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The first records of Cyanobacteria diversity in the benthos of the Israeli Coast of the Mediterranean Sea

Ekaterina S. Miroshnichenko[1], Sophia S. Barinova[2]* &
Larisa I. Ryabushko[1]

Ekaterina S. Miroshnichenko [1]
e-mail: mircyano@gmail.com

Sophia S. Barinova [2]*
e-mail: sophia@evo.haifa.ac.il

Larisa I. Ryabushko [1]
e-mail: larisa.ryabushko@yandex.ru

[1] Moscow Representative Office of A.O. Kovalevsky Institute of Biology of the Southern Seas RAS, Moscow, Russia

[2] Institute of Evolution, University of Haifa, Haifa, Israel

* corresponding author

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ABSTRACT

The work aims the study the species diversity and ecology of Cyanobacteria in the benthos on the Israeli coast of the Mediterranean Sea. As a result, 24 taxa of Cyanobacteria were found. Seven taxa were noted for the first time for this sea: *Aphanocapsa incerta*, *Aphanothece nidulans*, *Chlorogloea* cf. *microcystoides*, *Pseudanabaena mucicola*, *Chroococcus* sp., *Gloeocapsopsis* sp., *Trichocoleus* sp. Most Cyanobacteria species were benthic (90 %) and marine (67 %). There were only four indicators of saprobity, and all of them were freshwater species common in oligosaprobic and beta-mesosaprobic waters. Most species had a wide geographic distribution. Species marked of boreal (10 %), boreal-tropical (38 %), arctic-boreal-tropic (29 %) and cosmopolites (24 %) groups. The species richness of Cyanobacteria increased in the sites with the maximal anthropogenic loads from industrial and urban areas of the central Israel, and the minimal ones were in the protected areas.

Keywords: Cyanobacteria, benthos, diversity, ecology, phytogeography, environmental variables, Mediterranean Sea, Israeli coast

РЕЗЮМЕ

Мирошниченко Е.С., Баринова С.С., Рябушко Л.И. Первые данные о разнообразии цианобактерий в бентосе израильского побережья Средиземного моря. Работа направлена на изучение видового разнообразия и экологии цианобактерий бентоса израильского побережья Средиземного моря. В результате найдено 24 вида цианобактерий. Для моря впервые отмечено семь видов: *Aphanocapsa incerta*, *Aphanothece nidulans*, *Chlorogloea* cf. *microcystoides*, *Pseudanabaena mucicola*, *Chroococcus* sp., *Gloeocapsopsis* sp., *Trichocoleus* sp. Большинство видов Cyanobacteria являются бентосными (90 %) и морскими (67 %). Показателей сапробности отмечено всего четыре, которые относятся к пресноводным видам, обитающим в олигосапробных и бета-мезосапробных водах. Большинство видов имеют широкое географическое распространение. Отмечены бореальные (10 %), бореально-тропические (38 %), аркто-бореально-тропические (29 %) и космополитные (24 %) группы. Видовое богатство цианобактерий увеличивалось на станциях с максимальными антропогенными нагрузками со стороны промышленных и городских районов центрального Израиля, а минимальными – на охраняемых природных территориях.

Ключевые слова: цианобактерии, бентос, разнообразие, экология, фитогеография, факторы окружающей среды, Средиземное море, побережье Израиля

Cyanobacteria inhabit all seas of the World Ocean in various forms and appearances, which differ depending on the geographical distribution and ecological characteristics. Coastal habitats of cyanobacteria occupy a relatively small proportion in the marine benthos, but they are ecologically heterogeneous and contain a high species diversity (Golubich et al. 1999, Whitton 2012). This is why marine benthic communities require close attention.

The study of cyanobacteria in the Mediterranean Sea has a long history, and nowadays, 253 species have been identified (Navarro & Uriarte 1945, Komárek & Anagnostidis 1999, 2005, Caroppo et al. 2006, Taskin et al. 2008, De La Rosa et al. 2013, Komárek 2013, Lakkis 2013, Ulcay et al. 2015, Gkelis et al. 2016, Vondrásková et al. 2017), being 88 species more than known at the beginning of the 21st Century (Boudouresque 2004). The highest number of species was recorded in the Aegean (Komárek & Anagnostidis 1999, 2005, Caroppo et al. 2006, Taskin et al. 2008, Komárek 2013, Gkelis et al. 2016) and Adriatic seas (Komárek & Anagnostidis 1999, 2005, Komárek 2013, Vondrásková et al. 2017): 108 and 102 species, respectively. The least studied are those from the western and southern parts of the Mediterranean coast, totaling 28 (Navarro & Uriarte 1945, De La Rosa et al. 2013) and 11 species (Komárek & Anagnostidis 1999, 2005, Komárek 2013), respectively. In the Asian part of the sea, from the list of 97 cyanobacteria species compiled by us, 56 species were noted on the coast of Turkey (Taskin et al. 2008), 44 species on the coast of the island of Cyprus (Ulcay et al. 2015), and 18 species on the coast of Lebanon (Lakkis 2013).

Despite their notable contribution to marine biodiversity and great ecological significance (Whitton 2012), marine benthic cyanobacteria, in general, appear to be not studied, especially on the coast of the Israeli sector of the Eastern Mediterranean. Contrarily, benthic marine macroalgae have been studied in Israel for many years and are represented by 160 species from three taxonomic phyla (Einav & Israel 2008). The large-scale research of cyanobacteria in continental waters of Israel showed that this group is dominant along with diatoms and green microalgae, totaling 432 species (Barinova et al. 2022). Despite the above-mentioned facts, there are no studies on the diversity of benthic marine cyanobacteria on the Israeli coast of the Mediterranean Sea.

Therefore, the work aims to study the species diversity and ecology of cyanobacteria in the benthos of the Israeli coast of the Mediterranean Sea.

MATERIAL AND METHODS

Study area

The coastline of Israel on the Mediterranean Sea is an almost smooth line, stretches from south to north for a distance of about 200 km and has only one bay in the Haifa area (Fig. 1). Only a few small streams flow into the sea along the entire coast. The sampling period is the most watery during the year, however, no significant inflow of fresh water was found. The information for the sampling sites position was taken from the published paper (Einav & Israel 2008) and our field observations. All sites along the Mediterranean coast of Israel that represented in previous study of macrophytes by R. Enav and A. Israel were visited for phytobenthos sampling. A total of 25 sites evenly distributed along the coast were studied (Figs 1, 2).

Sampling and material processing

In order to establish the taxonomic composition of cyanobacterial communities, samples of biological periphyton were collected along the coastal shore in the Eastern Mediterranean. A total of 25 samples were taken during the March–May 2021 from 25 sites, but cyanobacteria was found in 13 of them (Table 1, Fig. 1).

Samples were taken by scraping-off the benthic community on the shore at a depth of 0–70 cm. The community was pictured at each sampling site (Fig. 2). The samples were taken in 3–5 replicates and placed in 50 ml plastic tubes. They were transported to Institute of Evolution in an icebox. The samples were 1) used for direct microscopy, 2) dried in 50 ml tubes, and 3) used as a fixed sample in 3 % neutral formaldehyde. Each sample received own unique number and the data about it was put in our database in Microsoft Access, and stored in the Collection of Institute of Evolution for later studies.

Direct microscopy was performed at Institute of Evolution, University of Haifa in living and fixed samples under magnification 400–1000. The detected species were measured and photographed using an OMAX 3D-500 digital camera. Known species were identified using conventional definitions whenever possible down to the genus or species level.

Part of the dried material in 50 ml tubes was transported to A.O. Kovalevsky Institute of Biology of the Southern Seas of Russian Academy of Sciences for studies. Twenty-five dried samples of marine benthos from the coastal sites were soaked in water with a salinity of 35 ‰ for 1 hour before processing. The slides with samples were examined in native preparations (Barbour et al. 1999, Miroshnichenko 2021) in a light microscope Bresser BioScience Trino (Germany) with Levenhuk M1000 Plus microscope digital camera at the ×400 and ×1000 magnifications.

The taxonomic identification based on morphological features, the ecological characteristics, and geographical distribution of the cyanobacterial species were determined using specialized identification books and databases (Komárek & Anagnostidis 1999, 2005, Komárek 2013, www.algaebase.org, www.marinespecies.org). The bioindicator values were performed using species-specific ecological preferences of the identified cyanobacteria (Barinova et al. 2019). The species occurrence in samples (O, %) was calculated from the ratio of the number of samples in which the species was found to the total number of samples, in percent (Shitikov et al. 2003). The frequency of the species occurrence in the specific sample was assessed visually (F) and expressed on a 5-score scale from 1 (very rare) to 5 (very frequent) (Whitton et al. 1991). The similarity of the species composition of cyanobacteria communities was assessed using the Sørensen index (Sørensen 1948). We scored the anthropogenic load on the base of its description in the macroalgae study (Einav & Israel 2008).

The collection of samples was carried out simultaneously with the measurement of environmental variables. The temperature, conductivity, and pH of water were measured at the sampling time using HANNA Waterproof Portable pH/Termometer. Water samples for the nitrate nitrogen analysis were collected at the sampling site in plastic tubes with a volume of 50 mL and transported to the lab in an icebox. The nitrate nitrogen concentration was measured using a HANNA kit according to a spectrophotometric method in the laboratory of Institute of Evolution. The salinity was measured in psu with a Refractometer Salinometer, Seawater Salinity Meter (Ade Advanced Optics, Oregon, U.S.A.). The GPS coordinates of sampling sites were determined with GARNMIN GISMAP 64.

Table 1. Sites name, abbreviation, sampling dates, and GPS coordinates in the Mediterranean coast.

No.	Name	Abbreviation	Date	Latitude, North	Longitude, East
1	Yam Rosh HaNiqra	RN	06.03.2021	33°05'36"	35°06'28"
2	Shave Zion	Nh	06.03.2021	32°58'00"	35°04'53"
3	Akko	Ac	06.03.2021	32°55'42"	35°04'08"
4	Haifa Bat Galim Casino	HC	06.05.2021	32°50'02"	34°58'35"
5	Yam - Atlit, Newe Yam	At	06.05.2021	32°42'21"	34°56'15"
6	Tel HaTaninim, Zarqa	TT	06.05.2021	32°32'21"	34°54'06"
7	Caesarea, Al Hayam	Qe	06.05.2021	32°29'40"	34°53'24"
8	Hadera, Tal Afar	Ha	06.05.2021	32°26'46"	34°52'40"
9	Nature Reserve "Gador"	Ga	06.05.2021	32°24'50"	34°52'15"
10	Bet Yanai	Ya	06.05.2021	32°23'09"	34°51'47"
11	Bat Yam	BY	23.04.2021	32°01'59"	34°44'32"
12	Yam Evtah	Ye	23.04.2021	31°44'42"	34°35'59"
13	Askkelon north	As	23.04.2021	31°42'12"	34°34'23"

Figure 1 Map of the sampling sites (black dots) on the Israeli coast of the Mediterranean Sea in March-May 2021. Blue stars: sites where cyanobacteria were revealed

Figure 2 Sampling sites in the March–May 2021 in the eastern Mediterranean coast: A – site 1, Rosh HaNiqra; B – site 4, Haifa Bat Galim Casino; C – site 15, Gador; D – site 21, Bat Yam; E – site 24, Ashkelon

RESULTS

Species list of cyanobacteria found in benthos of the Israeli coast of the Mediterranean Sea

As a result of the study of 25 samples from the coast of the Mediterranean Sea, cyanobacteria were found only in 13 samples. There were 24 taxa belonging to 7 orders, 13 families, and 17 genera. Seven taxa were recorded for the first time for the Mediterranean Sea: *Aphanocapsa incerta*, *Aphanothece nidulans*, *Chlorogloea* cf. *microcystoides*, *Pseudanabaena mucicola*, and three taxa, identified only as those belonging to the genera *Chroococcus*, *Gloeocapsopsis*, and *Trichocoleus* (Table 2).

Most of cyanobacteria species were benthic (19 species, 90 %). In the cyanobacterial community, marine (14 species,

Table 2. The list of cyanobacteria species from benthos of the Israeli coast of the Mediterranean Sea and their characteristics

No.	Taxa	*O*, %	Ec	Hal	*S*	PhG
1	*Aphanocapsa incerta* (Lemmermann) G. Cronberg & Komárek 1994 *	4	B-P	FW	β	C
2	*Aphanocapsa litoralis* Hansgirg 1892	8	B-P	M, B, FW	-	ABT not
3	*Aphanothece nidulans* P. Richter 1884 *	4	B	FW	o-β	BT not
4	*Calothrix contarenii* Bornet & Flahault 1886	12	B	M	-	BT not
5	*Calothrix fusca* var. *marina* Ervegović 1932	12	B	M	-	B
6	*Calothrix parietina* Thuret ex Bornet & Flahault 1886	4	B	FW	o	C
7	*Chlorogloea* cf. *microcystoides* Geitler 1925*	12	B	FW	-	C
8	*Chroococcus* sp. *	8	-	-	-	-
9	*Cyanostylon microcystoides* Geitler 1928	8	B	FW	-	B not
10	*Entophysalis deusta* (Meneghini) F.E. Drouet & W.A. Daily 1948	24	B	M	-	BT not
11	*Gloeocapsopsis crepidinum* (Thuret) Geitler ex Komárek 1993	4	B	FW	-	ABT not
12	*Gloeocapsopsis* sp. *	20	-	-	-	-
13	*Kyrtuthrix dalmatica* Ercegovic 1929	8	B	M	-	BT
14	*Lyngbya confervoides* C. Agardh ex Gomont 1892	32	B	M	-	C
15	*Lyngbya semiplena* J. Agardh ex Gomont 1892	12	B	M	-	BT not
16	*Phormidium nigroviride* (Thwaites ex Gomont) Anagnostidis & Komárek 1988	8	B	M	-	C
17	*Pseudanabaena mucicola* (Naumann & Huber-Pestalozzi) Schwabe 1964 *	4	B	FW, B	β	ABT not
18	*Rivularia polyotis* Roth ex Bornet & Flahault 1886	4	B	M	-	BT not
19	*Scytonematopsis crustacea* (Thuret ex Bornet & Flahault) Kováčik & Komárek 1988	12	B	M	-	ABT not
20	*Spirulina tenerrima* Kützing ex Gomont 1892	4	B	M	-	ABT not
22	*Trichocoleus tenerrimus* (Gomont) Anagnostidis 2001	8	B	M	-	ABT not
21	*Trichocoleus* sp. *	8	-	-	-	-
23	*Xenococcus pallidus* (Hansgirg) Komárek & Anagnostidis 1995	4	B	M	-	BT
24	*Xenococcus schousboei* Thuret 1880	12	B	M	-	BT not

Notes: * – noted for the first time in this sea; ***O*** – occurrence of species in samples; **Ec** – ecology: B – benthic, B-P – benthic and planktonic, **Hal** – halobity: M – marine species, B – brackish, FW – freshwater; ***S*** – saprobity: o – oligosaprobiont; o-β – oligo-beta-mesosaprobiont; β – beta-mesosaprobiont; **PhG** – phytogeographic elements: B – boreal species, BT – boreal-tropical, ABT – arctic-boreal-tropical, C – cosmopolite, not – notal species found in the Southern Hemisphere.

67 %) and freshwater (6 species, 29 %) species prevailed. Only four species were the saprobity indicators, which were freshwater species common in oligosaprobic and beta-mesosaprobic waters. Most species had a wide geographic distribution and are usually found in the Northern Hemisphere (100 %), including 62 % species also found in the Southern Hemisphere. Among them, the boreal (10 %), boreal-tropical (38 %), arctic-boreal-tropic (29 %) groups and cosmopolites (24 %) were noted.

Description of new records for the Mediterranean Sea cyanobacterial species

Below are microphotographs of seven live species earlier not found in the Mediterranean Sea, which were taken on a light microscope (Fig. 3, A–G). The following is a description of a cyanobacterial species new to the region in the annotated list.

Order SYNECHOCOCCALES
Family Merismopediaceae
Genus *Aphanocapsa* C.Nägeli 1849

***Aphanocapsa incerta* (Lemmermann) G. Cronberg et Komárek 1994** (Table 2; Fig. 3A); basionym: *Polycystis incerta* Lemmermann 1899; = *Microcystis incerta* (Lemmermann) Lemmermann 1903; *Microcystis pulverea* var. *incerta* (Lemmermann) W.B. Crow 1923; *Microcystis pulverea* f. *incerta* (Lemmermann) Elenkin 1938; *Diplocystis incerta* (Lemmermann) F.E. Drouet & W.A. Daily 1948; *Anacystis incerta* (Lemmermann) Drouet et Daily 1952

The species was found in March of the Akko area, the northern Israel in the Mediterranean Sea (sample site Akko). The occurrence in the samples is 4 %. Colonies of this species with yellowish mucilage, spherical with densely spaced spherical bright blue-green cells with a diameter of 1.5–2.0 μm. The species is benthic and planktonic, freshwater one, cosmopolite, and β-mesosaprobiont.

Family Pseudanabaenaceae
Genus *Pseudanabaena* Lauterborn 1915

***Pseudanabaena mucicola* (Naumann & Huber-Pestalozzi) Schwabe 1964** (Table 2, Fig. 3F); basionym: *Phormidium mucicola* Nauman et Huber-Pestalozzi 1929; = *Lyngbya naumannii* Iltis 1972

The species was found in May near Hadera Tal Afar (central part, site Ha). The occurrence in the samples is 4 %. Trichomes without sheaths, not long, irregularly curved, with cell size 1.2–1.4 μm; cells are barrel-shaped, more or less

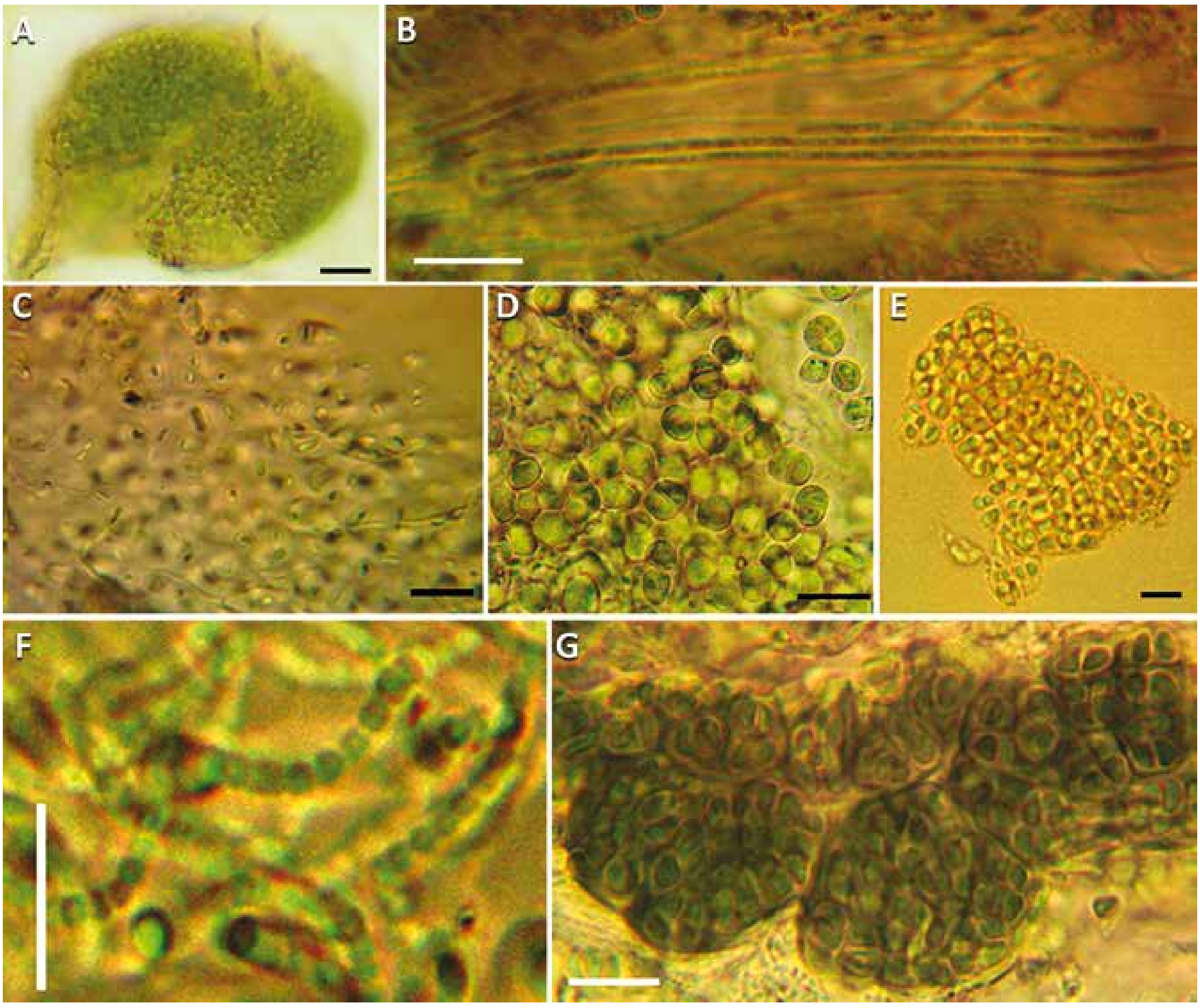

Figure 3 Cyanobacteria species new to the Mediterranean Sea from the benthos of the Israeli coast: A – *Aphanocapsa incerta* (Lemmermann) G. Cronberg & Komárek 1994; B – *Trichocoleus* sp.; C – *Aphanothece nidulans* P. Richter 1884; D – *Chroococcus* sp.; E – *Chlorogloea* cf. *microcystoides* Geitler 1925; F – *Pseudanabaena mucicola* (Naumann & Huber-Pestalozzi) Schwabe 1964; G – *Gloeocapsopsis* sp. Scale bar: 10 μm

Table 3. Visual assessment of the abundance scores of cyanobacteria species in samples of the site community.

Taxon	Site												
	Ac	Nh	RN	As	Ye	BY	Ya	Ga	Ha	Oe	TT	At	HC
Aphanocapsa incerta	3	·	·	·	·	·	·	·	·	·	·	·	·
Aphanocapsa litoralis	·	·	·	·	·	3	·	·	2	·	·	·	·
Aphanothece nidulans	·	·	·	·	·	·	·	·	2	·	·	·	·
Calothrix contarenii	·	·	2	·	·	3	2	·	·	·	·	·	·
Calothrix fusca var. *marina*	·	·	2	·	·	2	2	·	·	·	·	·	·
Calothrix parietina	·	·	·	·	·	4	·	·	·	·	·	·	·
Chlorogloea cf. *microcystoides*	3	·	·	2	·	·	·	·	·	4	·	·	·
Chroococcus sp.	·	2	3	·	·	·	·	·	3	·	·	·	·
Cyanostylon microcystoides	·	·	·	·	·	4	·	·	3	·	·	·	·
Entophysalis deusta	·	4	3	·	·	3	3	·	4	·	·	·	3
Gloeocapsopsis crepidinum	2	·	·	·	·	·	·	·	·	·	·	·	·
Gloeocapsopsis sp.	·	3	·	·	·	3	3	·	3	·	·	·	·
Kyrtuthrix dalmatica	·	·	·	·	·	3	·	·	3	·	·	·	·
Lyngbya confervoides	4	4	·	·	1	5	5	1	3	·	5	·	·
Lyngbya semiplena	2	·	·	·	·	·	·	·	·	·	3	2	·
Phormidium nigroviride	·	·	·	·	·	2	·	·	·	·	3	·	·
Pseudanabaena mucicola	·	·	·	·	·	·	·	·	2	·	·	·	·
Rivularia polyotis	·	·	·	·	·	3	·	·	·	·	·	·	·
Scytonematopsis crustacea	·	4	·	·	·	4	·	·	4	·	·	·	·
Spirulina tenerrima	·	·	·	·	·	·	·	·	1	·	·	·	·
Trichocoleus sp.	·	·	·	·	·	·	·	·	3	·	2	·	·
Trichocoleus tenerrimus	·	3	·	·	·	·	·	·	1	·	·	·	·
Xenococcus pallidus	·	·	·	·	·	·	3	·	·	·	·	·	·
Xenococcus schousboei	2	·	·	·	·	·	2	·	·	4	·	·	·

Notes: abundance scores: 1 – very rare, 2 – rare, 3 – not rare, 4 – frequent, 5 – very frequent.

Table 4. Environmental variables, anthropogenic load scores and species richness of Cyanobacteria in the Mediterranean coast sampling sites in March-May 2021.

No	Site	N-NO$_3$, mg L^{-1}	pH	EC, msm cm^{-1}	Temperature, °C	Salinity, psu	Anthropog. load, score	Number of species
1	RN	3.9	7.9	10.66	18.6	40.0	1	4
2	Nh	0.0	7.9	10.68	18.6	39.5	3	6
3	Ac	0.0	7.9	10.69	18.6	40.0	4	6
4	HC	1.1	7.6	10.50	18.6	40.0	2	1
5	At	0.9	7.6	10.53	18.6	40.0	3	1
6	TT	0.0	7.7	10.52	18.6	40.0	5	4
7	Qe	0.7	7.7	10.51	18.6	41.0	1	2
8	Ha	2.2	7.7	10.49	18.6	41.0	1	12
9	Ga	0.8	7.6	10.46	18.6	40.0	nd	1
10	Ya	2.4	7.6	10.41	18.6	40.0	nd	7
11	BY	0.7	7.5	10.55	18.6	39.0	6	12
12	Ye	1.6	8.0	10.53	18.6	40.0	nd	1
13	As	1.3	8.0	10.45	18.6	40.0	nd	1

Note: nd – not determined.

square. The species is benthic, epiphyte, freshwater and brackish, β-mesosaprobiont, arctic-boreal-tropical-notal species.

Family Trichocoleusaceae
Genus *Trichocoleus* Anagnostidis 2001

***Trichocoleus* sp.** (Table 2, Fig. 3B)

The species was found in May near Hadera Tal Afar and Tel Ha Taninim (central part, sites Ha, TT). The occurrence in the samples is 8 %. The filaments are up to 15 μm, thick, long, with wide, colorless and sometimes yellowish sheaths, containing several densely packed trichomes. Trichomes are blue-green, sometimes yellow-green, not constricted, with visible cell walls with cell size 0.8–1.0 μm wide and 1.9–2.4 μm length. *Trichocoleus polythrix*, *T. tenerrimus*, and *T. wuitneri* previously detected in the Mediterranean Sea differ from found species in the filament organization, color, structure of the mucilageous sheaths, and the color and size of trichomes.

Order CHROOCOCCALES
Family Aphanothecaceae
Genus *Aphanothece* C. Nägeli 1849

***Aphanothece nidulans* P. Richter 1884** (Table 2, Fig. 3C); = *Aphanothece saxicola* f. *nidulans* (P. Richter) Elenkin 1938; *Anacystis nidulans* (Richter) Drouet et Daily 1952

This species was found in May near Hadera Tal Afar (central part, site Ha). The occurrence in the samples is 4 %. The colony is shapeless, with colorless mucilage, in which cylindrical cells are loosely packed with their own envelopes clearly visible at the edge of the colony. Cells 1.7–1.9 μm wide and 3.4–3.9 μm long. The species is benthic, freshwater, boreal-tropical-notal, o-β-mesosaprobiont.

Family Entophysalidaceae
Genus *Chlorogloea* Wille 1900

***Chlorogloea* cf. *microcystoides* Geitler 1925** (Table 2, Fig. 3E)

The species was found in March near Akko (north coast, site Ac), in April near Ashkelon South (southern part, site As), and in May near Caesarea Al Hayam (central part, site Qe). The occurrence in samples is 12 %. Colonies are brown-green, prostrate, composed of subcolonies with their own yellowish envelopes. Cells are yellowish to blue-green, surrounded by colorless envelopes, and in colonies arranged more or less in rows, close to each other; therefore, their shapes vary from round to polygonal with a diameter of 3.4–4.1 μm. This species differs from the diagnosis only in ecological characteristics, according to which it cannot live in marine ecosystems (Komárek & Anagnostidis 1999). The species is benthic, freshwater one, and cosmopolite.

Family Chroococcaceae
Genus *Chroococcus* Nägeli 1849

***Chroococcus* sp.** (Table 2, Fig. 3D)

The species was found in March near Shave Zion (north coast, site Nh) and in May near Hadera Tal Afar (central part, site Ha). The occurrence in the samples is 8 %. The colony consists of densely packed round and semicircular yellow-green cells with their own colorless thin mucilageous envelopes, with a diameter of 3.0–6.0 μm. The species differs from *Chroococcus* spp., previously described for the Mediterranean Sea, in the appearance of colonies, sizes, and cell color.

Order CHROOCOCCIDIOPSIDALES
Chroococcidiopsidales family incertae sedis
Genus *Gloeocapsopsis* Geitler ex Komárek 1993

***Gloeocapsopsis* sp.** (Table 2, Fig. 3G)

The species was found in March near Shave Zion and Yam Rosh HaNiqra (northern part, sites Nh, RN), in April near Bat Yam (southern part, site BY), in May near Bet Yanai and Hadera Tal Afar (central part, sites Ya, Ha). The occurrence in the samples is 20 %. The colonies are compact, irregular, and consist of densely packed subcolonies containing cells with their own envelopes. Mucilage color from slightly purple to blackish at the edges, cells dark blue-green, hemispherical

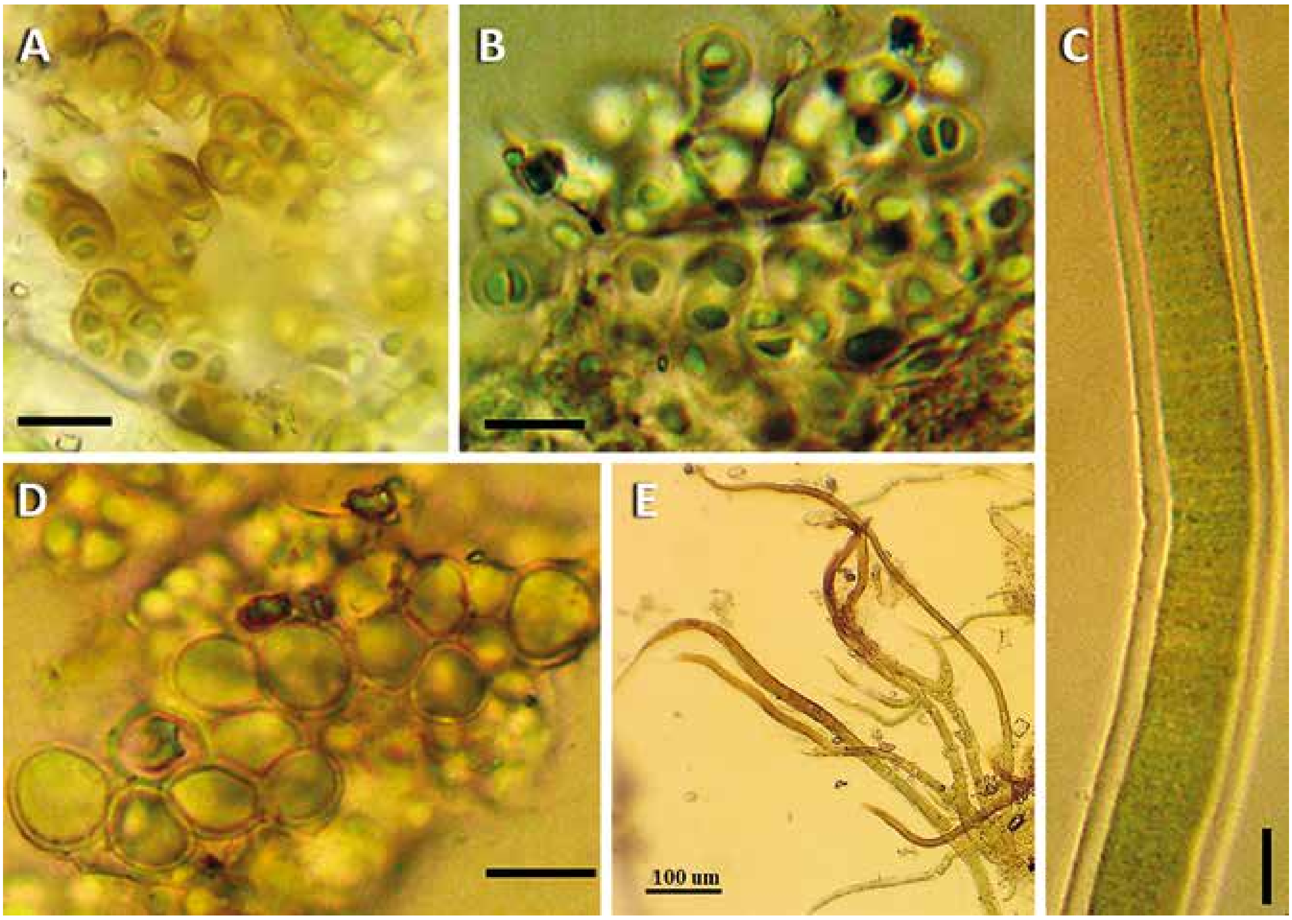

Figure 4 Dominant species of cyanobacteria in samples from Israeli coast: A – *Entophysalis deusta* (Meneghini) F.E. Drouet & W.A. Daily 1948; B – *Cyanostylon microcystoides* Geitler 1928; C – *Lyngbya confervoides* C. Agardh ex Gomont 1892; D – *Xenococcus schousboei* Thuret 1880; E – *Scytonematopsis crustacea* (Thuret ex Bornet & Flahault) Kováčik & Komárek 1988. Scale bar: 10 µm (a – c, d) and 100 µm (e)

with a diameter of 2.5–4.5 µm. Two species with blackish mucilage, *Gloeocapsopsis polyedrica*, and *G. chroococcoides*, differ significantly from the species found by us in terms of color and structure of cell envelopes, size and color, and ecological characteristics. In the Mediterranean Sea, the species *Gloeocapsa compacta* with dark, almost black mucilage was previously noted, but its generic morphological characters also differ significantly from those of the species found by us.

Characteristics of cyanobacterial communities on the studied sites

In general, cyanobacteria were found in 52 % of the samples, where, in addition to macrophytes, there was also substrate fouling. Twelve species were found in the northern part of the coast, twenty ones in the central part, and thirteen ones in the southern part. The highest occurrence in samples (O) had *Lyngbya confervoides* (32 %), *Entophysalis deusta* (24 %), *Gloeocapsopsis* sp. (20 %).

A visual assessment of the occurrence of species according to the scores (F) in samples (Table 3) showed that cyanobacteria are unevenly distributed over the microhabitats. The highest score (4–5) was noted in eight species.

In the samples, the dominant complex includes *Entophysalis deusta* (Fig. 4A), *Calothrix parietina*, *Chlorogloea* cf. *microcystoides* (Fig. 3E), *Cyanostylon microcystoides* (Fig. 4B), *Lyngbya confervoides* (Fig. 4C), *Scytonematopsis crustacea* (Fig. 4E), and *Xenococcus schousboei* (Fig. 4D). The species *L. confervoides* was the most frequent one among the dominant species in the community.

In order to identify the habitats variables of revealed cyanobacteria species, an expeditionary field work was undertaken to collect data on communities and determine water quality parameters along the Mediterranean coast at the same sites where macroalgae were collected earlier (Einav & Israel 2008). The results of determining the environmental variables are shown in Table 4 for the respective 13 sites only.

Our screening analysis of water quality parameters at the 13 sites along the Mediterranean coast showed (Fig. 5a–d) that the electrical conductivity decreases from north to south, in general following the distribution of water pH (Fig. 5a).

At the same time, the amount of nitrate nitrogen is highest at the northern sites and follows a similar distribution of the water pH, as seen in the trends in Fig. 5b. Figs 5a, b, c demonstrated the tendency to lower values of pH, conductivity, and nitrate nitrogen as opposed to water salinity at the sites under study. The species richness of cyanobacteria fluctuated from north to south with the largest species number at Hadera where the power plant cooling water intake and Bat Yam where there are massive human settlements. Such sites as Gador, Hof HaCarmel, and Atlit are parts of protected areas of the Carmel Mountain Biosphere Natural Reserve and Gador Natural Reserve, where the species richness of cyanobacteria was lowest. We represent in Fig. 4c the anthropogenic load scores based on the data from (Einav & Israel 2008). It can be seen that species

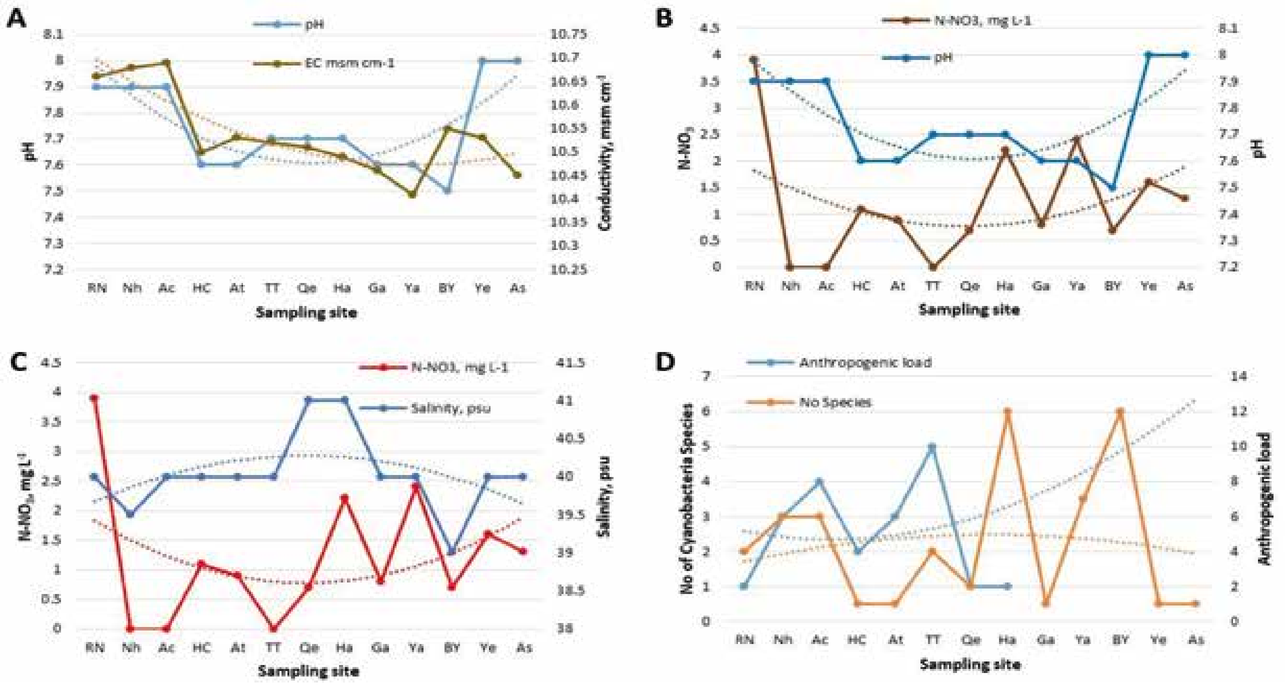

Figure 5 Distribution of environmental variables in March–May 2021 and species richness of Cyanobacteria at the sites of the Eastern Mediterranean coastline. Sites and anthropogenic load are according to (Einav & Israel 2008)

richness distribution, in general, followed the load scores and therefore demonstrated stimulation of cyanobacteria diversity by anthropogenic activity. In Figs 5b, c, a sharp increase in the nitrate nitrogen concentration can be seen at the northern station (Rosh HaNiqra) in 2021 which is opposite to the 2008 anthropogenic load. It can be the result of the oil pollution catastrophe that happened during our sampling period, moved southwest to northeast, and mostly affected biota on the northern sites of the Eastern Mediterranean coast of Israel (Fig. 2). Fig. 2b demonstrates oil pollution of station Haifa Bat Galim Casino that also was found in the northern sites of the Mediterranean coast under study.

DISCUSSION

In the benthic cyanobacterial community, characteristic features for the Mediterranean seashore were noticed, with the dominance of marine benthic species with wide geographical distribution. The contribution of freshwater species to the Israeli coastal zone is 29 %. The presence of freshwater species in the marine coastal community is also observed in other seas (Beljakova & Fushtey 2004, Gorin et al. 2016, Vinogradova & Bryantseva 2017, Miroshnichenko 2021) but differs only in their proportion. Also, four indicator species were identified, which are freshwater ones. All of this probably indicates the migration of freshwater species into the Israeli coastal zone with continental waters, in which there are 432 cyanobacterial species in total (Barinova & Smith 2022).

According to the published lists of cyanobacteria from different areas of the Mediterranean Sea, the similarity coefficient (Ks) of cyanobacteria communities on the coast of Israel and neighboring water areas is low, ranging from 19 % with the Lebanon coast community (Lakkis 2013) to 26 % with the Cyprus coast community (Ulcay et al. 2015), giving 15 % similarity with those in the eastern part of the sea (Komárek & Anagnostidis 1999, 2005, Caroppo et al. 2006, Taskin et al. 2008, Komárek 2013, Ulcay et al. 2015, Gkelis et al. 2016).

The eight species, including dominants in the Israeli coastal zone, are widely distributed in the marine ecosystems of the Mediterranean Sea. For example, *Rivularia polyotis*, *Lyngbya confervoides*, and *Phormidium nigroviride* were found in benthos of the most of the Mediterranean ecosystems: in Alboran, Balearic, Adriatic, Ionian, Aegean, Cyprus seas, as well as on the coast of Turkey, Lebanon, and Africa (Navarro & Uriarte 1945, Komárek & Anagnostidis 1999, 2005, Caroppo et al. 2006, Taskin et al. 2008, De La Rosa et al. 2013, Komárek 2013, Lakkis 2013, Ulcay et al. 2015, Gkelis et al. 2016, Vondrásková et al. 2017). More than half of the above ecosystems are inhabited by *Calothrix contarenii*, *Entophysalis deusta*, *Lyngbya semiplena*, *Scytonematopsis crustacea*, and *Trichocoleus tenerrimus*. All of the listed species preferentially inhabit rocky substrates in the surf zone (Kaštovský et al. 2021), and it can be assumed that these cyanobacterial species are typical for the Mediterranean coast. However, our data on the benthic cyanobacteria of the Israeli coast are new. Thus, the list of identified dominant cyanobacteria on the sea coast differs from that in freshwater bodies, where *Phormidium*, *Oscillatoria*, *Microcystis*, *Merismopedia* and *Aphanocapsa* (Barinova 2020, Barinova & Smith 2022) prevail.

In contrast to the identified trend towards a decrease in the species diversity of cyanobacteria from the continental waters of Israel from north to south (Barinova 2011, Barinova et al. 2015), species richness of cyanobacteria from the marine coast under study was greatest among the sites with significant anthropogenic load. Cyanobacteria can successfully grow under limited concentrations of biogenic elements and rapidly changing environmental conditions on the seacoast due to their unique adaptive mechanisms, including nitrogen-fixing activity (Golubic et al. 1999, Whitton 2012). Twenty-five percent of cyanobacterial species in benthos were heterocystous nitrogen-fixing ones, making significant contribution to the enrichment of coastal waters with nitrogen-containing substances, whose values correlated with the oil pollution degree and the increasing anthropogenic load. Cyanobacterial communities in the Jordan River had similar features (Barinova 2020), such as the dramatic decrease of the microalgae diversity and the increase in the proportion of cyanobacteria in the community downstream after the polluted water discharge.

CONCLUSION

Nowadays, the benthic community of cyanobacteria of the Mediterranean Sea, including the Israeli coast, remains poorly studied, and the present study expands knowledge in this field. There are first records of biodiversity of Cyanobacteria in the benthos of the Mediterranean coast of Israel, where 24 species from 7 orders, 13 families, and 17 genera have been found. Seven species have been noted in the Mediterranean Sea for the first time. Dominant and frequently encountered cyanobacterial species of on the Israeli coast differ from those in its continental waters and are typical for numerous marine coastal habitats. In the cyanobacterial community, benthic marine (67 %) and freshwater (29 %) species have been found to dominate. Most of the species have a wide geographic distribution and are usually found in the Northern Hemisphere (100 %), including 62 % of species also found in the Southern Hemisphere. Boreal (10 %), boreal-tropical (38 %), arctic-boreal-tropical (29 %) groups and cosmopolites (24 %) have been noted in the community. Cyanobacterial species richness was the greatest at the sites with oil pollution and other anthropogenic loads.

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