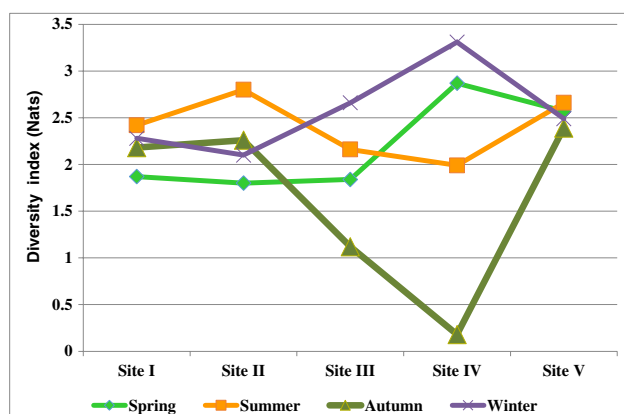
closterium and *Pseudo-nitzschia* sp.), two mediophytes (*Chaetoceros affinis* and *Skeletonema costatum*), and two dinoflagellates (*Dinophysis caudata* and *Prorocentrum micans*) (Table 5). These species almost contributed with relatively low total count to the main bulk, except for *Cylindrotheca closterium*, *Merismopedia tenuissima*, and *Skeletonema costatum*. The two former species attained a maximum of 36,100 and 171,200 unit/L, respectively during winter, while the latter species showed a pronouncedly high count (1,341,700 unit/L) during autumn (Table 5).

Diversity index

Absolute values of the diversity index showed wide temporal and spatial variations from the minimal diversity index of 0.18 nats recorded during autumn at Site IV and

Table 5 Harmful and toxic algae (unit/liter) recorded in El-Mex bay during 2018–2019

	Spring 2018	Summer 2018	Autumn 2018	Winter 2019	Toxins	References
<i>Anabaenopsis circularis</i> (G.S.West) Wolo-szynska, V.V.Miller	0–87	92–593	0–18	0–44	Microcystin	Coulibaly et al. (2014)
<i>Chaetoceros affinis</i> Lauder	0–2400	0	0–5400	0	Bloom-forming—kill fish	Lim et al. (2014)
<i>Cylindrotheca closterium</i> (Ehrenberg) Reimann & J.C.Lewin	3200–5400	200–9400	800–3300	8300–36,100	Water discoloration & Potentially harmful	Mikhail (1997) Wang et al. (2008)
<i>Dinophysis caudata</i> W.S. Kent	0–100	0	0	0	Pectenotoxin-2 (Lipo-philic, diarrhetic Shellfish Toxins)	Basti et al. (2015) Fernández et al. (2019)
<i>Kamptonema formosum</i> (Bory ex Gomont) Strunecký, Komárek & J. Smarda	0–829	0–192	0	0–48	Microcystins, homo-anatoxin-a	Carmichael (2013)
<i>Merismopedia tenuissima</i> Lemmermann	0–12,000	0–150,200	3200–193,200	13,600–171,200	Nodularin	Jakubowska and Szeląg-Wasielewska (2015)
<i>Microcystis aeruginosa</i> (Kützing) Kützing	0	0	0	0–200	PTS, Microcystins	Moura et al. (2018)
<i>Planktothrix agardhii</i> (Gomont) Anagnostidis & Komárek	0–2791	0–1736	70–933	175–1954	Microcystins	Tonk et al. (2005)
<i>Pseudo-nitzschia</i> sp.	0–1500	0–200	0–1100	100–400	Domoic acid	Orsini et al (2002)
<i>Oscillatoria limnetica</i> (Lemmermann) Komárek	0–384	0–1082	0–428	0–3968	Microcystins	Mohamed (2016)
<i>Oscillatoria tenuis</i> C.Agardh ex Gomont	0–445	0–2982	0–1509	0–87	Microcystins	Carmichael (2013)
<i>Prorocentrum micans</i> Ehrenberg	300–9050	0–300	0–100	0–800	High biomass harmful	Ignatiades and Gotsis-Skretas (2010)
<i>Skeletonema costatum</i> (Greville) Cleve	0	200–31,100	13,700–1,341,700	0–1500	Brown water, water coloration, clogging fish gills & arresting the development of invertebrate eggs	Gastrich (2000) Mendez and Ferrari (2002) Malone (2007) D'Ippolito et al. (2002)

**Fig. 4** Seasonal variations of species diversity at the different stations in El-Mex Bay during 2018–2019

the maximum of 3.31 nats during winter at the same site (Fig. 4). On the temporal scale, winter (2019) sustained the highest average diversity (2.57 nats), while autumn (2018) recorded the lowest value (1.63 nats). On the other hand, all the sites recorded close average values of diversity index, except for Site V (2.53 nats).

Statistical analysis

The statistical analysis of the data revealed that the Trebouxiophyceae and bacillariophytes were mainly influenced by silicate. On the other hand, the Cyanophyceae and Chlorophyceae were the most influenced groups by the physicochemical parameters. Dinophyceae and Mediphyceae were positively affected by pH, dissolved oxygen, temperature, and salinity, while they were negatively affected by ammonium and nitrite. The Conjugatophyceae

and Euglenophyceae were negatively influenced by the temperature and were positively affected by nitrate and total nitrogen. The cosinophytes were mainly affected by total nitrogen and nitrate (Fig. 5). For harmful algae, the principal component analysis between the abundance of each species and the physicochemical parameters showed different relationships (Fig. 6). The similarity index revealed three clusters (Fig. 7).

Macroalgal abundance at El-Mex Bay during 2018–2019

El-Mex Bay has a physiognomic monotony where the algal flora was represented by only two chlorophyte species (*Ulva fasciata* Delile and *Ulva intestinalis* Linnaeus), mostly alternating each other in the different sites. The former species was the less abundant, appearing only in

Fig. 5 Principle component analysis between the phytoplankton groups and the physicochemical parameters in El-Mex Bay (2018–2019)

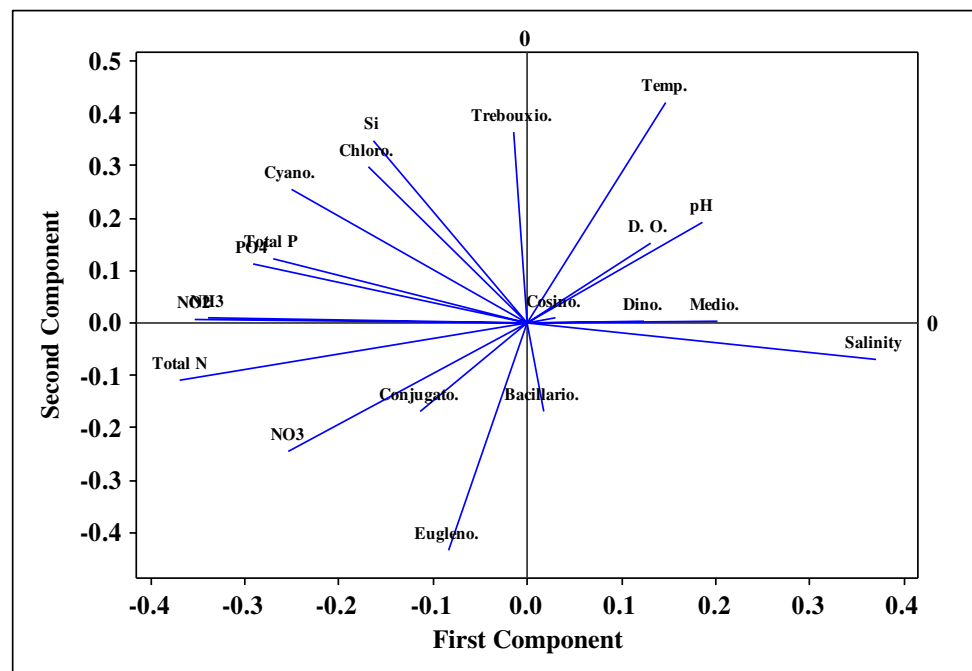


Fig. 6 Principle component analysis between the harmful algae and the physico-chemical parameters in El-Mex Bay (2018–2019). The full name of abbreviated species is found in Table 5 in the same order

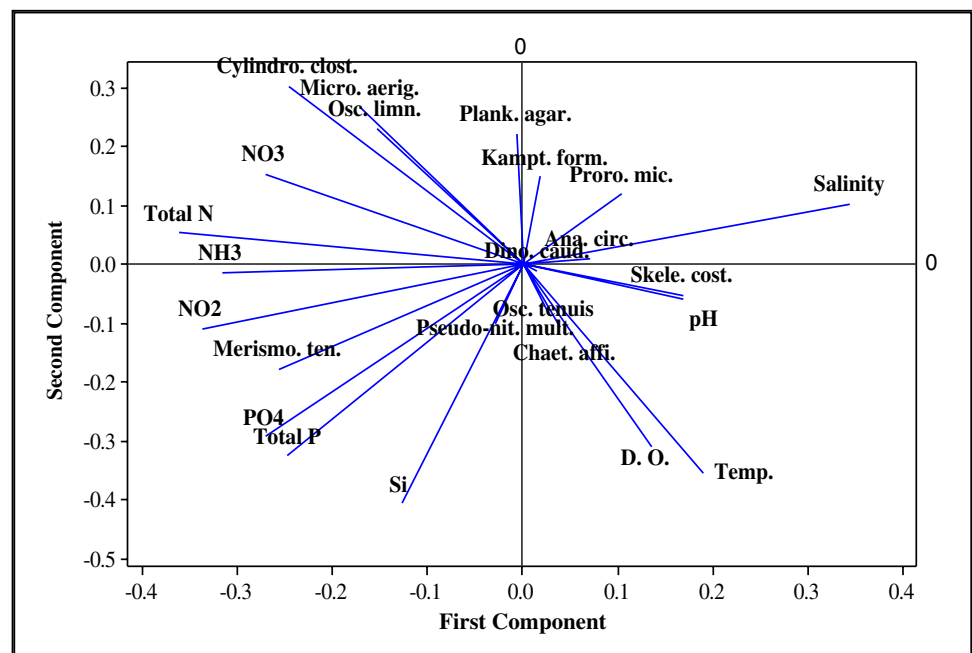
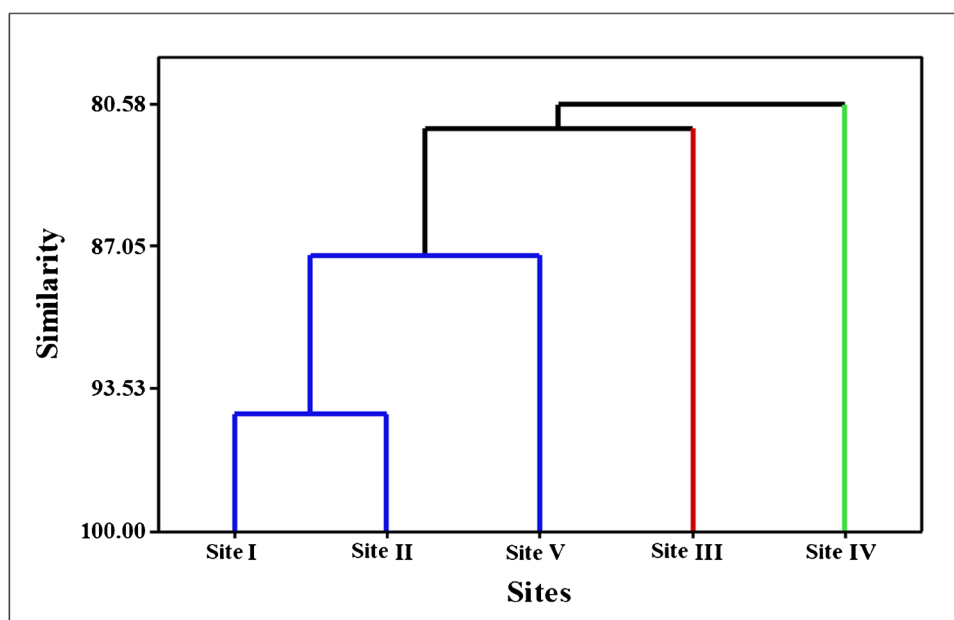


Fig. 7 Bray–Curtis of similarity of the different sites of El-Mex Bay during 2018–2019 based on phytoplankton abundance and physicochemical parameters



sites III and IV, while the latter species was more abundant, appearing in four sites (I, II, III, and V). For *U. fasciata*, the average cover was (14.05 and 33.27%) at Site III and IV respectively, and formed the lowest total average (9.46%), while the average cover of *U. intestinalis* ranged from (12.91%) at Site V to (19.46%) at Site I (Table 6), with total average cover (13.49%). On the temporal scale, the cover of *U. fasciata* was relatively low and did not exceed 9%, except during winter (2019), it attained the double. For *U. intestinalis*, it attained the highest cover (16.59%) during autumn (2018) (Table 6).

The wet biomass of *U. fasciata* at sites III and IV attained an average of 137.61 and 354.37 g FW/m², respectively (Table 6), with a total average of 98.4 g FW/m². The average wet biomass of *U. intestinalis* ranged from 49.59 (Site I) to 155.75 g FW/m² (Site III) (Table 6), with a total average of 77.72 g FW/m². On the temporal scale, the biomass of *U. fasciata* was low during summer, with an average of 77.63 g FW/m², while it attained high values of 135.11 and 136.30 g FW/m² during spring and winter, respectively. For *U. intestinalis*, it attained the highest value (149.72 g FW/m²) during autumn (2018), against the lowest biomass during winter (2019) (23.31 g FW/m²) (Table 6).

The results of the principal component analysis between the abundance of *Ulva* spp. (cover and wet biomass) and the physicochemical parameters of El-Mex Bay during (2018–2019) revealed that the cover and wet biomass of *U. fasciata* was mainly influenced negatively by silicate followed by phosphate and total phosphorus, while the abundance of *U. intestinalis* showed the inverse pattern (Fig. 8).

Discussion

One of the major environmental problems in Alexandria city is seawater pollution, where various pollutants are dumped daily by industrial, agricultural, and domestic sources over Alexandria coasts through several outfalls. El-Mex Bay is one of these disposal sites (Abdallah 2007). It is a highly dynamic system subjected to a high allochthonous injection leading to continuous replenishment of nutrients throughout the year accompanied by the exchange of water with the open sea. Manifestation and symptoms of nutrient enrichment in El-Mex Bay impacted the ecological conditions of the Bay and caused pronounced drastic environmental changes, consequently affecting the biota (Labib 1997).

On a global scale, the temperature is considered an important explanatory variable for the rate of oxygen consumption, phytoplankton nutrient uptake (López-Urrutia and Morán 2015), metabolism, growth rates, survival, distribution, biomass (Chen et al. 2017; Okbah et al. 2017), and community structure (Edwards et al. 2016; Zalat et al. 2021). In the present study, the high temperature limited the growth of Euglenophyceae and Conjugatophyceae, while it enhanced the Dinophyceae and Mediophyceae. The temperature range was compatible with that recorded by Okbah et al. (2013) and Zakaria et al. (2007) which were 18–31 and 14.5–31.0 °C in El-Mex Bay water, respectively. Changes in pH can indirectly affect phytoplankton by altering the dissolved metal concentrations so that timing and abundance of species (Granéli and Haraldsson 1993). Dissolved oxygen is a key descriptor

Table 6 Cover % (species/m²) and wet biomass (g FW/m²) of *U. va* spp. at the five sites of El- Mex Bay during 2018–2019

Species/ Station	Site I	Site II	Site III	Site IV	Site V	Biomass			Site I	Site II	Site III	Site IV	Site V	Site V	Seasonal average
	Cover														
	Spring 2018														
<i>U. fasciata</i>	0	0	12.09	17.08	0	0	0	0	0	0	136.41	404.01	0	0	135.11
<i>U. intestinalis</i>	8.31	14.29	9.92	0	38.91	27.02	101.48	78.6	0	-	14.29	51.78			
	Summer 2018														
<i>U. fasciata</i>	0	0	0	25.56	0	0	0	0	0	0	310.51	0	0	0	77.63
<i>U. intestinalis</i>	17.67	16.26	22.20	0	87.94	116.46	200.02	0	0	0	11.23	101.11			
	Autumn 2018														
<i>U. fasciata</i>	0	0	0	44.55	0	0	0	0	0	0	435.48	0	0	0	87.10
<i>U. intestinalis</i>	13.61	28.56	40.03	0	0.75	67.48	234.72	344.38	0	102.03	16.59	149.72			
	Winter 2019														
<i>U. fasciata</i>	0	0	44.10	45.9	0	0	0	414.02	267.47	0	18.00	136.30			
<i>U. intestinalis</i>	38.25	9.04	0	0	11.98	15.89	67.6	0	0	33.04	11.85	23.31			
Average of sites (<i>U. fasciata</i>)	0	0	14.05	33.27	0	0	0	137.61	354.37	0					
Average of sites (<i>U. intestinalis</i>)	19.46	17.04	18.04	0	12.91	49.59	130.07	155.75	0	67.54					

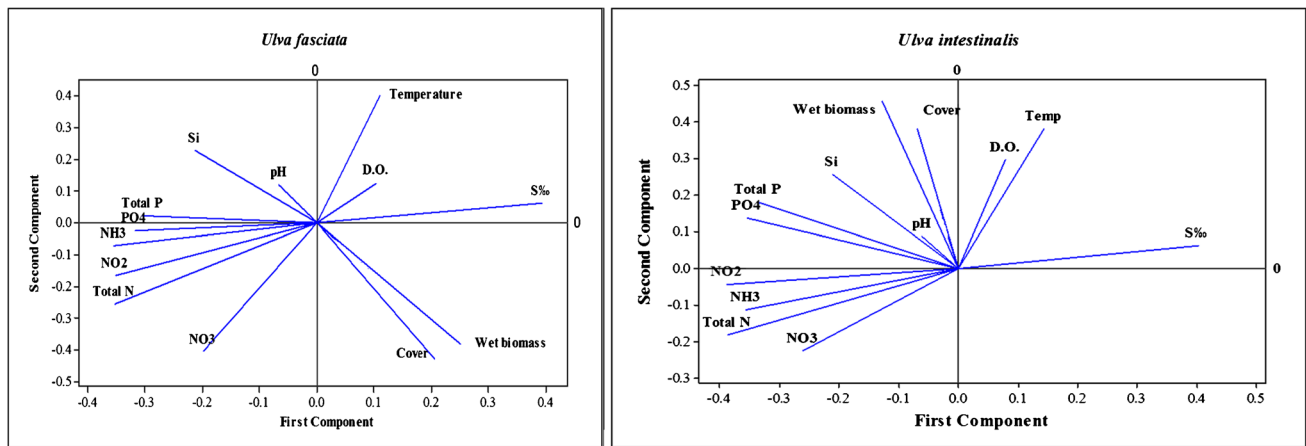


Fig. 8 Principle component analysis between the coverage and wet biomass of *Ulva* spp. and the physico-chemical parameters in El-Mex Bay (2018–2019)

of water quality in coastal areas where prolonged changes in oxygen levels could lead to modification in the local biotic community structure (Jack et al. 2009). In general, for a diversified warm-water biota, the optimum concentrations should not be less than 4.65 mgO₂/L, while for a cold-water biota, concentrations should not be lower than 5.59 mg O₂/L for desirable healthy growth (Grundy 1971; Arin 1974). Referring to Stachowitsch and Avcin (1988), the oxygen concentration < 2 mg/l reflects hypoxia and negatively impacts marine organisms. Accordingly, the Bay was well oxygenated reaching 12.72 mg/L at Site IV during autumn which exceeded the ranges of all the previous studies. On the spatial scale, the distribution of surface salinity throughout El-Mex Bay demonstrated wide-range variations relative to the dispersal pattern of wastewaters discharged into the Bay. Near-shore waters salinity sustained usually low values and increasing seaward to exceed 30‰ in the open part of the Bay (Dorgham 2011). Based on the surface salinity in El-Mex Bay, four water masses overlying each other could be identified, where the area and position of each mass are directly governed by wind direction showing a seasonal pattern. Water masses include (1) mixed land drainage of a salinity < 10.00 ppt, (2) mixed water (10.0–30.0 ppt), (3) diluted seawater (30.0–38.5 ppt), and (4) Mediterranean seawater (> 38.50 ppt) (Soliman and Gharib 1998; Zakaria et al. 2007). In the current study, the salinity at all sites falls between mixed land drainage salinity and mixed water salinity, except for Site IV which followed the diluted seawater salinity regime. On the other hand, El-Sherif (1989) reported that the drain water flows as a surface current into the Bay along the western and the northwest coasts during

the autumn, where a dense water mass with a high phytoplankton count occupies the center of the bay, associated with an increase in salinity during this season. Our results agreed with El-Sherif (1989), where a dense water mass with a high phytoplankton count was recorded at Site IV during autumn, with salinity (30.55–38.44‰).

In natural waters, nutrient salts are considered essential compounds for living organisms in aquatic systems. They represent the fertility of water, on which primary productivity and, eventually fish production depend. The large content of phosphate is considered a potential pollutant due to the huge load of domestic and drainage effluents discharging into El-Mex Bay (Said et al. 1994; Fahmy et al. 1997). PO₄ concentration ranged from 0.03 to 10.73 µM/L in El-Mex Bay during the study period, which was higher than that of Labib (1997) (0.6–4.4 µM/L), Shreadah et al. (2014) (1.93–7.01 µM/L) and particularly EEAA (2003, 2004, 2005) and exceeded the criteria of Stirn (1988) for polluted water (0.3–0.5 µM/L). Due to the high phosphate content in El-Mex Bay during the study, this salt was not a limiting factor for the growth of phytoplankton groups, except for Cyanophyceae and Chlorophyceae. The nitrogenous compounds are the most significant indicators of water quality. The concentrations of ammonium (9.32–141.68 µM) and nitrate (1.48 to 151.6 µM) in El-Mex Bay were excessively high, compared with the previous studies and exceeded that adopted by Vucak and Stirn (1982) for eutrophic areas (> 2.0 µM/l NH₄ and > 4.0 µM/l NO₃). Silicate is another important parameter controlling marine productivity and is considered a good indicator of freshwater dispersion. It is potential for diatom blooms (Okbah et al. 2017). In this study, the bacillariophytes were antagonized with silicate concentration.

This may be due to the uptake of silicate by this group (previously included in diatoms class) during their growth (Dorgham et al. 2004). On the other hand, the range of silicate ($3.92\text{--}232.86\text{ }\mu\text{M/L}$) highly exceeded that of all previous studies. However, coastal waters have, in general, quite high silicate contents since they are affected by land-based sources (Riley and Chester 1971). Chlorophyll-a concentration reached a maximum of 28.59 during winter at Site I. This agreed with the records over the past three decades in the Bay that indicated pronouncedly high chlorophyll-a concentrations in the bay as reported by Dorgham (2011), who classified the Bay as eutrophicated based on these concentrations and the high nutrient levels. In the current study, we can classify the Bay as a nutrient over-enriched area due to the high level of nutrients, but well-oxygenated sites.

The phytoplankton community of El-Mex Bay consisted mainly of a high number of fresh and brackish water species distributed all over the bay (102 species). Those species can tolerate the salinity gradient, prevailing in the Bay. During the present study, the phytoplankton abundance attained an average of 0.419×10^6 unit/L. However, this value was lower than that recorded by Gharib (1998) (0.940×10^6 unit/L) and the abnormal increase reported by Dorgham (1997) (31.4×10^6 unit/L) while, they were higher than that of Dorgham et al. (1987) and El-Sherif (1989) (0.043 and 0.097×10^6 unit/L), respectively. The difference in the phytoplankton abundance can be attributed to the variability of ecological conditions prevailing in the Bay.

The similarity index of the different sites in El-Mex Bay (2018–2019) based on phytoplankton abundance and physicochemical parameters showed three clusters. The first and second clusters consisted of St. IV and III respectively, while the third one included St. I, II, and V. The first two clusters that include one site each reflected the difference in the phytoplankton community structure and the physicochemical parameters than the other three close stations.

The composition, abundance, and growth of phytoplankton species are affected by a variety of environmental variables such as salinity, nutrients, and temperature (Dayala et al. 2014). As all marine coastal areas, Mediophyceae (previously included in the diatoms group in the preceding classification) demonstrated the most effective contribution to the total phytoplankton count. They are perennial forms with short generation time (Goma et al. 2005), usually producing great successive blooming pulses (Labib 2002). The prevalence of Mediophyceae might be due to their ability to adapt quickly to changes in hydrographical conditions (Rajesh et al. 2001) or attributed to the expected high silicate content in the outlet of El-Umoum drain (Dorgham et al.

1987). Their predominance over different groups is similar to observations in many other eutrophic Egyptian Mediterranean water, for example, Eastern Harbor, Kayet Bey (Labib 2002; Khairy et al. 2014), in Rosetta and Abu-Qir (Shams El Din et al. 2014). It is worth mentioning that the co-sharing of Chlorophyceae, Cyanophyceae, and Euglenophytes may be attributed to the allochthonous freshwater forms with the high load of nutrients. This was confirmed by the negative relationship between cell densities of Cyanophyceae and Chlorophyceae and salinity.

Although El-Mex Bay is highly polluted, the diversity experienced mostly high values characteristic of healthy marine ecosystems (close to 3 or > 3) (Whilm and Doris 1966), except for St. IV (0.18 nats) during autumn due to the absolute dominance of *Skeletonema costatum*.

During this study, the community harbored few dominant species during the different seasons. The peak of autumn was mainly due to the overwhelming of the neritic mediophyte, *S. costatum* contributing by 61.26% to total abundance. It is a cosmopolitan and familiar red tide causative species (Mingazzini et al. 1992) and is considered an eutrophication indicator worldwide (Pucher-Petković and Marasović 1980; Mihnea 1985; Revelante and Gilmartin 1985; Toming and Jaanus 2007) and was responsible for brown water coloration (Gastrich 2000; Mendez and Ferrari 2002), clogging fish gills (Malone 2007), and arresting the development of invertebrate eggs (D'Ippolito et al. 2002). Its flourishing coincided with high salinity, low levels of nitrogenous compounds, which was consistent with the principle component analysis. Dorgham (1997) reported a red tide in El-Mex Bay during the early summer with an average count of 118.5×10^6 unit/L with an absolute dominance of *S. costatum*. Furthermore, the species caused two red tide events (Labib 1997; Mikhail 2008) accompanied by water discoloration. The second dominant species *Cylindrotheca closterium* is a pollution indicator (Ignatiades and Pagou 1985) and potentially harmful, causing water discoloration (Wang et al. 2008). It was prominent at all sites during winter and was negatively influenced by temperature and positively affected by nitrogenous compounds. These results were supported by the principal component analysis. *Cyclotella* sp. was responsible for the peak during spring. It showed only an inverse relationship with nitrate ($r = -0.356$). The species was reported as the most dominant mediophyte in the Bay (El-Sherif 1989). The genus *Cyclotella* is of wide distribution in the Egyptian Mediterranean Coast (Gergis 1983) in addition to the Egyptian Delta lakes (Samaan 1974). This may be due to that it is the euryhaline genus (Roubex and Lancelot 2008). Furthermore, Palmer (1969) classified the genus *Cyclotella* among the organic pollution indicators. Summer and winter high density were attributed to the

proliferation of *Merismopedia tenuissima* that exhibited close association with high nutrient concentrations, while it was negatively affected by salinity which was confirmed by the principal component analysis.

During the study period in El-Mex Bay, several harmful and/or toxic phytoplankton species were detected, mostly were cyanophytes which are microcystin producers. This toxin causes lethal poisoning and disturbances in the main development process, especially the initial life phases of many planktonic and fish species (Zanchett and Oliveira-Filho 2013). For a human being, it is hepatotoxic, inhibiting protein phosphatases, genotoxic, neurotoxic, and tumorigenic (Turner et al. 2018). The diatomate *Pseudo-nitzschia* sp. produces domoic acid which is a potent exotoxin linked to marine mammal mortalities, while the mediophyte *Chaetoceros affinis* can be responsible for fish mortality. The dinoflagellates *Dinophysis caudata* and *Prorocentrum micans* were found to be harmful to autochthonous species (Zaghloul 1994). Although the total count of most of these harmful species did not exceed 100 cells/L, they were considered dangerous as some algal toxins are extremely potent (Turner et al. 2018). However, they could be considered as a symptom of eutrophication as reported by previous studies (Madkour et al. 2007).

Macroalgae

The use of bioindicators to monitor coastal pollution has advantages over the physicochemical ones as they are supposed to be a direct measure of pollution influence on the aquatic ecosystem (Wan et al. 2017). The ecological importance and distinguishing features of macroalgae, particularly as indicators of nutrient pollution, make them favorable for evaluation endpoints for numeric nutrient criteria development for water quality management purposes (EPA 2014).

El-Mex Bay had not been investigated before for macroalgal distribution in the previous studies. During the present study, the algal flora was represented only by two green algal species namely *Ulva fasciata* and *Ulva intestinalis*. The *Ulva* spp. are opportunistic species that can thrive causing ecological problems due to the formation of persistent blooms which may be enhanced by anthropogenic nutrient inputs from industrial, agricultural, and domestic wastes (Guidone and Thornber 2013; Smetacek and Zingone 2013). The *U. fasciata* was restricted to Sites III and IV accompanied with the relatively low level of silicate with total average (87.35 and 60.62 μM), phosphate (2.22 and 0.88 μM), and total phosphorus (4.27 and 2.45 μM) in these sites respectively, while *U. intestinalis* showed inverse pattern thriving in the sites associated with a high level of these nutrients. This could explain their distribution alternatively. On the other hand, both could survive in freshwater conditions exhibiting very

broad salinity tolerance (6.51–38.41‰) (Edwards et al. 1988; Cohen and Fong 2004) and a high level of nitrogenous compounds. The presence of these species, particularly *U. intestinalis*, let to suggest that El-Mex Bay suffers from pollution and deterioration of water quality.

Conclusion

El-Mex Bay suffers from the continuous supply of nutrients that surpassed the permissible values, causing deterioration in water quality to a non-favorable degree for healthy populations of algal flora. This was reflected by the presence of 13 harmful and/or toxic algal species that can cause serious problems to human health. In addition, the presence of two opportunistic algal species (*Ulva fasciata* and *U. intestinalis*) in the bay is an indicator of nutrient enrichment. Pollution recovery of the Bay is a must and can be performed by different treatments, among which the biological one is the best.

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Declarations

All authors state that there are no ethical statements contained in the manuscripts.

Conflict of interest The authors declare no competing interests.

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