Environmental Processes (2022) 9:19
https://doi.org/10.1007/s40710-022-00573-z

ORIGINAL ARTICLE

Seasonal Occurrence of Cyanobacteria and First Detection of Microcystin-LR in Water Column of Foum-Gleita Reservoir, Mauritania

Ahmed S. Sadegh[1,2] · Zeinebou Sidoumou[1] · Mamadou Dia[2] · Juan L. G. Pinchetti[3] · Noureddine Bouaïcha[4]

Received: 23 October 2021 / Accepted: 2 February 2022

Abstract

This work was carried out to study the seasonal occurrence of cyanobacteria and their microcystin-LR in the water column of Foum-Gleita reservoir (Mauritania). Limnological and biological factors were investigated at three depths (surface, −3, and −6 m) in this reservoir during a full year. Nutrients were analyzed by Spectrophotometry, phytoplankton was analyzed by Inverted Microscopy, microsystins were analyzed by High Performance Liquid Chromatography-tandem Mass Spectrometry, and environmental factor relationships were analyzed by Pearson's correlation and Multiple Linear Regression. Physicochemical analyses have shown that this reservoir is hypertrophic with dissolved inorganic nitrogen and total phosphorus concentrations relatively high, varying from 1.39 to 6.53 and 0.21 to 0.57 mg/L, respectively. The annual surface water temperature was exceptionally high (27.8±3.6 °C), characterizing Sahelian climatic conditions. Phytoplankton analyses have shown dominance of two potentially toxic cyanobacteria species, *Microcystis aeruginosa* and *Dolichospermum flos-aquae*, during the warm season (May-September). Microcystin analysis revealed only the presence of the most toxic variant, microcystin-LR. Microcystin-LR concentration in the surface water samples, during cyanobacterial blooms, was consistently high (5.638 µg/L), exceeding 5-times the World Health Organization drinking water limit (1 µg/L); however, it was much lower (0.83 µg/L) at depth (−6 m). Analysis of environmental factor relationships showed that the most influential factors on abundance of *Microcystis aeruginosa* and *Dolichospermum flos-aquae* and variability of microcystin-LR concentrations were total phosphorus, dissolved inorganic nitrogen, iron, temperature and pH. Finally, the study clearly demonstrated the need for regular monitoring of cyanobacteria and cyanotoxins in the reservoir.

Highlights

- Phosphate mines contribute to the eutrophication of Foum-Gleita reservoir (Mauritania).
- Cyanobacteria phylum with higher abundance of Microcystis aeruginosa and Dolichospermum flos-aquae mainly dominated the phytoplankton community during the warm season.

Extended author information available on the last page of the article

Published online: 15 March 2022

- Abundance of Microcystis aeruginosa and Dolichospermum flos-aquae tended to be higher when the DIN/TP ration <10.
- First detection of microcystin-LR in a freshwater ecosystem in Mauritania.

Keywords *Microcystis aeruginosa* · *Dolichospermum flos-aquae* · Microcystin-LR · Foum-Gleita Reservoir · Mauritania

1 Introduction

Freshwater ecosystems are often subject to eutrophication, mainly due to excessive discharges of phosphorus (P) and nitrogen (N) from origins of anthropogenic and/or natural, i.e., soil erosion (Huisman et al. 2018; Wurtsbaugh et al. 2019). This increasing eutrophication leads to excessive blooms of harmful cyanobacteria (cyanoHAB), whose extent and frequency are increasing worldwide (Vilán et al. 2013; Preece et al. 2017; Paerl 2018; Celikkol et al. 2021; Coffer et al. 2021; Tanvir et al. 2021). Recent studies have reported that nutrient loads and high temperatures promote the expansion of cyanoHAB in freshwater ecosystems (Benayache et al. 2019; Griffith and Gobler 2019; Jankowiak et al. 2019; Wurtsbaugh et al. 2019; Namsaraev et al. 2020; Coffer et al. 2021; Rashidi et al. 2021). One of the consequences of cyanobacteria proliferation is the production of cyanotoxins, which can contribute to degrading water quality and increasing risks to human and animal health (Niamien-Ebrottie et al. 2015; Svircev et al. 2017; Schinck et al. 2020; Heil and Muni-Morgan 2021). Among these cyanotoxins, microcystins (MC) are most commonly found in cyanobacterial blooms around the world and are one of the most dangerous pollutants in freshwater in terms of concentration and risk to human health (Corbel et al. 2014; Chiaa et al. 2018; Bouaïcha et al. 2019; Overlinge et al. 2021).

On the African continent, the environmental conditions are very conducive to continued proliferation of potentially toxic cyanobacteria (Ndlela et al. 2016). For example, in the North African basin, in Egypt (Mohamed 2016), in Morocco (Oudra et al. 2001; Ouhsassi et al. 2021), in Algeria (Nasri et al. 2007; Nasri and Bouaïcha 2017) and in Tunisia (El Herry et al. 2008; Fathalli et al. 2015) blooms of cyanobacteria have been observed in several surface freshwaters during the warmer months, particularly in summer and early fall.

Some arid West African countries, such as Mauritania, have made significant efforts to use surface water resources through the construction of dams. However, wastewater discharges, industrial pollutants, soils erosion and deposition of effluents rich in nitrates and phosphorus in these reservoirs potentiate the development of certain toxic cyanobacterial species (Nyenje et al. 2010; Ndlela et al. 2016). In Mauritania, the problem of cyanobacteria and their toxins is posed in a general way for all water bodies. The lack of knowledge and information on this subject remains significant. At the national level, the availability and quality of water resources are among the factors hindering local development. Therefore, the Foum-Gleita reservoir studied in this work has been subject to long several anthropogenic effects including: demographic pressure due to the arrival of nomads who are victims of the increasing drought in the Sahel, discharge of urban wastewater, intensive livestock farming, irrigation and runoff from agricultural practices, and sedimentation of eroded earth and phosphate particles derived from phosphate rocks present in the watershed of this res-

ervoir, which should further contribute to eutrophication of the water and, subsequently, to the proliferation of cyanobacteria throughout the year in this reservoir.

The aim of this study was to assess, for the first time, the seasonal occurrence of cyanobacteria and their microcystins in the water column of the Foum-Gleita reservoir (Mauritania) as well as the environmental factors likely to control their development. To achieve the objectives of this study, standard methods were used, such as inverted Microscopy for the phytoplankton analysis, Spectrophotometry for the nutrients analysis, Fluorimetry for the chlorophyll analysis, High Performance Liquid Chromatography-tandem Mass Spectrometry (HPLC/MS) for the cyanotoxins analysis, and Multiple Linear Regression for analysis of the relationships between the limnological factors of studied reservoir. The results obtained from this study contribute to development of the water monitoring and management plans to avoid major damage to the environment and human health caused by cyanobacterial blooms and cyanotoxins, and contribute to better understanding and assessing the potential impacts of eutrophication on the quality and functioning of affected freshwater ecosystems on which many human populations depend.

2 Materials and Methods

2.1 Studied Area and Sampling

Foum-Gleita reservoir is located in the southeast of Mauritania about 95 km east of Kaédi, (capital of Gorgol region). It is a vault type, implemented in 1984. Its water body is 160 km^2 (normal surface) and 50 km^2 (minimal surface) and has a storage capacity of 1×10^9 m^3 and a maximum depth of 9 m. Catchment area of Foum-Gleita reservoir covers 21,000 km^2 with two principal rivers, *Black Gorgol* and *White Gorgol*. The Foum-Gleita reservoir is located at the confluence of the Black Gorgol River, upstream of its confluence with the White Gorgol River and the Senegal River. Black Gorgol River pours into the Foum-Gleita reservoir and White Gorgol River towards the confluence point. Filling dynamics of the Foum-Gleita reservoir essentially depend on the intermittent flows of the Black Gorgol River. These flows only take place during the rainy season from July to September. About 49% of the water flow from this reservoir is used for drinking water of human and livestock farming, and 36% for irrigation (downstream).

Watershed of the Foum-Gleita reservoir is subject to a typically Sahelian climate, characterized by a short rainy season (July-September) and a long dry season of 9 to 10 months (October-June) divided into two periods: a cool period (October- February) and a warm period (March-June). In addition, it is characterized by average precipitation about 255 mm/year and an average annual temperature of 31 °C (19 minimum and 44 °C maximum). This watershed is both an agricultural and mining (phosphate) region. The main types of land use within the catchment area are phosphate mines (94,500 ha), agriculture (11,200 ha downstream and 9,000 ha upstream), intensive livestock farming (10,000 camels, 15,000 sheep and goats, and 25,000 cattle), and 3,300 domestic animals (donkey and horses).

During this study, the waters of Foum-Gleita reservoir were monthly monitored from September 2017 to August 2018. During this regular monitoring period, the sampling was carried out on a deep site located at the water intake tower of the reservoir (Fig. 1). This site was chosen based on its accessibility and its exposure to winds and anthropogenic pollution-

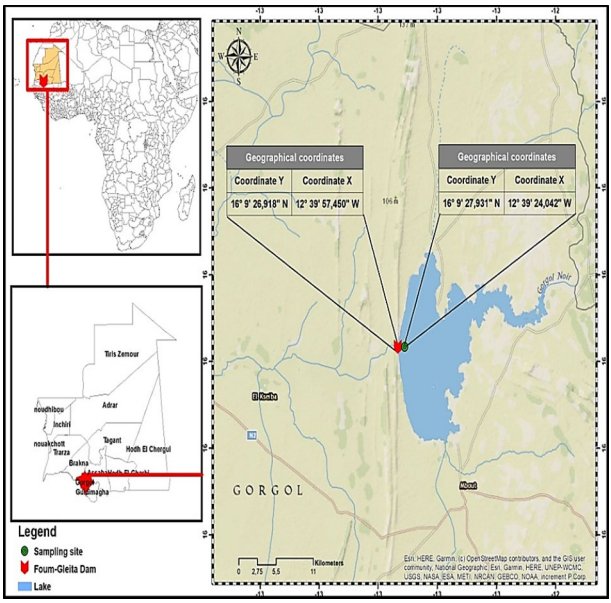

Fig. 1 Localization map of Foum-Gleita reservoir and the sampling site

This sampling site is at the dyke of Foum-Gleita reservoir, where the phytoplankton scums formed in other reservoir areas and the nutrient-rich sediments are generally concentrated under the combined effect of rain torrents and winds. At this site, the samples were taken at three depth levels (Surface, − 3 m and − 6 m). Two liters of water from each depth (surface, − 3 and − 6 m) were regularly taken from this site, from which four samples were prepared for further analysis of chlorophyll-a, chemical parameters (orthophosphates, total phosphorus, ammonium, nitrite, nitrate and iron), phytoplankton enumeration, and detection of particulate and dissolved microcystins (MCs). Water samples intended for the analysis of chemical parameters were immediately stored in a portable refrigerator (approximately 4 °C), and then they were brought back to the laboratory and stored at 4 °C, Those intended for the identification and enumeration of phytoplankton were stored with Lugol's iodine solution (5% v/v) for further analysis.

2.2 Physicochemical Characterization and Trophic State Index Determination

Transparency, temperature, pH and salinity of raw water were measured *in situ*. Transparency was estimated using a Secchi disk. Temperature, pH and salinity were measured by a multi-parameter C4E Calypso. Dissolved oxygen was determined by Winkler's chemical method.

To determine the different nutrient concentrations (orthophosphate or dissolved phosphorus, total phosphorus, ammonium, nitrite, nitrate, and iron) the nutrient samples that were taken at three depths (surface, − 3 and − 6 m) were analyzed on a DR2800 spectrophotometer (Hach) according to the methods of Rodier (1996). Dissolved phosphorus (DIP) and total phosphorus (TP) concentrations (mg/L) were determined by ascorbic acid method and persulfate digestion method, respectively (Rodier 1996). Nitrite ($N\text{-}NO_2^-$), nitrate ($N\text{-}NO_3^-$) and ammonium ($N\text{-}NH_4^+$) concentrations (mg/L) were determined with Zam-

belli, Sulfosalicylic acid and Nessler reaction methods, respectively (Rodier 1996). Then the total dissolved inorganic nitrogen (DIN) was calculated as the sum of $N\text{-}NO_2^-$, $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$. Iron (Fe) concentrations were measured by phenentroline 1-10-dimethyl-2.6 addition method (Bergounhou et al. 1996).

To perform chlorophyll-a (Chl-a) analysis, GF/C glass microfiber filters 0.45 µm (Whatman, diameter: 25 mm) were used to filter raw water samples (250 mL). These filters were then extracted in 5 mL of methanol in cold and darkness. Chlorophyll-a (Chl-a) were then determined by the fluorimetric method using a Jenway 6200 fluorimeter according to the method of Neuveux (1974).

Trophic State Index of Foum-Gleita reservoir was determined by the method of Carlson (1977). Since the raw waters of this reservoir have always been cloudy by the very high clay content, the Secchi disk depth has been omitted in calculation of the TSI indices of this reservoir. Therefore, the values of this index were calculated using only the Chl-a (µg/L) and TP (µg/L) concentrations according to method described in Ghashghaie et al. (2018). The overall TSI (varies between 1 and 100) is therefore the average of TSI (Chl-a) and TSI (TP). The classification table of Ebrahimpour et al. (2012) was used to categorize the trophic state of this reservoir studied.

2.3 Phytoplankton Analysis and Microcystins Detection

Phytoplankton was analyzed by inverted microscopy according to the method of Utermöhl (1958). To identify and enumerate the phytoplankton, 10 mL aliquots of each stored sample were placed for 24 h on a gridded chamber before being visually scanned by an inverted microscope (Leitz, Fluovert) at 20x and 40x. Phytoplankton groups were identified according to the morphological characteristics described in Bourrelly (1972, 1981, 1985), Reynaud and Laloë (1985) and Olenina et al. (2006), and then quantified in cells per liter with a minimum of 100 units counted per sample. Minor cyanobacterial taxa have been identified only at the genus level, while the two dominant taxa have been identified at the species level, using universal keys of taxonomy (Geitler 1932; Komárek and Anagnostides 1999, 2005; Wacklin et al. 2009). Biovolumes expressed in mm^3/L were then estimated for *Dolichospermum* sp., *Microcytis* sp., *Planktothrix* sp. and *Oscillatoria* sp. species. Briefly, the dimension and the mean number of cells from 50 *Dolichospermum* filaments and 50 *Microcystis* colonies per sample were estimated. For *Planktothrix* and *Oscillatoria*, the average width and length of 50 filaments per sample were also estimated. Biovolume of each taxon was calculated assuming that each *Dolichospermum* and *Microcystis* cell is a sphere and each *Oscillatoria* and *Planktothrix* filament is a cylinder. Number of cells per liter for *Microcystis* and *Dolichospermum* species and filaments per liter for *Planktothrix* and *Oscillatoria* species were then multiplied by the average biovolume of cells and filaments (Hillebrand et al. 1999).

Extraction of microcystins (MC) was performed by filtration of raw water samples (500 mL) through GF/C glass according to the method described in Bouhaddada et al. (2016). Samples pre-concentration was carried by solid phase extraction. For each sample, a filter and a filtrate were recovered. The filtrates were then pre-concentrated on solid phase on a C18 cartridge (type: SPD Bakerbond 3 mL-200 mg from J.T. Baker). The filters of each sample, on which solid particles and microorganisms were retained, were extracted with 10 mL of methanol (75%), and then placed in an ultrasound bath for 15 min in order to lyse

the cells and release the toxins. The extract from each filter was then refiltered on a glass microfiber filters (GF/C Whatman; diameter: 25 mm; porosity: 0.45 µm) and evaporated to dryness in a Rotavapor at 40 °C. The dry residue was taken up in 300 µL of methanol (50%). Then the analysis and the quantification of microcystins fractions were carried by high performance liquid chromatography-tandem mass spectrometry (HPLC/MS) using a Spectraphysics 8000 HPLC system and a Bruker ESI mass spectrometer as described in Bouhaddada et al. (2016) with small modifications. Briefly: ESI- electrospray ionization, analyzer/detector: 1 Hz, cone voltage: 90 V, mass/load ratio: 50 to 1500 m/z, DataAnalysis 3.4 and HyStar 3.2 software. A Chrompack-Netherlands C18 Microsphere reverse phase column (150×4.6 mm, 5 µm) maintained at 30 °C was used for the chromatographic separation. Mobile phase consisted of two solvents A (MilliQ water + 0.1% TFA v/v) and B (Acetonitrile + 0.1% TFA v/v) with a flow rate of 1 mL/min (injected volume: 20 µL; detection wavelength: 238 nm). Three standard solutions containing MC-LR, MC-RR and MC-YR (Biochemicals Alexis) were injected to identify the peak corresponding to a given microcystin (MC) by comparing the retention times and the mass/charge ratios of the three standard solutions of microcystin with those of the different variants present in the water samples. Finally, full scan spectra were obtained (Mass range: 100–1200 Da). Analyses in MS-MS were carried by CID (Collision Induced Dissociation) using argon at 3.4 mbar in a collision cell (collision energy: 50 and 70 eV). Ion currents ($[M+H]^+$ and $[M+H]^+ + [M+2\ H]^{2+}$) were used to assess the microcystin relative concentrations.

2.4 Relationship Between Environmental Factors

Statistical analyzes were performed using SPSS software. To compare all environmental variables (limnological and biological) resulting from the sample analysis taken at three depths in Foum-Gleita reservoir: Temperature, pH, Salinity, Dissolved Oxygen, Orthophosphate (Dissolved Phosphorus), Total Phosphorus, Ammonium, Nitrate, Nitrite, Total Dissolved Inorganic Nitrogen, DIN/TP ratio, Iron, Chlorophyll-a, Cyanobacterial biovolumes, and Microcystin-LR concentrations, a one-way ANOVA followed by a post-hoc Tukey test was realized. To identify the relationship between these variables, a Pearson Correlation Matrix was then performed. The strength of the correlations between these variables was evaluated according to absolute value of r following the guide suggested by Evans (1996). Relationships between the independent variables (pH, Temperature, Dissolved Inorganic Nitrogen, Total Phosphorus and Iron) and the dependent variables (Cyanobacterial biovolumes, and Microcystin-LR concentrations) were explored by a Stepwise Multiple Linear Regression with forward selection method in order to detect the exact contribution of each independent variable by incrementally adding and/or removing predictor variables, in the models, in order to find the variables subset R^2 resulting in the best performing model with the highest value of *ajusted* R^2. The variable values (Dissolved Inorganic Nitrogen, Total Phosphorus, Iron, Cyanobacterial biovolumes, and Microcystin-LR concentrations) were transformed into decimal logarithm or $\log_{10}$ except for the water pH and temperature.

3 Results

3.1 Physicochemical Characterization and Trophic State

Spatiotemporal variations of physicochemical parameters in the waters site sampled at three depths (surface, −3, and −6 m) in the Foum-Gleita reservoir during the study period are shown in Table 1. Temperature, pH, dissolved oxygen and salinity varied on a temporal basis within depths and spatially between depths. Average water temperatures of sampling site show dissimilar variations ranging from 27.9 °C in surface to 24.2 °C at depth (−6 m), with the maximum value observed in the warm-dry season, in May 2018 precisely (Fig. 2). At all sampling depths and throughout the study period, the reservoir water was slightly

Table 1 Physicochemical parameters at different depths of sampling site in Foum-Gleita reservoir from September 2017 to August 2018

Parameters	Surface		−3 m		−6 m		Difference between depths (ANOVA)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	F	*p-Values*
T (°C)	27.9 ± 3.5^{a}	20.6–30.7	24.9 ± 3.4^{b}	18.7–29.3	$24.2 \pm 4.2^{b,c}$	16.2–29.1	$F_{2, 33} = 3.462$	0.043*
pH	7.7 ± 0.26^{a}	7.2–8.1	8.39 ± 0.47^{b}	7.7–9.4	$8.7 \pm 0.64^{b,c}$	7.9–9.8	$F_{2, 33} = 16.304$	0.000*
Salinity (PSU)	0.27 ± 0.07^{a}	0.20–0.47	0.33 ± 0.06^{b}	0.26–0.47	$0.35 \pm 0.05^{b,c}$	0.27–0.47	$F_{2, 33} = 5.220$	0.011*
DO (mg/L)	8.85 ± 2.53^{a}	5.1–14.3	5.27 ± 2.11^{b}	2.90–8.80	$4.24 \pm 1.51^{b,c}$	2.5–6.7	$F_{2, 33} = 16.047$	0.000*
Secchi (m)	0.31 ± 0.11	0.17–0.49	–	–	–	–	–	–
$P–PO_4^{-3}$ (mg/L)	0.30 ± 0.12	0.15–0.49	0.33 ± 0.11	0.21–0.51	0.37 ± 0.12	0.22–0.54	$F_{2, 33} = 0.887$	0.421
TP (mg/L)	0.35 ± 0.12	0.22–0.57	0.38 ± 0.12	0.25–0.58	0.43 ± 0.12	0.25–0.59	$F_{2, 33} = 1.273$	0.294
$N\text{-}NO_3^-$ (mg/L)	3.61 ± 1.29	2.03–5.15	4.12 ± 2.69	1.08–7.11	4.66 ± 4.66	1.38–7.76	$F_{2, 33} = 0.881$	0.070
$N\text{-}NO_2^-$ (mg/L)	0.06 ± 0.01^{a}	0.04–0.09	0.09 ± 0.03^{b}	0.05–0.17	0.13 ± 0.05^{c}	0.04–0.22	$F_{2, 33} = 10.778$	0.000*
$N\text{-}NH_4^+$ (mg/L)	0.19 ± 0.05^{a}	0.11–0.28	0.24 ± 0.04^{b}	0.17–0.31	$0.27 \pm 0.05^{b,c}$	0.19–0.39	$F_{2, 33} = 8.424$	0.001*
DIN (mg/L)	3.86 ± 1.25	2.29–5.33	4.46 ± 2.67	1.44–7.42	5.07 ± 2.82	1.81–8.22	$F_{2, 33} = 3.246$	0.052
DIN/TP	13.27 ± 7.41	4.33–24.09	14.60 ± 10.49	2.48–28.30	14.14 ± 9.81	3.06–28.29	$F_{2, 33} = 0.933$	0.403
Fe (mg/L)	0.15 ± 0.05^{a}	0.09–0.27	0.18 ± 0.03^{b}	0.15–0.28	$0.21 \pm 0.03^{b,c}$	0.16–0.28	$F_{2, 33} = 4.690$	0.016*
Chl-a (µg/L)	9.19 ± 5.35^{a}	4.13–19.31	4.72 ± 3.45^{b}	1.51–14.13	$3.24 \pm 1.48^{b,c}$	1.12–6.05	$F_{2, 33} = 8.078$	0.001*

SD = standard deviation; T = water temperature; pH = water hydrogen potential; DO = dissolved oxygen; Secchi = Secchi disk depth; $N\text{-}NO_3^-$ = nitrate; $N\text{-}NO_2^-$ = nitrite; $N\text{-}NH_4^+$ = ammonium; DIN = dissolved inorganic nitrogen; $P\text{-}PO_4^{-3}$ (or DIP) = dissolved phosphorus; TP = total phosphorus; DIN/TP = DIN/TP mass ratio; Fe = iron; Chl-a = chlorophyll-a; Letters (a, b, and c) = values are significantly different ($p < 0.05$); * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

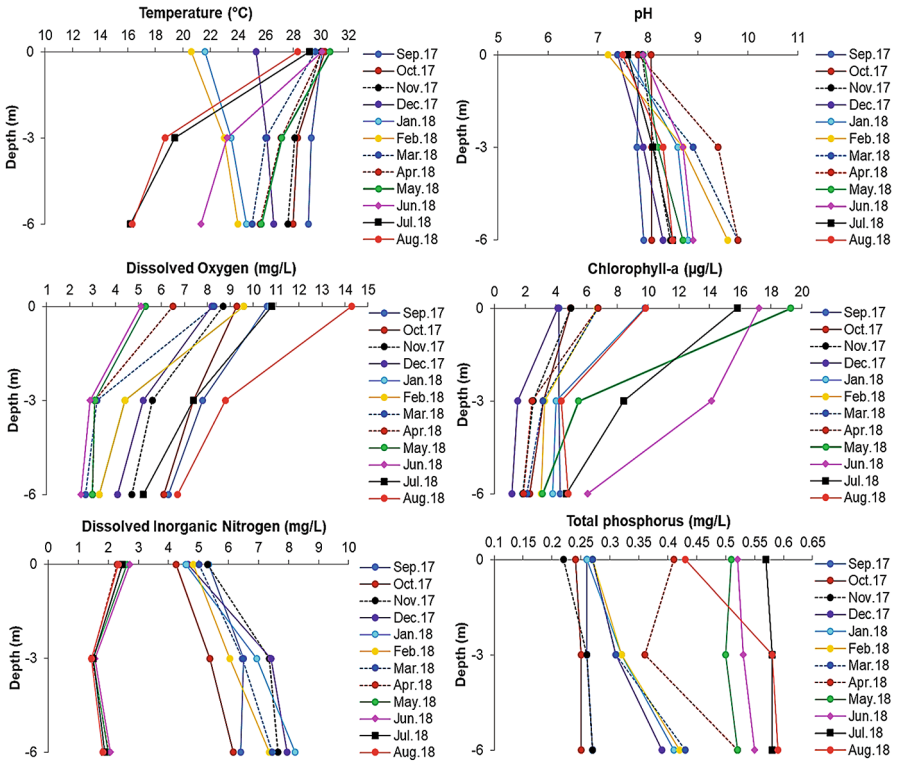

Fig. 2 Vertical profiles of water temperature, pH, dissolved oxygen (DO), chlorophyll-a, dissolved inorganic nitrogen (DIP) and total phosphorus (TP) in Foum-Gleita reservoir from September 2017 to August 2018

alkaline with an average pH ranging from 7.7 in surface to 8.7 at depth (−6 m). However, the water sampling sites of this reservoir are relatively ventilated in surface and ill ventilated in bottom with mean dissolved oxygen concentrations ranging from 8.85 mg/L at surface to 4.24 mg/L at depth (−6 m). In addition, the nutrient concentrations varied on a temporal basis within depths. The site sampling is not significantly different in mean of dissolved phosphorus, total phosphorus, nitrate, total dissolved inorganic nitrogen concentrations and DIN/TP ratio; however, significant differences have been observed only between mean nitrite and ammonium concentrations (ANOVA, Table 1). Mean total phosphorus (TP) concentrations were higher at depth (−6 m) than at surface throughout the sampling period (0.43 to 0.35 mg/L, respectively). Meanwhile, average dissolved phosphorus (DIP) concentrations ranged from 0.30 to 0.37 mg/L at surface, 0.21 to 0.51 mg/L at depth of −3 m and 0.22 to 0.54 mg/L at depth of −6 m. Mean nitrate (NO_3-N) and DIN concentrations were higher at depth (−6 m) ranging from 1.38 to 7.76 and 1.81 to 8.22 mg/L, respectively. In contrast, mean DIN/TP ratio in surface was lower than the ratios at the two other depths. DIN/TP ratio ranged from 4.33 to 24.09, 2.48 to 28.31 and 3.07 to 28.30 at surface, depth of −3 m and depth of −6 m, respectively (Table 1). Mean iron concentrations were dissimilar at all depths ranging from 0.15 to 0.21 mg/L at surface and bottom, respectively. Mean chlorophyll-a concentrations in the water samples ranged from 3.24 to 9.19 µg/L at depth

(−6 m) and surface, respectively, with a maximum value of 19.31 µg/L detected at the water surface during the warm-dry season, in May 2018 precisely (Fig. 2), which was significantly different only from the values of depths −3 and −6 m ($p=0.001$ and $p=0.018$, respectively).

Considering the monthly values of Trophic State Indices (TSI) calculated during the monitoring period of Foum-Gleita reservoir, the reservoir studied has two TSI-Carlson values ranging from 66 to 70 in cool-dry season and 70 to 80 in warm-dry season and can be classified as eutrophic in cool-dry season to hypertrophic in warm-dry season (Fig. 3).

3.2 Cyanobacteria Dynamics and Microcystin-LR Variability

Phytoplankton abundance in the three depths of sampling site (surface, −3, and −6 m) varied with season with high values in the warm-dry season (April-November) and low values in the cool-dry season (December-March). Phytoplankton was composed of six phyla including Euglenozoa, Miozoa, Cryptophyta, Bacillariophyta, Cyanobacteria, and Chlorophyta. Cyanobacteria was the second phylum, accounting for 25 to 33% of the community, with the highest abundances occurring at depth (−3 m) during the warm-dry season. Cyanobacteria phylum in this reservoir were presented by five solitary filamentous genera (*Spirulina*, *Lyngbya*, *Planktothrix, Oscillatoria*, and *Dolichospermum*) as well as three colony-forming genera (*Gloeocapsa, Chroococus* and *Microcystis*).

During the study period, the cyanobacteria phylum was totally dominated by *Dolichospermum flos-aquae* and *Microcystis aeruginosa*, which represent 49 and 40%, respectively. Indeed, these two species showed a constant presence at all depths of the sampling site (Figs. 4 and 5). Also, the highest biovolumes of these two dominant species, i.e., *D. flos-aquae* and *M. aeruginosa*, were observed in surface water of this reservoir during the warm-rainy season months with two well pronounced peaks in September 2017 (8.73 and 4.79 mm^3/L, respectively) and August 2018 (7.41 and 4.65 mm^3/L, respectively). However, both *Oscillatoria* sp. and *Planktothrix* sp. were less abundant and showed an irregular monthly presence. *Oscillatoria* sp. only appeared in the sampling site at the end of the rainy season to the first of the dry season (September, October and November) with a biovolume peak of 0.03 mm^3/L noted at the surface in September 2017 (0.031 mm^3/L). Also, *Planktothrix* sp.

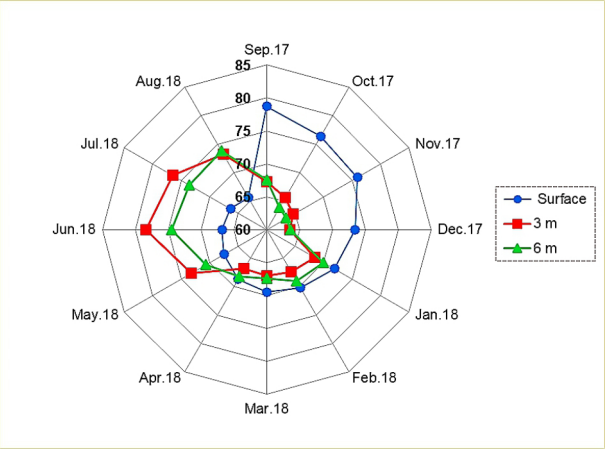

Fig. 3 Trophic state index calculated at different depths in Foum-Gleita reservoir from September 2017 to August 2018

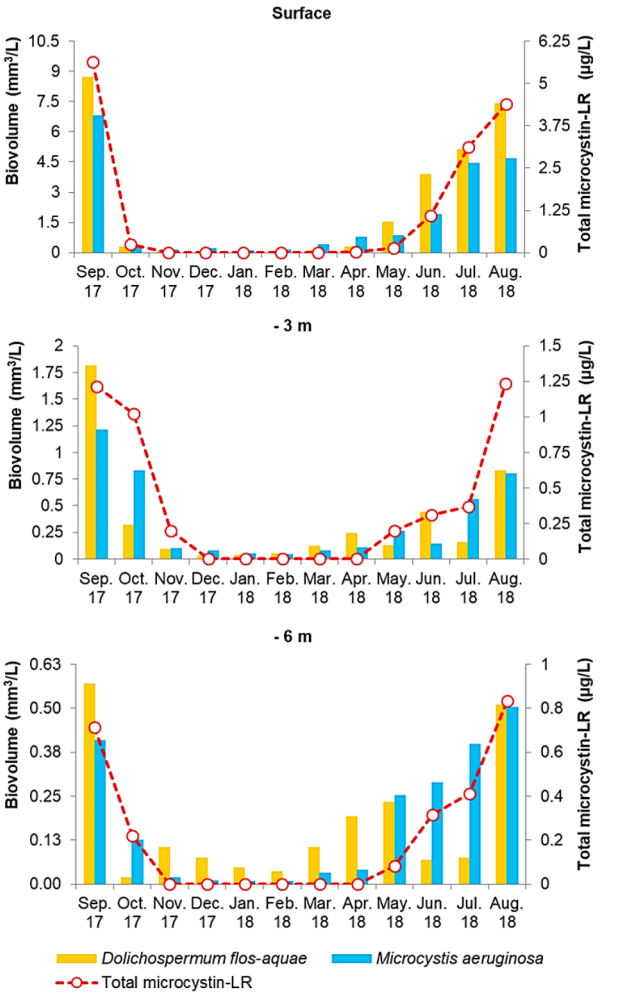

Fig. 4 Dynamic of *Microcystis aeruginosa* and *Dolichospermum flos-aquae*, and variability of total microcystin-LR concentration at different depths in Foum-Gleita reservoir from September 2017 to August 2018

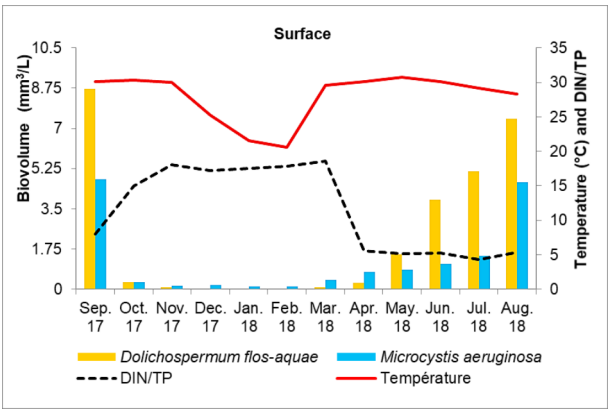

Fig. 5 Abundance of *Microcystis aeruginosa* and *Dolichospermum flos-aquae* as a function of DIN/TP ratio and Temperature (°C) at surface water in Foum-Gleita reservoir from September 2017 to August 2018

was observed at all depths with low irregular biovolumes during the warm- dry season with a peak of 0.001 mm^3/L registered at the surface and the depth of −3 m in July 2018. This is the reason why these last three species were neglected in data analysis. On the other hand, these results suggest that the biovolumes of cyanobacteria are higher in surface water than in deep water of the studied reservoir.

Species observed in Foum-Gleita reservoir during the study period, *Microcystis aeruginosa, Dolichospermum flos-aquae*, *Oscillatoria* sp., and *Planktothrix* sp., are known in the literature as potentially toxic and can biosynthesize microcystins (MCs). Microcystin identification and quantification in the water sampling site showed only one variant: microcystin-LR (Fig. 6). Measurable microcystin-LR (MC-LR) levels were detected for all investigated months with total concentrations (extracellular + intracellular) ranging from 0.001 to 5.638 µg/L. As indicated in Fig. 4, MC-LR concentrations varied on a temporal basis at various depths and spatially between depths. Total MC-LR concentrations ranged from 0.001 to 5.638, from 0.001 to 1.230 and from 0.001 to 0.830 µg/L at surface and depth of −3 and −6 m, respectively. Dissolved microcystin-LR (extracellular) concentrations were always lower than the particulate (intracellular) concentrations, with proportions in the water samples at all depths never exceeding 0.5% of total microcystin-LR concentrations. Total microcystin-LR concentrations followed the same pattern as for *Dolichospermum* sp. and *Microcystis* sp. abundance, reaching a maximum concentration of 5.638 µg/L at surface water, where the biovolumes of these two cyanobacterial species were highest in late summer-early autumn (Fig. 4). However, the lowest levels of microcystin-LR were observed during cool period to first warm-dry season (November-March) when cyanobacterial abundance was lowest (Fig. 4). On the other hand, these results suggest that the concentrations of microcystin-LR are higher in surface water than in deep water of the studied reservoir.

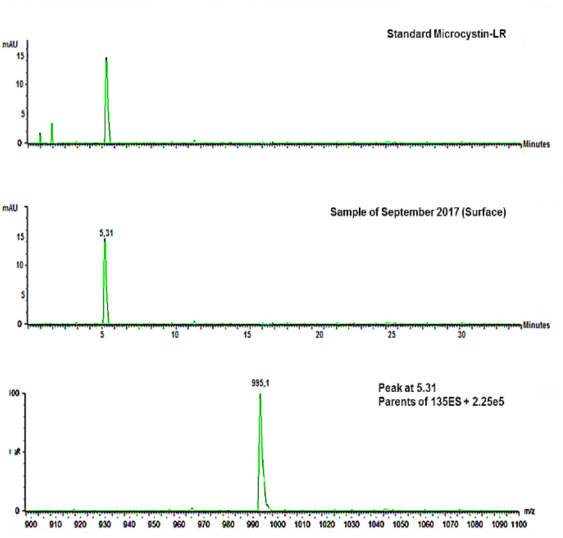

Fig. 6 LC-MS/MS precursor ion spectrum of the peak at 5.31 min exhibits parent ion [M+H]+ of MC-LR [m/z: 995.1] (lower) and LC-UV chromatograms of cyanobacterial bloom sample extract harvested in September 2017 at surface water of sampling site (middle) and microcystin-LR standard (upper)

3.3 Relationship Between Environmental Factors

According the Pearson's correlation matrix (Table 2), a strongly positive and significant correlation was observed between *Microcystis aeruginosa* biovolume, temperature ($p<0.01$) and concentrations of dissolved inorganic nitrogen ($p<0.01$), and a moderately significantly negative correlation was observed with water pH ($p<0.05$) and concentrations of total phosphorus ($p<0.05$). In contrast, a strongly significantly positive correlation was observed with DIN/TP mass ratio ($p<0.01$). Controversily, *Dolichospermum flos-aquae* biovolume was very strongly positively correlated to concentrations of total phosphorus ($p<0.001$), moderately negatively correlated to concentrations of DIN ($p<0.05$) and DIN/TP mass ratio ($p<0.05$), and not significantly correlated to water pH ($r=-0.1780$). Concentrations of iron were strongly positively correlated ($p<0.05$) to *M. aeruginosa* biovolume, and moderately positively correlated ($p<0.05$) to *D. fos-aquae* biovolume. Total concentrations of microcystin-LR were moderately positively correlated to water temperature ($p<0.05$) and concentrations of iron ($p<0.05$), strongly positively correlated to concentrations of DIN ($p<0.01$) and DIN/TP mass ratio ($p<0.01$), and moderately negatively correlated to concentrations of total phosphorus ($p<0.05$). In addition, total concentrations of microcystin-LR were strongly positively correlated to *M. aeruginosa* biovolume ($p<0.001$), and not significantly correlated to *D. fos-aquae* biovolume ($r=-0.264$).

According the Multiple Linear Regression analysis (Table 3), the significant values obtained for adjusted R^2 (R^{2a}) were high ranging from 0.902 for *Microcystis aeruginosa* to 0.489 for *Dolichospermum fos-aquae*, and 0.909 for microcystin-LR. Concentrations of dissolved inorganic nitrogen, total phosphorus and iron, and water temperature explained 90% and 91% of variability of *M. aeruginosa* biovolume and microcystin-LR concentrations, respectively. However, water pH and concentrations of dissolved inorganic nitrogen, total phosphorus and iron explained 50% of variability of *D. fos-aquae* biovolume. Dissolved inorganic nitrogen (DIN) concentration explained 18.2% and 86.3% of the biovolumes variability of *D. flos*-aquae and *M. aeruginosa*, respectively. Addition of total phosphorus (TP) concentration caused a slight increase in *D. flos-aquae* biovolume (1.1%), but it caused a strong decrease in *M. aeruginosa* biovolume (−21.3%). Water temperature (T) explained slightly less (3.3%) and much more (23.3%) biovolume variances of D. *flos-aquae* and *M. aeruginosa*, respectively. Addition of pH resulted in a large increase in *D. flos-aquae* biovolume (27%) and had no effect on *M. aeruginosa* biovolume. Addition of iron resulted in a 6% and 2% increase in biovolumes of *D. flos-aquae* and *M. aeruginosa*, respectively. TP and DIN concentrations were the most negative (Beta=−12.628) and positive (Beta=+2.631) influencing factors for predicting *D. flos-aquae* biovolume, while the iron (Beta=+0.015) and pH (Beta=−0.878) showed the weakest effect. However, for *M. aeruginosa* biovolume, the most influential variables were the concentrations of TP (Beta=+4.722) followed by that of DIN (Beta=−1.942) and iron (Beta=−0.160), and water temperature *(Beta=−0.206)*. DIN concentration is considered to best explain the variability of microcystin-LR (MC-LR) concentration. Addition of TP and water temperature increased the variability of this toxin (8% and 5.3%, respectively). However, MC-LR concentration decreased slightly with the addition of pH (0.2%), and increased after the substitution of pH by iron (5.5%). Therefore, the most influential factors on MC-LR concentration were the concentrations of TP (Beta=−0.590) followed by those of DIN (Beta=+0.312) and iron (Beta=+0.019) and water temperature (Beta=+0.007).

4 Discussion

4.1 Limnological Factors and Dynamic of Cyanobacterial Blooms

The physicochemical results obtained show that the studied reservoir was characterized by an advanced eutrophication. Water temperature and the nitrogen (N) and phosphorus (P) concentrations were always high in the Foum-Gleita reservoir throughout the study period. This striking limnological change was probably related to various factors such as increasing urbanization, agricultural activities, phosphate mines present in the watershed of this reservoir, absence of sewage treatment networks, and long sunshine (about 350 days) accompanied by the increase of water temperature, which probably contributed both to a greater supply of nutrients (N and P), and to the amplification of eutrophication phenomenon. Therefore, a continuous release of nutrients combined with a typical Sahelian climate, characterized by two distinct seasons, i.e., a short warmer rainy season (July-September) and a long dry season (October-June), offers a considerable opportunity for development of cyanobacteria in this reservoir. These results are consistent with work that reports that the region with proportionally the greatest blooms of cyanobacteria in United States was a semi-arid landscape subject to severe droughts, and when water scarcity in this region was associated with high nutrient inputs, the likelihood of cyanobacterial blooms increases (Marion et al. 2017). Similarly, Fernandez et al. (2012) reported that cyanobacterial blooms were recurrent during summer and early fall since 1982 in the hypertrophic reservoir of Paso de las Piedras (Argentina). Additionally, Ndela et al. (2016) reported that water-scarce regions of Africa, which are characterized by low rainfall, have higher reports of cyanobacterial blooms than regions with high rainfall.

The results relating to the dynamics of cyanobacteria are consistent with the studies that have shown that phytoplankton succession in tropical aquatic ecosystems is characterized by a distinct change between rainy and dry seasons such as: Chlorophyta/Cyanobacteria in Lake Tanganyika, Tanzania (Descy et al. 2005); Bacillariophyta/Cyanobacteria in Lake Guiers, Senegal (Bouvy et al. 2006; Tian et al. 2012); and in Lake Victoria, Kenya (Kling et al. 2001). In temperate regions such as North Africa, phytoplankton communities were generally dominated by Bacillariophyta phylum in winter and Chlorophyta phylum in spring-summer, succeeded by Cyanobacteria phylum in autumn (El Herry et al. 2008; Gellati et al. 2017; Hammou et al. 2018). In other regions such as Europe and America, studies carried out in 143 lakes have shown that the cyanobacteria biomass increases strongly with temperature in lakes with high rates of light absorption (Kosten et al. 2012). Other studies carried out on Lake Erie (border between Canada and the United States) reported that the cyanobacteria abundance increased considerably in response to an increase in nitrogen, with large increases combined with high N and P concentrations and water temperature (Jankowiak et al. 2019). A study carried out in south-central Chile suggests that eutrophication is the main factor in the proliferation of certain cyanobacteria genera such as *Aphanizomenon*, *Aphanocapsa*, *Aphanothece* and *Dolichospermum* independently of water temperature following the formation of these genera of blooms in freshwater ecosystems at low temperatures (10.8–15.6 °C) in autumn and winter (Almanza et al. 2019). The highest abundance of two dominant cyanobacterial species *Microcystis aeruginosa* and *Dolichospermum flos-aquae* was recorded when DIN/TP ratio was less than 10. Bogard et al. (2020) tested the evolution of phytoplankton during the addition of a nitrogen gradient (0 to 18 mg/L) in the hypertro-

Table 2 Correlations between environmental factors of Foum-Gleita reservoir

	T	pH	Salinity	DO	$N\text{-}NO_3^-$	$N\text{-}NO_2^-$	$N\text{-}NH_4^+$	DIN	$P\text{-}PO_4^{-3}$ (or DIP)	TP	DIN/TP	Fe	Chl-a	MC-LR
T	1													
pH	–0.356	1												
Salinity	–0.286	0.522	1											
DO	–0.311	0.179	0.466	1										
$N\text{-}NO_3^-$	0.486	–0.415	–0.104	–0.208	1									
$N\text{-}NO_2^-$	0.537	–0.594*	–0.257	–0.330	0.892***	1								
$N\text{-}NH_4^+$	0.522	–0.439	–0.198	–0.282	0.991***	0.905***	1							
DIN	0.489	–0.420	–0.111	–0.213	1.000***	0.896***	0.992***	1						
$P\text{-}PO_4^{-3}$ (or DIP)	–0.384	0.123	0.110	0.172	0.910***	–0.745**	–0.910***	–0.909***	1					
TP	–0.313	0.034	–0.011	0.091	–0.884***	–0.688*	–0.871***	–0.882***	0.990***	1				
DIN/TP	0.512	–0.392	–0.155	–0.264	0.991***	0.915***	0.990***	0.992***	–0.923***	–0.892***	1			
Fe	0.43	–0.646*	–0.311	–0.385	0.350	0.50	0.383	0.355	–0.056	0.016	0.360	1		
Chl-a	0.648*	–0.512	–0.357	–0.347	0.902***	0.942***	0.936***	0.906***	–0.840**	–0.778**	0.935***	0.474	1	
MC-LR	0.530*	–0.645*	–0.423	–0.410	0.703*	0.935***	0.736**	0.710**	–0.573	–0.497*	0.757**	0.680*	0.887***	1
Dolichospermum	–0.067	–0.178	0.030	–0.009	–0.596*	–0.420	–0.599*	–0.594*	0.845**	0.861***	–0.546*	0.498*	–0.524	–0.264
Microcystis	0.757**	–0.605*	–0.363	–0.379	0.702*	0.936***	0.730**	0.709**	–0.570	–0.497*	0.753**	0.649*	0.868***	0.989***

T = water temperature; pH = water hydrogen potential; DO = dissolved oxygen; $N\text{-}NO_3^-$ = nitrate; $N\text{-}NO_2^-$ = nitrite; $N\text{-}NH_4^+$ = ammonium; DIN = dissolved inorganic nitrogen; $P\text{-}PO_4^{-3}$ (or DIP) = dissolved phosphorus; TP = total phosphorus; DIN/TP = DIN/TP mass ratio; Fe = iron; Chl-a = chlorophyll-a; *Dolichospermum* = *Dolichospermum flos-aquae*; *Microcystis* = *Microcystis aeruginosa*: MC-LR = microcystin-LR

Significance of correlation coefficients (Pearson's r) is indicated by *$0.01 < p < 0.05$, **$0.001 < p < 0.01$, and ***$p < 0.001$

phic and shallow Lake Wascana (Canada) containing high concentrations of total dissolved phosphorus (400 to 500 µg/L) and orthophosphate (280 to 400 µg/L), similar to the average values recorded in the Foum-Gleita reservoir. The results of this experiment showed that high concentrations of N (up to 18 mg/L/week) led to the predominance of chlorophyta over cyanobacteria and to the reduction of microcystin (MCs) concentrations. Conversely, low to moderate N concentrations (1 to 3 mg/L/week) favored the dominance of toxic cyanobacteria and increased MC content. Therefore, our study provides a new insight into the effects of moderate N concentrations (up to 8 mg/L) on phytoplankton community composition with a predominance of the cyanobacterial phylum in phosphorus (P) rich freshwater ecosystems. Within ecosystems with no-limiting nitrogen and phosphorus, such as Foum-Gleita reservoir, high water temperatures can promote the development of cyanobacteria by maximizing their growth rates compared to other phytoplankton groups (Carey et al. 2012; Paerl and Paul 2012). Although the growth trends of *D. flos-aquae* and *M. aeruginosa* in this reservoir were similar in the three depths, their biovolume was approximately 25 times higher at the surface. These results confirm the hypothesis that the atmospheric nitrogen-fixing genus *Dolichospermum* is generally competitive under low nitrogen concentrations, while the non-atmospheric nitrogen-fixing genus *Microcystis* require water richer in this nutrient (Li et al. 2012). Besides the absolute concentrations of nitrogen and phosphorus, their N/P mass ratio was also considered as a main parameter to determine the cyanobacteria growth (Li et al. 2018). In this study, strongly positive and significant correlations ($r=0.709$, $p<0.001$) were observed between the DIN/TP ratios and the biovolumes of *M. aeruginosa*, and moderately and significantly negative ($r=–0.594$, $p<0.01$) between the DIN/TP ratios and the biovolumes of *D. flos-aquae*. However, several studies have reported that TN or TP concentrations are better predictors of cyanobacterial dominance than the TN/TP ratio (Downing et al. 2001; Kosten et al. 2012). Since nitrogen and phosphorus concentrations in Foum-Gleita reservoir were extremely high throughout the year and were always above levels required for the phytoplankton growth (Reynolds 1997), they were not the only factors of co-dominance of *Microcystis aeruginosa* and *Dolichospermum flos-aquae* in waters of this reservoir. Therefore, other limnological factors such as pH, temperature and iron concentration may interact with dissolved inorganic nitrogen and total phosphorus to determine the relative dominance of these two species. These factors taken together could not only improve the growth of toxic cyanobacteria but also affect the cyanobacteria dynamics in the waters of this reservoir.

We observed in this study that only *M. aeruginosa* showed a positive and significant correlation ($r=0.757$, $p<0.001$) with water temperature. Therefore, the lack of significant correlation between water temperature and *D. flos-aquae* abundance can probably be due to the low temperature variation during the study period (20 to 30 °C). It has been suggested that global warming will not increase bloom frequencies only by promoting the cyanobacteria growth (Huisman et al. 2018), but also indirectly via an increase in phosphorus (P) release from sediments (Jeppesen et al. 2009). These factors taken together, such as high DIN and TP levels, uniform and high temperature conditions could not only enhance the growth of toxic cyanobacteria but also affect the cyanobacteria dynamics in the waters of this reservoir. Water pH of this reservoir (7.1 to 7.8) can also contribute to the proliferation of cyanobacteria where moderate and significantly negative correlations ($r=–0.605$, $p<0.01$) and weakly positive ($r=–0.178$, $p<0.05$) were observed between water pH and biovolume of *M. aeruginosa* and *D. flos-aquae*, respectively. Yang et al. (2018) reported that high

Table 3 Linear regression models explaining cyanobacterial abundance and microcystin-LR variability in water column of Foum-Gleita reservoir (Mauritania). Models explain *Microcystis aeruginosa* and *Dolichospermum flos-aquae* biovolume (log MycroBiov and log DolichoBiov) and microcystin-LR concentrations (log [MC-LR]) by dissolved inorganic nitrogen (log DIN), total phosphorus (log TP), water temperature (T), water pH (pH) and iron (log Fe)

	Beta values		
	log DolichoBiov (mm^3/L)	**log MycroBiov (mm^3/L)**	**log [MC-LR] (µg/L)**
Predictor variables			
log DIN (mg/L)	2.631*	–1.942**	0.312*
log TP (mg/L)	–12.628**	4.722*	–0.590*
T (°C)	–	–0.206*	0.007**
pH	–0.878*	–	–
log Fe (mg/L)	0.015*	–0.160***	0.019***
Constant	–3.027**	2.917***	–1.324**
Models recapitulative			
R^{2a}	0.489	0.902	0.909
Model Sig.	<0.0001	<0.0001	<0.0001
F-test	$F_{2, 33}=9.724$	$F_{2, 33}=72.470$	$F_{2, 33}=55.150$

Regression coefficients significance=* ($0.01<p<0.05$), ** ($0.001<p<0.01$), and *** ($p<0.001$). Number of observations=36

temperature and pH favor *Microcystis aeruginosa* to outcompete the green alga *Scenedesmus obliquus*. Our results also showed strongly positive ($r=0.649$, $p<0.01$) and moderately positive ($r=0.498$, $p<0.05$) correlations between iron concentration and biovolumes of *M aeruginosa* and *D. flos-aquae*, respectively. This is in agreement with the results of experimental studies involving the addition of iron (Fe) alone as well as in combination with N and/or P to water samples from Lake Erie (USA) and several oligotrophic lakes in Sweden, which showed that Fe enrichment alone did not lead to a significant increase in phytoplankton biomass, but the combined addition of N, P and Fe produced larger increases in biomass than the addition of N and P alone (Twiss et al. 2000; Vrede and Tranvik 2006; North et al. 2007). Morton and Lee (1974) reported that low Fe concentrations (0.1 to 1.0 mg/L) caused a shift of the dominant type of cultured algae from green algae to *M. aeruginosa*. Similarly, Wever et al. (2007) reported that the results of the study in Lake Tanganyika (East African Rift Valley) showed that the combined addition of iron, phosphorus and nitrogen to the lake water samples stimulates the growth of cyanobacteria but not that of chlorophytes or diatoms. The results of another study evaluating the competitive capacity of *Microcystis aeruginosa* against *Pseudanabaena* sp. in co-cultures with low (0.08 µM) and high (1 µM) $FeCl_3$ concentrations showed that the cell abundance of *M. aeruginosa* decreased by 18.4% under the high Fe concentration but increased by 23.7% below the low concentration, suggesting that *M. aeruginosa* had a competitive advantage over *Pseudanabaena* sp. in the presence of this nutrient (Wang et al. 2015).

4.2 Limnological Factors and Variability of Microcystin-LR

Although 279 congeners of microcystins (MCs) have been characterized (Bouaïcha et al. 2019), only one microcystin variant most common and most toxic, microcystin-LR (MC-LR), has been detected for the first time in freshwater ecosystems of Mauritania, in particular, in water of Foum-Gleita reservoir, with a peak (5.638 µg/L) exceeding 5 times the guideline value recommended by the World Health Organization for drinking water which is 1 µg/L (Taranu et al. 2019; WHO 1998). Indeed, microcystin-LR (MC-LR) has generally been detected as the main variant of cyanobacterial blooms, particularly in Africa and Europe, but it is frequently produced with one or more than 10 other minor variants (Ndlela et al. 2016; Puddick et al. 2016). However, numerous studies have demonstrated that the biosynthesis of microcystins (MCs) depends on the strain (Dittmann et al. 2015) and certain environmental factors such as the availability of nutrients (N and P), light intensity, iron limitation, water temperature and pH which are implicated in enhancing or suppressing the expression of microcystin synthetase genes (Puddick et al. 2016; Taranu et al. 2019). However, there are still gaps in the understanding how these environmental factors can modulate the relative abundance of MC variants and their concentrations in a cyanobacterial bloom. In this study, we observed that the MC-LR concentrations was positively correlated with the concentrations of DIN ($r=0.710$, $p<0.01$), Fe ($r=0.680$, $p<0.05$), and water temperature ($r=0.530$, $p<0.05$), and negatively correlated with TP concentration ($r=–0.497$, $p<0.05$). Upon progressive addition of these predictor variables in the multiple linear regression model, we observed that DIN concentration alone explained 72.3% of the variability of MC-LR concentrations, suggesting that increasing N resulted in an increase in MC-LR content. This is in agreement with other studies showing that MC content rich in N increases with increasing N availability (Van de Waal et al. 2009; Horst et al. 2014). However, a

recent cultivation experiment testing the effect of N on the biosynthesis of MCs by a non-heterocyst species (*Microcystis aeruginosa* PCC 7806) showed that a high concentration of N leads to a decrease in gene expression microcystin synthetase (Pan et al. 2019). In contrast, Sivonen (1990) reported that high N concentration in the culture medium increased both growth and intracellular concentrations of MCs of non-atmospheric nitrogen-fixing *Oscillatoria agardhii* 97 and CYA 128 strains. Conversely, Rapala et al. (1997) reported that P concentrations appear to be linked with toxin production from both heterocystic and non-heterocystic species. Therefore, there may be a threshold concentration of N, above which other factors such as P and Fe concentrations and water temperature may affect the toxicity of these species.

Furthermore, this study showed a strongly positive and significant correlation between the concentrations of microcystin-LR (MC-LR) and the biovolumes of *M. aeruginosa* ($r=0.989$, $p<0.001$). This strong relationship suggests that the presence of this toxin in the waters of Foum-Gleita reservoir depends on the abundance of this species. However, to confirm that *M. aeruginosa* was the only species responsible for the production of MC-LR, it would be necessary to isolate at least the majority of the species, then to search for the marker linked to the biosynthesis of cyanotoxins, (gene of microcystin synthetase A: mcyA) in each cyanobacterial isolate via PCR analysis.

5 Conclusions

First conclusion of this study is that Foum-Gleita reservoir is a hypertrophic ecosystem, rich in phosphorus and nitrogen, and subjected to a Sahelian climate. During the monitoring period, no sampling depth was spared by toxic cyanobacteria since all samples revealed presence of these microorganisms with biovolumes and a specific composition varying from one depth to another. Probably, this situation is linked to increasing urbanization, agricultural activities, phosphate mines present in the watershed of this reservoir, and increase in water temperature. Results obtained during this work show that a potential risk to public health linked to cyanotoxins is present in Foum-Gleita reservoir, and probably, in other water bodies of this country. Massive presence of *Microcystis aeruginosa* and *Dolichospermum flos-aquae* and microcystins-LR at high concentrations (5.638 µg/L) in raw water samples from this reservoir clearly demonstrates the need for regular monitoring of cyanobacteria and cyanotoxins in the waters of this reservoir. In addition, this study provides a new insight into the effects of moderate N concentrations (up to 8 mg/L) on phytoplankton community composition with a predominance of the cyanobacterial phylum in phosphorus-rich freshwater ecosystems (P).

Acknowledgements Ahmed S. Sadegh thanks the organizers of CEMEPE 2021 and SECOTOX Conference (20–24 July 2021, Thessaloniki, Greece) where part of this research was initially presented. The support of the European Program for Territorial Cooperation PCT-MAC 2014–2020 through the REBECA-CCT project (MAC/1.1.B/269) is acknowledged.

Authors' Contributions A.S. Sadegh designed, planned and carried out the experiment, the data analysis, the results interpretation, writing-original draft, review and editing. Z. Sidoumou was involved in planning and supervised the project. M. Dia co-supervised the project. J.L.G. Pinchetti contributed to the interpretation of the results, review and editing. N. Bouaïcha contributed to the design and implementation of the research, to the review and editing. All authors have read and approved the final text.

Funding University of Nouakchott Al-Aasriya (UNA) and Mauritanian Institute of Oceanographic and Fisheries Researches (IMROP) funded this study. University of Las Palmas de Gran Canaria through the REBECA-CCT project (MAC/1.1.B/269) supported the participation in the CEMEPE 2021 and SECOTOX Conference.

Availability of Data and Materials (Data Transparency) The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Declaration of Competing Interest There is no conflict of interest with regard to this work.

References

Almanza V, Pedreros P, Laughinghouse HDIV, Féliz J, Parra O, Azocar M, Urrutia R (2019) Association between trophic stat, watershed use, and blooms of cyanobacteria in south-central Chile. Limnol 75:30–41. http://agris.fao.org/agris-search/search.do?recordID=US201900095661 consulted on 15/12/2021 at 15H: 15 min

Benayache NY, Nguyen-Quang T, Hushchyna K, McLellan K, Afri-Mehennaoui FZ, Bouaicha N (2019) An overview of cyanobacteria harmful algal bloom (CyanoHAB) issues in freshwater ecosystems. https://doi.org/10.5772/intechopen.84155. IntechOpen

Bergounhou C, Deniel MH, Micheau JC, Lavabre D, Levy G, Biasini G (1996) Protonation de la 1,10-phénanthroline. Bull Union Phys 787(90):1519–1525. http://materiel-physique.ens-lyon.fr/Logiciels/CD%20N%C2%B0%203%20BUP%20DOC%20V%204.0/Disk%201/TEXTES/1996/07871519.PDF consulted on 02/09/2021 at 11H: 03 min

Bogard JM, Vogt JR, Hayes MN, Leavitt RP (2020) Unabated nitrogen pollution favors growth of toxic cyanobacteria over chlorophytes in most hypereutrophic lakes. Environ Sci Technol 54(6):3219–3227. https://doi.org/pubs.acs.org/doi/10.1021/acs.est.9b06299

Bouaïcha N, Miles CO, Beach DG, Labidi Z, Djabri A, Benayache NY, Nguyen-Quang T (2019) Structural diversity, characterization and toxicology of microcystins. Toxins 11(12):714. https://doi.org/10.3390/toxins11120714

Bouhaddada R, Nélieu S, Nasri H, Delarue G, Bouaicha N (2016) High diversity of microcystins in a *Microcystis* bloom from an Algerian lake. Environ Pollut 216:836–844. https://doi.org/10.1016/j.envpol.2016.06.055

Bourrelly P (1972) Les algues d'eau douce. Initiation à la systématique. Tome I: Les Algues Vertes. Editions N. Boubée & Cie, France

Bourrelly P (1981) Les algues d'eau douce. Initiation à la systématique. Tome II: Les Algues Jaunes et Brunes. Chrysophycées, Phéophycées, Xanthophycées et Diatomées. Editions N. Boubée & Cie, France

Bourrelly P (1985) Les algues d'eau douce. Initiation à la systématique. Tome III: Les algues Bleues et Rouges. Eugléniens, Péridiniens et cryptomonadines. Editions N. Boubée & Cie, France

Bouvy M, Ba N, Ka S, Sane S, Pagano M, Arfi R (2006) Phytoplankton community structure and species assemblage succession in a shallow tropical lake (Lake Guiers, Senegal). Aquat Microb Ecol 45:147–161. https://doi.org/10.3354/ame045147

Carey CC, Ibelings BW, Hoffmann EP, Hamilton DP, Brookes JD (2012) Eco-physiological adaptations that favour freshwater cyanobacteria in a changing climate. Water Res 46(5):1407–1394. https://doi.org/10.1016/j.watres.2011.12.016

Carlson RE (1977) A trophic state index for lakes. Limnol Oceanogr 22(2):361–369. https://doi.org/10.4319/lo.1977.22.2.0361

Celikkol S, Fortin N, Tromas N, Andriananjamanantsoa H, Greer CW (2021) Bioavailable nutrients (N and P) and precipitation patterns drive cyanobacterial blooms in Missisquoi Bay, Lake Champlain. Microorganisms 9(10):2097. https://doi.org/10.3390/microorganisms9102097

Chiaa AM, Jankowiak GJ, Kramer JB, Goleski AJ, I-Shuo Huang I, Zimba VP, Bittencourt-Oliveira CM, Gobler JC (2018) Succession and toxicity of *Microcystis* and *Anabaena* (*Dolichospermum*) blooms are controlled by nutrient-dependent allelopathic interactions. Harmful Algae 74:67–77. https://doi.org/10.1016/j.hal.2018.03.002

Coffer MM, Blake A, Schaeffer AB, Foreman K, Porteous A, Loftin AK, Stumpf PR, Werdell JP, Urquhart E, Albert JR, Darling AJ (2021) Assessing cyanobacterial frequency and abundance at surface waters near drinking water intakes across the United States. Water Res 201:117377. https://doi.org/10.1016/j.watres.2021.117377

Corbel S, Mougin C, Bouaïcha N (2014) Cyanobacterial toxins: modes of actions, fate in aquatic and soil ecosystems, phytotoxicity and bioaccumulation in agricultural crops. Chemosphere 96:1–15. https://doi.org/10.1016/j.chemosphere.2013.07.056

Descy JP, Hardy MA, Sténuite S, Pirlot S, Leporcq B, Kimirei I, Sekadende B, Mwaitega SR, Sinyenza D (2005) Phytoplankton pigments and community composition in Lake Tanganyika. Freshwat Biol 50(4):668–684. https://doi.org/10.1111/j.1365-2427.2005.01358.x

Dittmann E, Gugger M, Sivonen K, Fewer DP (2015) Natural product biosynthetic diversity and comparative genomics of the cyanobacteria. Trends Microbiol 23(10):642–652. https://doi.org/10.1016/j.tim.2015.07.008

Downing JA, Watson SB, Mccauley E (2001) Predicting cyanobacteria dominance in lakes. Can J Fish Aquat Sci 58(10):1905–1908. https://doi.org/10.1139/cjfas-58-10-1905

Ebrahimpour S, Mohammadzade H, Naderi A, Azarpeykan A (2012) Evaluation of lakes eutrophication using GIS (case study: Zaribar marshy lake). Proceedings of 16th Congress of Iran Geology Association, (IGA' 12), Shiraz University, Shiraz, Iran

El Herry S, Fathallib A, Jenhani-Ben RA, Bouaichaa N (2008) Seasonal occurrence and toxicity of *Microcystis* spp. and *Oscillatoria tenuis* in the Lebna Dam, Tunisia. Water Res 42(4–5):1263–1273. https://doi.org/10.1016/j.watres.2007.09.019

Evans JC (1996) Straight forward statistics for the behavioral sciences. Thomson Brooks, Cole Publishing Co. Wisconsin. USA

Fathalli A, Romdhane SM, Vasconcelos V, Jenhani RBA (2015) Biodiversity of cyanobacteria in Tunisian freshwater reservoirs: occurrence and potent toxicity – a review. Water Supply Res T 64(6):755–772. https://doi.org/10.2166/aqua.2015.119

Geitler L (1932) Cyanophyceae. Akademische Verlagsgesellshaft, Leipszig. Germany

Gellati FZ, Touati H, Tambosco K, Quiblier C, Bensouilah M (2017) Unusual cohabitation and competition between *Planktothrix rubescens* and *Microcystis* sp. (Cyanobacteria) in a subtropical reservoir (Hammam Debagh) located in Algeria. PLoS ONE 12:e0183540. https://doi.org/10.1371/journal.pone.0183540

Ghashghaie M, Maralan MRS, Ostad-Ali-Askari K, Eslamian S, Singh VP (2018) Determining the eutrophication state of Ecbatan Reservoir using Carlson Index. Am J Eng App Sci 11(2):491–500. https://doi.org/10.3844/ajeassp.2018.491.500

Griffith AW, Gobler CJ (2019) Harmful algal blooms: a climate change co-stressor in marine and freshwater ecosystems. Harmful Algae 91:101590. https://doi.org/10.1016/j.hal.2019.03.008

Hammou HA, Latour D, Samoudi S, Mouhri K (2018) Occurrence of the first toxic *Microcystis* bloom in a recent Moroccan Reservoir. Water Resour J 45:409–417. https://doi.org/10.1134/S0097807818030028

Heil C, Muni-Morgan LA (2021) Florida's harmful algal bloom (HAB) problem: escalating risks to human, environmental and economic health with climate change. Front Ecol Evol 9:646080. https://doi.org/10.3389/fevo.2021.646080

Hillebrand H, Durselen CD, Kirschtele D, Pollingher U, Zohary T (1999) Biovolume calculation for pelagic and benthic microalgae. J Phycol 35(2):403–424. https://doi.org/10.1046/j.1529-8817.1999.3520403.x

Horst GP, Sarnelle O, White JD, Hamilton SK, Kaul RB, Bressie JD (2014) Nitrogen availability increases the toxin quota of a harmful cyanobacterium, *Microcystis aeruginosa*. Water Res 54:188–198. https://doi.org/10.1016/j.watres.2014.01.063

Huisman J, Codd GA, Paerl HW, Ibelings BW, Verspagen JMH, Visser PM (2018) Cyanobacterial blooms. Nat Rev Microbiol 16:471–483. https://doi.org/10.1038/s41579-018-0040-1

Jankowiak J, Hattenrath-Lehmann T, Kramer BJ, Ladds M, Gobler CJ (2019) Deciphering the effects of nitrogen, phosphorus, and temperature on cyanobacterial bloom intensification, diversity, and toxicity in western Lake Erie. Limnol Oceanogr 64(3):1347–1370. https://doi.org/10.1002/lno.11120

Kling HJ, Muggidde R, Hecky RE (2001) Recent changes in the phytoplankton community of Lake Victoria in response to eutrophication. In: The Great Lakes of the World (GLOW): Food web, Health, and integrity. Munawar M, Skjoldal HR (eds). Backhuys. Netherlands: 47–65

Komárek J, Anagnostides K (1999) Cyanoprokaryota, Part 1: Chroococcales, Süsswasserflora von Mitteleuropa, Bd 19/1. Spektrum Akademischer Verlag. Germany

Komárek J, Anagnostides K (2005) Cyanoprokaryota, Part 2: Oscillatoriales, Süsswasserflora von Mitteleuropa, Bd 19/2. Spektrum Akademischer Verlag. Germany

Kosten S, Huszar VLM, Bécares E, Costa LS, Donk E, Hansson LA, Jeppesen E, Kruk C, Lacerot G, Mazzeo N, De Meester L, Moss B, Lürling M, Nõges T, Romo S, Scheffer M (2012) Warmer climates boost cyanobacterial dominance in shallow lakes. Glob Change Biol 18(1):118–126. https://doi.org/10.1111/j.1365-2486.2011.02488.x

Li H, Xing P, Wu QL (2012) The high resilience of the bacterioplankton community in the face of a catastrophic disturbance by a heavy *Microcystis* bloom. FEMS Microbiol Ecol 28(4):192–201. https://doi.org/10.1111/j.1574-6941.2012.01417.x

Li J, Hansson LA, Hansson L, Persson KM (2018) Nutrient control to prevent the occurrence of cyanobacterial blooms in a eutrophic lake in southern Sweden, used for drinking water supply. Water 10(7):919. https://doi.org/10.3390/w10070919

Marion JW, Zhang F, Cutting D, Lee J (2017) Associations between county-level land cover classes and cyanobacteria blooms in the United States. Ecol Eng 108:556–563. https://doi.org/10.1016/j.ecoleng.2017.07.032

Mohamed ZA (2016) Harmful cyanobacteria and their cyanotoxins in Egyptian fresh waters – state of knowledge and research. Afr J Aquat Sci 41(4):361–368. https://doi.org/10.2989/16085914.2016.1219313

Morton SD, Lee TH (1974) Algal blooms--possible effects of iron. Environ Sci Tech 40(9):673–674. https://doi.org/10.1139/f83-164

Namsaraev Z, Melnikova A, Komova A, Ivanov V, Rudenko A, Ivanov E (2020) Algal bloom occurrence and effects in russia. Water 12(1):285. https://doi.org/10.3390/w12010285

Nasri H, Bouaïcha N (2017) Blooms of toxic cyanobacteria in freshwater in Algeria. Water Conserv Manag 1(2):05–06. https://doi.org/10.26480/wcm.02.2017.05.06

Nasri H, Bouaïcha N, Harche MK (2007) A new morphospecies of *Microcystis* sp. forming bloom in the Cheffia Dam (Algeria): Seasonal variation of *Microcystin* concentrations in raw water and their removal in a full-scale treatment plant. Environ Toxicol 22(4):341–448. https://doi.org/10.1002/tox.20275

Ndlela LL, Oberholster PJ, Van-Wyk JH, Cheng PH (2016) An overview of cyanobacterial bloom occurrences and research in Africa over the last decade. Harmful Algae 60:11–26. https://doi.org/10.1016/j.hal.2016.10.001

Neuveux J (1974) Recherche sur la chlorophylle a et la phéophytine a en milieu oligotrophe et en milieu eutophe (Méditérrannée). Thèse de 3ème cycles, Université Paris VI, France

Niamien-Ebrottie JE, Bhattacharyya S, Deep PR, Nayak B (2015) Cyanobacteria and cyanotoxins in the world: review. Internat J App Res 1(8):563–569. https://www.allresearchjournal.com/archives/2015/vol1issue8/PartJ/1-8-61-520.pdf consulted on 18/09/2021 at 19H: 46 min

North RL, Guildford SJ, Smith REH, Havens SM, Twiss MR (2007) Evidence for phosphorus, nitrogen, and iron co-limitation of phytoplankton communities in Lake Erie. Limnol Oceanogr 52(1):315–328. https://doi.org/10.4319/lo.2007.52.1.0315

Nyenje PM, Foppen JW, Uhlenbrook S, Kulabako R, Muwanga A (2010) Eutrophication and nutrient release in urban areas of sub-Saharan Africa — A review. Sci Total Environ 408(3):447–455. https://doi.org/doi:10.1016/j.scitotenv.2009.10.020

Olenina I, Hajdu S, Edler L, Andersson A, Wasmund N, Busch S, Göbel J, Gromisz S, Huseby S, Huttunen A, Jaanus A, Kokkonen P, Ledaine I, Niemkiewicz E (2006) Biovolumes and size-classes of phytoplankton in the Baltic Sea. HELCOM Baltic Balt Sea Environ Proc 106:1–144. https://epic.awi.de/id/eprint/30141/1/bsep106.pdf consulted on 11/10/2021 at 08H: 26 min

Oudra B, Loudiki M, Sbiyyaa B, Martins R, Vasconcelos V, Namikoshi N (2001) Isolation, characterization and quantification of microcystins (heptapeptides hepatotoxins) in *Microcystis aeruginosa* dominated bloom of Lalla Takerkoust lake-reservoir (Morocco). Toxicon 39(9):1375–1381. https://doi.org/10.1016/S0041-0101(01)00093-9

Ouhsassi M, Khay E-O, El-Laghdach A, Abdelouahab BF, El-Ouahrani A, Idaomar M, Abrini J (2021) Characterization of cyanobacteria microcystins (cyanotoxins) blooming in the Dams of Northern Morocco. Afr J Environ Sci Technol 15(3):124–141. https://doi.org/10.5897/AJEST2020.2967

Overlinge D, Torunska-Sitarz A, Kataržyte M, Pilkaityte R, Gyraite G, Mazur-Marzec H (2021) Characterization and diversity of Microcystins produced by cyanobacteria from the curonian lagoon (SE Baltic Sea). Toxins 13(2):838. https://doi.org/10.3390/toxins13120838

Paerl HW (2018) Why does N-limitation persist in the world's marine waters? Mar Chem 206:01–06. https://doi.org/10.1016/j.marchem.2018.09.001

Paerl HW, Paul VJ (2012) Climate change: links to global expansion of harmful cyanobacteria. Water Res 46(5):1349–1363. https://doi.org/10.1016/j.watres.2011.08.002

Pan D, Pavagadhia S, Umashankara S, Raia A, Benkea P, Raia M, Saxenaa G, Gangua V, Swarupa S (2019) Resource partitioning strategies during toxin production in *Microcystis aeruginosa* revealed by integrative omics analysis. Algal Res 42:10158. https://doi.org/10.1016/j.algal.2019.101582

Preece D, Becerra R, Robinson K, Dandy J (2017) Assessing alexithymia: Psychometric properties and factorial invariance of the 20-item Toronto Alexithymia Scale in nonclinical and psychiatric samples. J Psychopathol Behav Assess 40(2):276–287. https://doi.org/doi:10.1007/s10862-017-9634-6

Puddick J, Wood SA, Hawes L, Hamilton DP (2016) Fine-scale cryogenic sampling of planktonic microbial communities: Application to toxic cyanobacterial blooms. Limnol Oceanogr 14(9):600–609. https://doi.org/10.1002/lom3.10115

Rapala J, Sivonen K, Lyra C, Niemelä SI (1997) Variation of microcystins, cyanobacterial hepatotoxins, in Anabaena spp. as a function of growth stimuli. App Environ Microbiol 63(6):2206–2212. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC168513/, consulted on 21/11/2021 at 11H: 32 min

Rashidi H, Baulch H, Gill A, Bharadwaj L, Bradford L (2021) Monitoring, managing, and communicating risk of harmful algal blooms (HABs) in recreational resources across Canada. Environ Health Insights 15(43):117863022110144. https://doi.org/10.1177/11786302211014401

Reynaud PA, Laloë F (1985) La méthode des suspensions-dilutions adaptée à l'estimation des populations' algales dans une rizière. Rev School Biol Sol 22(2):161–192. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_5/b_fdi_30-30/31395.pdf consulted on 27/10/2021 at 09H: 53 min

Reynolds CS (1997) Vegetation Processes in the pelagic. a model for ecosystem theory. Excellence in Ecology. Oldendorf/Luhe Ecology Inst., Oldendorf (FRG), no. 9, 371p. https://www.sciencebase.gov/catalog/item/5053a803e4b097cd4fce9f5e consulted on 11/09/2021 at 14H: 18 min

Rodier J (1996) Analyse de l'eau: eau naturelle, eau résiduaire et eau de mer. Dunold, 8ème édition

Schinck PM, L'Ecuyer-Sauvageau C, Leroux J, Kermagoret C, Dupras J (2020) Risk, drinking water and harmful algal blooms: a contingent valuation of water bans. Water Resour Manage 34:3933–3947. https://doi.org/10.1007/s11269-020-02653-x

Sivonen K (1990) Effects of light, temperature, nitrate, orthophosphate, and bacteria on growth of and hepatotoxin production by *Oscillatoria agardhii* strains. App Environ Microbiol 56(9):2658–2666. https://doi.org/10.1128/AEM.56.9.2658-2666.1990

Svircev Z, Drobac D, Tokodi N, Mijovic B (2017) Toxicoloy of microcystins with reference to cases of human intoxications and epidemiological investigations of exposures to cyanobacteria and cyanotoxins. Arch Toxicol 91:621–650. https://doi.org/10.1007/s00204-016-1921-6

Tanvir UR, Hu Z, Zhang Y, Lu J (2021) Cyanobacterial community succession and associated cyanotoxin production in hypereutrophic and eutrophic freshwaters. Environ Pollut 290:118056. https://doi.org/10.1016/j.envpol.2021.118056

Taranu ZE, Pick FR, Creed IF, Zestepa A, Watson SB (2019) Meteorological and nutrient conditions influence microcystin congeners in freshwaters. Toxin Rev 11(11):620. https://doi.org/10.3390/toxins11110620

Tian C, Lu X, Pei H, Hu W, Xie J (2012) Seasonal dynamics of phytoplankton and its relationship with the environmental factors in Dongping Lake. China Environ Monit 185:2627–2645. https://doi.org/10.1007/s10661-012-2736-4

Twiss MR, Auclair J, Charlton MN (2000) An investigation into iron-stimulated phytoplankton productivity in epipelagic Lake Erie during thermal stratification using trace metal clean techniques. Can J Fish Aquat Sci 57(4):86–95. https://doi.org/10.1139/cjfas-57-4-870

Utermöhl H (1958) On the perfection of quantitative phytoplankton method. Int Ass Theo Appl Limnol Communication 9:01–38

Van De Waal DB, Verspagen JMH, Lurling M, Van Donk E, Visser PM, Huisman J (2009) The ecological stoichiometry of toxins produced by harmful cyanobacteria: an experimental test of the carbon-nutrient balance hypothesis. Ecol Lett 12:1326–1335. https://doi.org/10.1111/j.1461-0248.2009.01383.x

Vilán VAJ, Fernández ARJ, Nieto GJP, Lasheras, Juez CJF, Muñiz DC (2013) Support vector machines and multilayer perceptron networks used to evaluate the cyanotoxins presence from experimental cyanobacteria concentrations in the Trasona Reservoir (Northern Spain). Water Resour Manage 27:3457–3476. https://doi.org/10.1007/s11269-013-0358-4

Vrede T, Tranvik JL (2006) Iron constraints on planktonic primary production in oligotrophic lakes. Ecosystems 9:1094–1105. https://doi.org/10.1007/s10021-006-0167-1

Wacklin P, Hoffmann L, Komárek J (2009) Nomenclatural validation of the genetically revised cyanobacterial genus Dolichospermum (Ralfs ex Bornet and Flahault) comb. nova. Fottea 9:59–64. https://doi.org/10.5507/fot.2009.005

Wang XQ, Jiang HB, Qiu BS (2015) Effects of iron availability on competition between *Microcystis* and *Pseudanabaena* or *Chlorella* species. Eur J Phycol 50(3):260–270. https://doi.org/10.1080/09670262.2015.1020516

Wever DA, Muylaert K, Langlet D, Alleman L, Descry JP, Andre L, Cocquyt C, Vyverman W (2007) Differential response of phytoplankton to additions of nitrogen, phosphorus and iron in Lake Tanganyika. Freshwat Biol 53(2):264–277. https://doi.org/10.1111/j.1365-2427.2007.01890.x

WHO (1998) Guidelines for drinking-water quality. Addendum to vol, vol 2. World Health Organisation, Geneva

Wurtsbaugh WA, Paerl HW, Dodds WK (2019) Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. WIREs Water 6(5):e1373. https://doi.org/10.1002/wat2.1373

Yang Z, Buley PR, Fernandez-Figueroa GE, Barros UGM, Rajendran S, Wilson EA (2018) Hydrogen peroxide treatment promotes chlorophytes over toxic cyanobacteria in a hyper-eutrophic aquaculture pond. Environ Pollut 240:590–598. https://doi.org/10.1016/j.envpol.2018.05.012

Authors and Affiliations

Ahmed S. Sadegh[1,2] · Zeinebou Sidoumou[1] · Mamadou Dia[2] · Juan L. G. Pinchetti[3] · Noureddine Bouaïcha[4]

✉ Ahmed S. Sadegh
sidisadegh@yahoo.fr

[1] Unit of Marine Eco-biology, Environment, Health and Nutrition (EBIOMESN), Department of biology, University of Nouakchott Al-Aasriya (UNA), P.O. Box 7898, Nouakchott, Mauritania

[2] Laboratory of Biology and Ecology of Aquatic Organisms (LEBOA), Mauritanian Institute of Oceanographic and fisheries Research (IMROP), P.O. Box 22, Nouadhibou, Mauritania

[3] Spanish Bank of Algae (BEA), Institute of Oceanography and Global Change (IOCAG), University of Las Palmas de Gran Canaria, C/Juan de Quesada, 30, 35001 Canary Islands, Spain

[4] Laboratory of Ecology, Systematic and Evolution, UMR 8079 Univ. Paris-Saclay, CNRS, AgroParisTech, Paris- Saclay University, 91405 Orsay, France