Phytoplankton assemblage of a solar saltern in Port Fouad, Egypt

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Abstract

The present study is the first investigation of the phytoplankton community in one of Egypt's saltworks. The phytoplankton composition and distribution in five ponds of increasing salinity were investigated in the solar saltern of Port Fouad. The phytoplankton community consisted of 42 species belonging to cyanobacteria (16), diatoms (12), dinoflagellates (11), Euglenophyceae (2) and Chlorophyceae (1). The number of species decreased significantly and rapidly with increasing salinity, varying between 33 species in the first pond (P1) and one species in the crystallizer pond (P5). Conversely, the total phytoplankton density, except that recorded in P1, increased significantly with rising salinity, fluctuating between 8.7 and 56×10^5 individuals l^{-1} in P2 and P5 respectively. In spite of the local

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variations in climate and nutrient availability, the phytoplankton composition, density and spatial variations along the salinity gradient were, in many respects, very similar to what has been observed in other solar saltworks. The pond with the lowest salinity (P1 $-< 52$ g l^{-1}) was characterized by a significant diversity and blooming of diatoms and dinoflagellates. Intermediate salinity ponds (P2 and P3) with salinity ~ 112–180 g l^{-1} exhibited a decline in both species richness and density, but the stenohaline blue green algae (*Synechocystis salina*) did flourish. The highly saline concentrating ponds and crystallizers (P4 and P5) with salinity ~ 223–340 g l^{-1} were characterized by few species, the disappearance of blue green algae and the thriving of the halotolerant green alga *Dunaliella salina*.

1. Introduction

Solar salterns (saltworks) are man-made systems of interconnected ponds for the production of salt from seawater, by means of solar and wind evaporation (Korovessis & Lekkas 2000). Such salterns are designed to consist of a series of shallow ponds through which seawater flows and evaporates in stages, keeping the salinity of each pond within a narrow range. In the downstream flow, salts of low solubility compared to sodium chloride precipitate at different salinities. Calcium carbonate (calcite aragonite) drops out first at TDS ~ 100–120 g l^{-1}, followed by calcium sulphate (gypsum) at TDS ~ 180 g l^{-1}. Finally, sodium chloride (halite) precipitates in crystallizer ponds at TDS ~ 300–350 g l^{-1} (Gongora et al. 2005). According to the duration of operation, saltworks have been divided into continuous and seasonal. The first maintain a salinity gradient throughout their ponds and produce salt continuously during the entire year. The second maintain a salinity gradient and produce salt only during the summer (Davis 2000).

Solar salterns are not just salt production plants; they also function as integrated saline wetlands of a unique coastal aquatic ecosystem that combines considerable environmental heterogeneity with a steep salinity gradient (Costa et al. 1996). The planktonic and benthic communities of marine organisms (e.g. bacteria, algae, copepods, molluscs, worms) that develop along with the increasing salinity gradient in the evaporating ponds and crystallizers of saltworks create a biological system that can help or harm salt production (Davis 1993). The development of planktonic species that are adapted to narrow salinity ranges aid salt production by colouring the water to improve solar energy absorption and water evaporation, as well as by creating and maintaining appropriate quantities of organic substances that power the entire biological system at the desired level. Benthic communities seal ponds against water leakage and infiltration, permanently remove excess quantities of nitrogen and phosphate

from the overlying water and maintain desired thicknesses in all ponds (Davis 2000). On the other hand, mats of unicellular cyanobacteria that exist in the brine sometimes produce massive amounts of polysaccharide slime which adversely affects salt production process (Davis & Giordano 1996). Because of the importance of phytoplankton in salt production, their community structure and distribution have been studied in several solar saltworks all over the world (Ayadi et al. 2004, Dolapsakis et al. 2005, Chatchawan et al. 2011). Although there are many saltern ecosystems in Egypt, few studies have reported the community structure and ecological function of their biological system. Taher et al. (1995) was the only study that investigated the microbial mats in the sediments in the salina system of Port Fouad. The main objective of the present study was to provide new information on the composition and abundance of phytoplankton population in ponds of different salinity in a solar saltern in Port Fouad, Egypt. Species substitution with salinity gradient and the range of salt-tolerance of the different phytoplankton taxa was considered.

2. Material and methods

2.1. Study area

The study was conducted in the solar saltern (El Nasr Salina Company) situated on the extreme north-eastern coast of Sinai (about $31°12'$ to $31°14'$N and $32°18'$ to $32°20'$E). It is an artificial system formed of interconnected ponds of different salinities, from that of seawater up to sodium chloride saturation. The saltern extends over an area of about 1000 ha to the east of Port Said city, in the town of Port Fouad between the two northern branches of the Suez Canal. The saltern lies about 500 m from the Mediterranean Sea in the north. It consists of a series of shallow ponds with depths of 0.5–1.5 m and surface areas varying from 70 to a few hundred ha (Figure 1).

Seawater is pumped from the Suez Canal through an intake to a large pond (P1) where solar energy and wind combine and evaporation begins. The water volume is reduced and salinity levels gradually build up through consecutive evaporation ponds (P2–P3) and the production pond (P4). As the salinity increases, low-soluble salts precipitate as carbonates and sulphates. The saturated brine then passes through smaller ponds (P5, crystallizer ponds) where evaporation continues (Figure 2). Once the volume has been reduced to about 10% of the original, any furtherk concentration results in the deposition of sodium chloride.
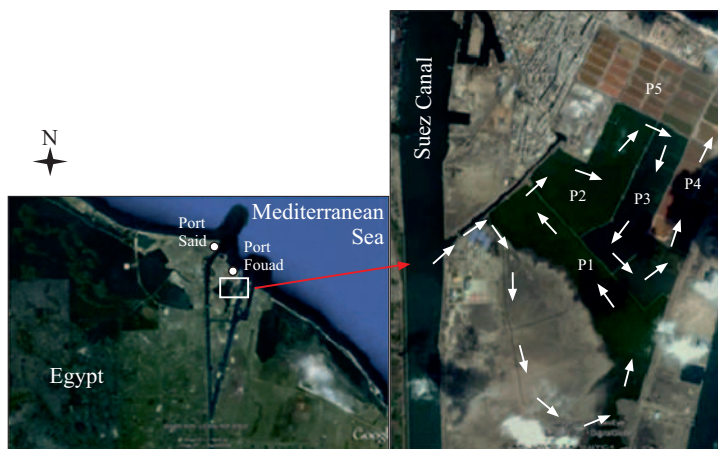
Figure 1. Maps showing location of the solar saltern at Port Fouad (Egypt) and the sampled ponds (P1–P5). The arrows indicate the direction of seawater flow in the ponds

Figure 2. A crystallizer pond of El Nasr Salina Company at Port Fouad, Egypt, photographed on 20 June 2010

2.2. Sampling

Five ponds with different salinities were sampled in summer (June 2010). Water samples were collected 20 cm below the surface using a 2-L Van Dorn bottle. Water temperature, transparency and pH were measured immediately in situ after sampling using a mercury glass thermometer graduated in $0.1°C$, a Secchi disc and a portable pH meter (Model HI 9124) respectively.

2.3. Laboratory analysis

Salinity was estimated as total dissolved salts (TDS) according to APHA (1995). A well-mixed sample was passed through a glass fibre filter, after which the filtrate was evaporated to dryness in a weighed dish, then dried to constant weight at 180°C. The increase in dish weight represents the salt content [g l^{-1}]. The total weight of major ions generally constitutes over 99% of the total salinity (Wetzel & Likens 2000). Nitrates and phosphates were determined in filtered seawater using GF/C filters according to the methods described by Parsons et al. (1984). For phytoplankton examination, water samples were preserved immediately using Lugol's iodine and concentrated by decanting. The algal count was conducted under an inverted microscope using Utermöhl's method (Utermöhl 1958) and identified to genus or species level by consulting the works of Prescott (1951), Hendey (1964), Dodge (1982) and Komárek & Anagnostidis (2005).

2.4. Statistical analysis

Pearson's correlation coefficient was performed using the SPSS 17 software program to examine the potential relationships among physico-chemical variables and phytoplankton diversity and density. Relations highly significant to the 0.05 level were noted.

3. Results

The waters of the Port Fouad saltworks were always clear, with the Secchi depth corresponding to the maximum depth of water due to the shallowness of the ponds (Table 1). The water of the shallower, more saline pond (P5, crystallizer pond) was warmer (29.3°C) than that of the deeper,

Table 1. Physicochemical parameters in the different ponds (P1–P5) of the solar saltern at Port Fouad

Parameters	Ponds				
	P1	P2	P3	P4	P5
depth [cm]	130	90	65	45	35
temperature [°C]	25.6	26.1	26.9	27.5	29.3
TDS [g l^{-1}]	51.4	112.6	179.5	223.9	340.2
pH	7.72	7.62	7.60	7.43	6.37
nitrates [μmol l^{-1}]	3.42	3.12	3.97	4.80	6.16
phosphates [μmol l^{-1}]	2.54	1.20	0.93	0.85	1.65

Table 2. Spatial distribution of the recorded species of phytoplankton in the different ponds (P1–P5) of the solar saltern at Port Fouad

Species	Ponds				
	P1	P2	P3	P4	P5
Cyanobacteria					
Aphanothece clathrata West & G. S. West	+	+	+	+	
Chroococcus minutus (Kützing) Nägeli	+	+	+		
C. turgidus (Kützing) Nägeli	+	+	+		
Gloeocapsa gigantea (West) Holl., Kosin. & Polj.	+				
Gomphosphaeria aponiana Kütz.	+	+	+		
Leptolyngbya fragilis (Gomont) Anag. & Komárek		+	+		
L. tenuis (Gomont) Anag. & Komárek	+	+	+	+	
Microcoleus sp.	+		+		
Oscillatoria indica Silva			+	+	
O. subbrevis Schemidle	+				
Planktolyngbya contorta (Lemm.) Anag. & Komárek			+		
Porphyrosiphon luteus (Gom.) Anag. & Komárek			+		
Pseudoanabaena sp.			+		
Spirulina subsalsa Oerst. ex Gomont	+	+	+		
Synechococcus elongatus Näg		+	+		
Synechocystis salina Wislouch			+	+	
Diatoms					
Amphora coffeaeformis (Agardh) Kützing	+	+			
A. decussata Grunow	+	+			
A. ovalis (Kützing) Kützing	+	+			
Cylindrotheca closterium (Ehr.) Reimann & Lewin	+	+	+		
Encyonopsis microcephala (Grunow) Krammer	+	+			
Gomphonema olivaceum (Hornemann) Brébisson	+	+			
Gyrosigma attenuatum (Kützing) Rabenhorst	+	+			
Nitzschia filiformis (Smith) Hustedt	+				
N. palea (Kützing) Smith	+	+			
N. panduriformis Gregory	+				
N. salinarum Grunow		+			
N. sigma (Kützing) Smith	+	+	+		
Dinoflagellates					
Akashiwa sanguine (Hiras.) Hansen & Moestrup	+	+	+		
Amphidinium sp.	+				
Gymnodinium catenatum Graham	+	+	+		
G. sanguineum Hirasaka	+				
G. uberrimum (Allman) Kofoid & Swezy	+				
Karenia brevis (Davis) Hansen & Moestrup	+	+			
Oxytoxum variable Schiller	+				
Prorocentrum micans Ehrenberg	+				
Protoperidinium inconspicum Lemmermann	+				
Scrippsiella spinifera Honsell et Cabrini	+				
S. trochoidea (Stein) Bal. ex Loeb. III	+	+	+		

Table 2. (*continued*)

Species	Ponds				
	P1	P2	P3	P4	P5
Euglenophyceae					
Lepocinclis acus (Müller) Marin & Melkonian	+	+	+		
L. oxyuris (Schmarda) Marin & Melkonian	+	+			
Chlorophyceae					
Dunaliella salina (Dunal) Teodoresco		+	+	+	+

less saline pond (P1, 25.6°C). The water salinity increased progressively throughout the series of interconnected ponds, giving a value of 340.2 g l^{-1} in the crystallizer pond, which was 7 times higher than that recorded (51.4 g l^{-1}) in the receiving seawater pond (P1). The pH decreases very gradually with increasing salinity gradient (Pearson's $r = 0.89$, $p < 0.05$), fluctuating between 6.37 in P5 and 7.72 in P1. Nitrate concentrations were the highest (6.16 μmol l^{-1}) in the crystallizer pond, while levels in the other ponds varied between 3.12 μmol l^{-1} and 4.80 μmol l^{-1} (Pearson's $r = 0.95$, $p < 0.05$). Concentrations of phosphates fluctuated between 0.93 μmol l^{-1} in P3 and 2.54 μmol l^{-1} in P1.

42 species of phytoplankton were identified in the whole saltern system; they consisted primarily of cyanobacteria (16 species), diatoms (12 species) and dinoflagellates (11 species), in addition to two species of Euglenophyceae and one species of Chlorophyceae (Table 2). Each pond was characterized by a specific phytoplankton community structure that varied in the number of species, total phytoplankton density and type of dominant species. As shown in Figure 3, the community structure in terms of the number of species decreased rapidly and significantly with increasing salinity in the ponds (Pearson's $r = -0.95$, $p < 0.05$), starting with a maximum of 33 species in the first pond (P1) and ending with only one species (*Dunaliella salina*) in the crystallizer pond (P5). Conversely, the total phytoplankton density, except that recorded in P1, increased significantly with rising salinity (Pearson's $r = 0.96$, $p < 0.05$), fluctuating between a minimum value of 8.7×10^5 individuals l^{-1} in P2 and a maximum of 56×10^5 individuals l^{-1} in P5 (Figure 3).

Marked differences were observed between the ponds in terms of the species richness of each group of phytoplankton. There was a conspicuous decrease in the number of diatoms and dinoflagellates with increasing salinity. They were well represented in the first and second ponds, but poorly represented in P3 and absent altogether in P4 and P5. Cyanobacteria
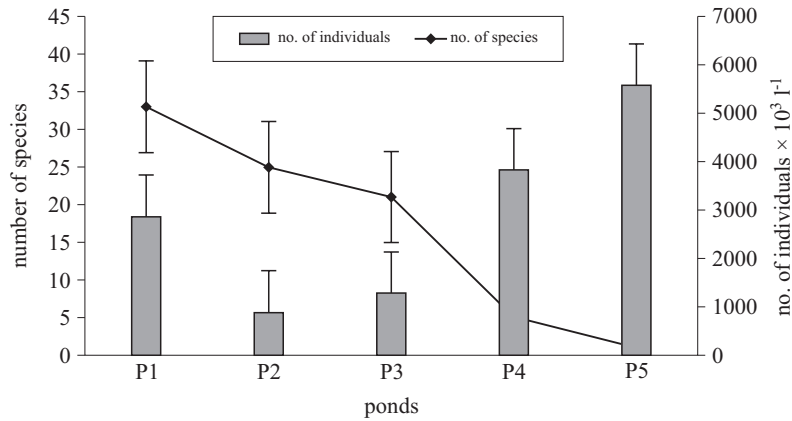
Figure 3. Total number of species and density of phytoplankton in the ponds of different salinity (P1–P5) at the Port Fouad solar saltern

were more diversified in P3 and were likewise so in P4, albeit with a lower number of species, but were absent in P5 (Figure 4).
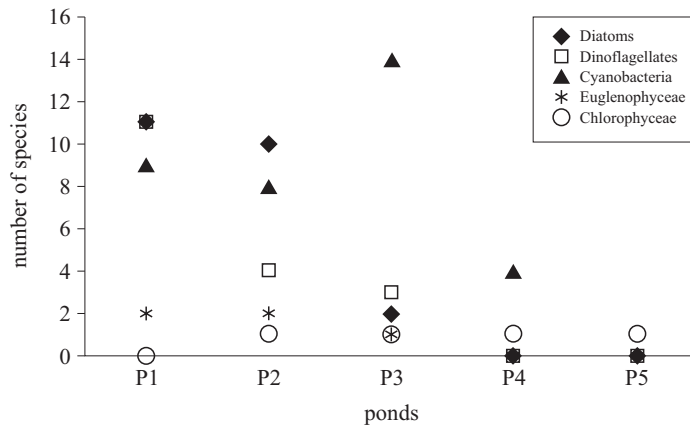
Figure 4. Species richness of each phytoplankton group in the ponds of different salinity (P1–P5) at the Port Fouad solar saltern

In terms of cell density, dinoflagellates and diatoms followed by Euglenophyceae appeared to be the predominant components in the first pond. They respectively contributed 45.6%, 33.1% and 15.6% of the total phytoplankton population (Figure 5). Among the most dominant dinoflagellate species were *Karenia brevis* contributing about 9.3×10^5 individuals l^{-1} (32.7% by number to the total density of phytoplankton) and *Scrippsiella trochoidea* (4.9%). Diatoms were represented mainly by *Cylindrotheca closterium* (8×10^5 individuals l^{-1}, 28%), while *Lepocinclis*
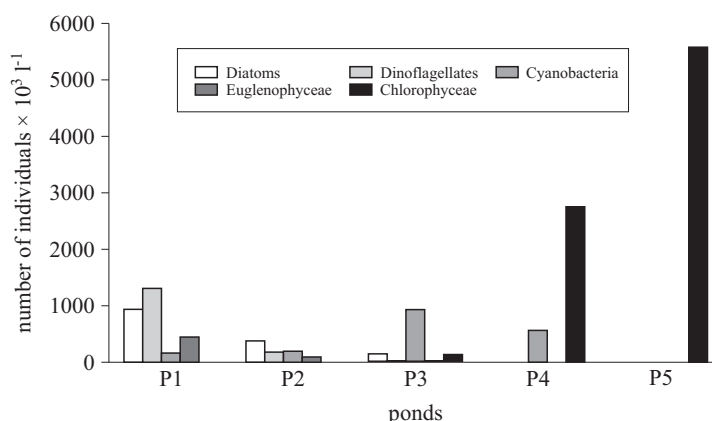
Figure 5. Density of each phytoplankton group in the different ponds (P1–P5) of the solar saltern in Port Fouad

acus (4.2×10^5 individuals l^{-1}, 14.7%) was the dominant species in Euglenophyceae. In the second pond, diatoms ranked first (42.7%) and were dominated mainly by *C. closterium* with about 25.4% of the total percentage abundance. Cyanobacteria and dinoflagellates came second with similar percentages (23.2% and 20.9% respectively).

In the third pond, cyanobacteria accounted for 74.1% of the total density of phytoplankton. An association of a unicellular species (*Synechocystis salina*), with a high density of 5.5×10^5 individuals l^{-1} (42.7%), and a filamentous species (*Leptolyngbya tenuis*) contributed to the bloom. *Synechocystis salina* was still present in the fourth pond but at a lower density (27.2%), as was *D. salina* (71.8%). The latter species was the sole survivor in the fifth pond. The contribution of Chlorophyceae was significant (Pearson's $r = 0.92$, $p < 0.05$) only in the highly saline ponds (P4 and P5) and was the only phytoplankton taxon in P5.

4. Discussion

Phytoplankton are key organisms in the biological system of saltworks, which must be established and maintained in the ponds in the proper condition to allow the economical and continuous production of high quality salt. Studies on either phytoplankton communities or other biota in Egyptian hypersaline environments, especially solar saltworks, are very scarce. This study constitutes the first investigation into the phytoplankton communities in Egyptian saltworks. The recorded phytoplankton displayed a higher diversity and a lower density in the ponds with salinities < 180 g l^{-1} (P1–P3). The decline of species number with increasing salinity is a common trend in the communities inhabiting saltworks (Ayadi et al. 2004, Toumi

et al. 2005, Mohebbi 2010). Since the existence of salinity gradients is common in solar salterns, it generates an abiotic environment of variable physical and chemical regimes. This variability is reflected in the quality of biota adapted to each habitat type in the solar saltworks system, leading to sequential blooms of diverse microbial species adapted to different ranges of salinity (Davis 2000). The results revealed that all the recorded diatoms belonged to pennate forms; centric diatoms did not occur in the ponds. Zhang et al. (1999) demonstrated from laboratory experiments that at higher salinities, the diatom assemblage consisted mainly of pennate forms, whereas centric diatoms associated with pennate diatoms and phytoflagellates dominated the cultured algae at lower salinities.

The present study showed differences among the ponds of different salinity which are driven by two essential factors: the quality of the water feeding the saltern, and the salinity gradients in the different ponds.   The first pond (P1), was characterized by a high diversity of phytoplankton with the simultaneous presence of a high density of diatoms, dinoflagellates and to a lesser extent of Euglenophyceae. This community structure resembles that of the first ponds of other saltworks (Abid et al. 2008, Evagelopoulos & Koutsoubas 2008). The environmental condition and community structure of this pond is influenced by the properties of the water feeding this saltern and are very similar to that recorded previously for this region of the Suez Canal by Madkour (2000, 2007).   This author concluded that this region of the Canal sustains eutrophic conditions as it receives a continuous flow from Lake Manzala, which is reported to be highly eutrophic. She also recorded high levels of nitrates and phosphates associated with high phytoplankton densities due to the abundance of *Cylindrotheca closterium* in this region. Although the salinity of the first pond (51.4 g l^{-1}) was higher than that previously recorded (38 g l^{-1}) in this region of the Suez Canal in summer by Madkour (2007), nutrient concentrations were high (3.42 and 2.54 μmol l^{-1} for nitrates and phosphates respectively), and the same as those previously recorded in the Suez Canal. These high nutrient values supported the high densities of some cosmopolitan species such as the diatom *C. closterium* and the dinoflagellates *Karenia brevis* and *Scrippsiella trochoidea*, which indicate continuity of eutrophic conditions. These blooming species in the first pond were reported as cosmopolitan species that inhabit the Mediterranean basin (Gómez 2003), and *C. closterium* was found blooming in a Mediterranean hypersaline coastal lagoon in summer (Gilabert 2001).

The diversity of phytoplankton in the second and third ponds exceeded the values recorded in coastal environments. This was obvious in the continuous predominance of diatoms, given the number of species in the

second pond (P2), but their density was lower than that recorded in the first pond (P1). *C. closterium*, a versatile species occurring in most of the ponds that is considered to be a pollution indicator species (Gaballah & Touliabah 2000), constituted the bulk of the diatom communities. Dinoflagellates were represented by a few stenohaline species (e.g. *Gymnodinium* spp., some designated here as *Karenia*), whereas cyanobacteria did not have a great impact on either the number of species or their density.

The abundances of diatoms and dinoflagellates decreased strongly in the third pond (P3), indicating the inability of these groups to withstand increasingly extreme living conditions as manifested by elevated salinity (179.5 g l^{-1}) and temperature (26.9°C). However, it seems that these parameters are the major factors controlling their growth, since nutrients were sufficient. Andersson et al. (1994) indicated that when nutrients are sufficient, both temperature and light intensity are the factors determining diatom growth. In contrast, it was found that the density of cyanobacteria (mostly *Synechocystis salina*, *Leptolyngbya*, *Aphanothece clathrata*, *Synechococcus* and *Microcoleus* sp.) increased significantly with salinity. Oren (2000) reviewed several studies on cyanobacteria in hypersaline environments and reported that dense communities of cyanobacteria are often a prominent feature of planktonic and benthic biota in high salinity concentration environments, including salterns. He concluded that many types of cyanobacteria of coccoid form (e.g. *Aphanothece*, *Synechocystis* and *Synechococcus*) and filamentous forms (e.g. *Microcoleus chthonoplastes* and *Phormibium*, here designated as *Leptolyngbya*) can grow at high salinities (up to 200 g l^{-1}).

In the extreme, hypersaline conditions of the high salinity ponds and the crystallizers, the environment is too harsh and biodiversity is consequently limited; while many taxonomic groups are absent, halophilic and halotolerant taxa persist and thrive (Rodriguez-Valera 1988). In the fourth pond, the phytoplankton consisted solely of the green alga *Dunaliella salina* along with four species of cyanobacteria, dominated by *S. salina*. In the crystallizer pond (P5), the phytoplankton community was nearly a monoculture of *D. salina*; cyanobacteria were absent. Worldwide, the phytoplankton community of highly saline, concentrating ponds and crystallizer ponds in saltworks and naturally hypersaline environments consist mainly of *Dunaliella* spp. owing to their high salinity tolerance (Davis & Giordano 1996, Dolapsakis et al. 2005, Mohebbi et al. 2009, 2011). It is worth mentioning that the role of *Dunaliella* is to release organic molecules such as enzymes, nitrogen compounds into the water, which favour the growth of halophilic bacteria and in turn accelerate evaporation (Mohebbi et al. 2011).

To conclude, salinity was a major controlling factor greatly influencing the richness, species diversity and abundance of phytoplankton in different ponds of the solar saltern at Port Fouad. In spite of local variations in climate and nutrient availability, the phytoplankton composition, density and spatial variations along the salinity gradient in the study area were, in many respects, nearly similar to what has been observed in other solar saltworks. The pond with the lowest salinity (P1) (< 52 g l^{-1}) was characterized by a significant diversity, and algal blooms (mainly diatoms and dinoflagellates) were due to coastal eutrophication. The intermediate salinity ponds (P2 and P3) with salinity ~ 112–180 g l^{-1} exhibited a decline in both species richness and density, but the stenohaline, non-mucilaginous blue-green algae (*S. salina*) flourished there. The highly saline concentrating ponds and crystallizers (P4 and P5) with salinity ~ 223–340 g l^{-1} support few species, although the halotolerant green algae *D. salina* does thrive; the blue-green algae disappear at saturation with sodium chloride.

Acknowledgements

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