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

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Abstract

This work was carried out to study the seasonal occurrence of cyanobacteria and their microcystin-LR in 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 factors relationships were analyzed by Pearson's correlation and Multiple Linear Regression. Physicochemical analyzes have shown that this reservoir is hypereutrophic 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. Annual surface water temperature was exceptionally high (27.8 ± 3.6°C), characterizing of a Sahelian climatic conditions. Phytoplankton analyzes have shown dominance of two toxic cyanobacteria species *Microcystis aeruginosa* and *Dolichospermum flos-aquae* during warm season (May-September). Microcystins analysis revealed presence of only 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 factors 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 need for regular monitoring of cyanobacteria and cyanotoxins in the waters of studied reservoir.

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 from soil erosion (Huisman et al. 2018; Wurtsbaugh et al. 2019). This increasing eutrophication leads to excessive blooms of harmful cyanobacteria (cyanoHAB), extent and frequency of which are increasing worldwide (Preece et al. 2017; Paerl 2018). 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). 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). 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; Bouaïcha et al. 2019).

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 fresh surface waters during the warmer months, particularly in summer and early fall. Some arid West African countries such as Mauritania have made significant efforts to mobilize surface water resources through the construction of dams. However, wastewater discharges, industrial pollutants, soil erosion and the 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). Therefore, the Foum-Gleita reservoir studied in this work has been subject to long several anthropogenic effects including: discharge of communal 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 reservoir, 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 the seasonal occurrence of cyanobacteria and their microcystins in the water column of Foum-Gleita reservoir (Mauritania) as well as the environmental factors likely to control their development.

2 Materials And Methods

2.1 Studied Area and Sampling

The 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 milliard m^3 and a maximum depth of 9 m. The catchment area of Foum-Gleita reservoir covers 21,000 km^2 with two principal rivers, the *Black Gorgol* and the *White Gorgol*. The reservoir is camped on the confluence of the Black Gorgol River, upstream of its confluence with the White Gorgol River and the Senegal River. The Black Gorgol pours into the reservoir and the White Gorgol towards the confluence point. The filling dynamics of Foum-Gleita reservoir essentially depend on the intermittent black Gorgol flows. These flows only take place during the rainy season from July to September. Watershed of 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).

For several years, Foum-Gleita reservoir has been subject to important demographic pressure due to the arrival of nomad’s victims of the increasing dryness in the Sahel. About 49% of the water flow from this reservoir is used for drinking water of human and livestock farming and 36% irrigation (downstream). 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). Given that the watershed of this reservoir is both an agricultural and mining (phosphate) region, the water quality of this reservoir suffers considerably from the leaching of nutrients such as phosphorus, particularly from soil erosion and phosphate rocks, and nitrogen mainly from Intensive livestock, and agriculture. For this reason, the waters of this reservoir show a history of cyanobacterial blooms.

During this study, the waters of Foum-Gleita reservoir were regularly monitored from September 2017 to August 2018. During this monitoring period, the sampling was carried out on a deep site located at the intake tower level (Fig. 1). This site is at dike of Foum-Gleita reservoir, where the flow of water and wind drains a lot of nutrient-laden sediments and phytoplankton scums formed in other areas of the reservoir. At this site, 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 are 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 chemical parameters analysis were immediately stored in a portable refrigerator (approximately 4°C) then they were brought back to the laboratory and stored at 4°C and those intended for identification and enumeration of phytoplankton were stored with Lugol's iodine solution (5% v/v) for further analysis.

2.2 Physicochemical Parameters Analysis 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 nutrients 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 Zambelli, 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 $N\text{-}NH4^+$. 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 microfiber filters 0.45 µm (Whatman, diameter: 47 mm) to separate dissolved and particulate microcystins, then processed according to the method described in Bouhadadda et al. (2016). 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 Bouhadadda 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 x 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 $[M + H]^+ + [M + 2H]^{2+}$) 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 samples analysis taken at three depths in Foum-Gleita reservoir: Transparency, 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. 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 Microcystine-LR concentrations) were explored by a Stepwise Multiple Linear Regression with forward selection method in order to detect the exact contribution of each independent variables 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 variables 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 And Discussion

3.1 Physicochemical Characterization and Eutrophication 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. Temperatures, pH, dissolved oxygen and salinity varied on a temporal basis within depths and spatially between depths, 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 was observed in the warm-dry season (May 2018 precisely). At all sampling depths and throughout the study period, the reservoir's water was slightly alkaline with a pH values ranged from 7.7 in surface to 8.7 at depth (-6 m). However, the waters sampling site of this reservoir are relatively ventilated in surface and ill ventilated in bottom with mean dissolved oxygen concentrations ranged from 8.85 mg/L in 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, and 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 in surface throughout the sampling period (0.43 to 0.35 mg/L, respectively). Meanwhile, dissolved phosphorus (DIP) concentrations ranged from 0.30 to 0.37 mg/L in surface, 0.21 to 0.51 mg/L at depth (-3 m) and 0.22 to 0.54 mg/L at depth (-6 m). Mean nitrate (NO_3-N) and DIN concentrations were higher at depth (-6 m) ranged 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 in 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 in surface, depth (-3 m) and depth (-6 m), respectively (Table 1). Mean iron concentrations were dissimilar within all depths ranging from 0.15 to 0.21 mg/L in surface and bottom, respectively. Mean concentrations of Chlorophyll-a in water samples were 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 water surface during the warm-dry season (in May 2018) that was significantly different only with the depths 3 an 6 m values ($p = 0.001$ and $p = 0.018$, respectively).

Table 1
Physicochemical parameters at different depths of sampling site in Foum-Gleita reservoir from September 2017 to August 2018 (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 ($P < 0.05$); * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$).

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 ± 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 ± 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 ± 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 ± 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	–	–	–	–	–	–
$P\text{-}PO_4^{-3}$ (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 ± 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 ± 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 ± 1.48[b,c]	1.12-6.05	$F_{2, 33} = 8.078$	0.001*

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 ranging from 66 to 70 in cool- dry season and 70 to 80 in warm- dry season can be classified as eutrophic in cool- dry season to hypereutrophic in warm- dry season (Fig. 2).

These results are consistent with studies that have shown that phytoplankton succession in tropical aquatic ecosystems is characterized by a distinct change between dry and rainy seasons (Tian et al. 2012). Although N and P concentrations were always high in Foum-Gleita reservoir throughout the study period, the highest abundance of two dominant cyanobacterial species *Microcystis aeruginosa* and *Dolichospermum flos-aquae* was recorded when DIN/TP ratio was less than 10. This situation is similar to that recently observed in shallow hypereutrophic lake Wascana- Canada (Bogard et al. 2020).

3.2 Cyanobacteria Dynamics and Microcystine-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 by 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 been totally dominated by *Dolichospermum flos-aquae* and *Microcystis aeruginosa* that represent 49 and 40%, respectively. Indeed, these two species showed a constant presence in all depths of the sampling site (Figs. 3 and 4). Also, the highest biovolumes of these two dominant species, *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 et 4.79 mm^3/L, respectively) and August 2018 (7.41 et 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 only during the end of rainy season to the first of dry season (September, October, and November) with a biovolume peak of 0.03 mm^3/L noted at surface in September 2017 (0.031 mm^3/L). Also, *Planktothrix* sp. was observed only in all depths with low irregular biovolumes during the warm- dry season with a peak of 0.001 mm^3/L registered at surface and depth (-3 m) in Jully 2018. This is reason why these last three species were neglected in data analysis.

Within ecosystems where non-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). Although the growth trend of *D. flos-aquae* and *M. aeruginosa* in this reservoir was similar in the three depths, their biovolume was approximately 25 times higher at the surface. These results were similar to

results, which reported that an atmospheric nitrogen-fixing genus, *Dolichospermum*, is generally a 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). Since nitrogen and phosphorus concentrations in Foum-Gleita reservoir were extremely high throughout the year and were always above levels required for growth of phytoplankton (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 waters of this reservoir.

Species observed in this 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 was found: microcystin-LR (Fig. 5). 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 Figure 3, MC-LR concentrations varied on a temporal basis within 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 in surface, -3 and -6 m, respectively. Dissolved microcystin-LR (extracellular) concentrations were always lower than the particulate (intracellular) concentrations, with proportions in the water samples in all depths never exceeded 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 in surface water, where the biovolumes of these two cyanobacterial species was highest in late summer-early autumn (Fig. 3). 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. 3).

Although 279 microcystin congeners 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). 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, some environmental factors such as availability of nutrients P and N, iron limitation, light intensity, water pH and temperature are involved in suppression or improvement of expression of microcystin synthetase genes (Puddick et al. 2016; WHO 1998).

3.3 Relationship between Environmental Factors

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

These results are consistent with those of Lake Erie study, which indicated that in response to dose gradients of nitrogen and phosphorus during a harmful cyanobacteria bloom, the relative abundance of diazotrophic genera such as *Aphanizomenon* and *Dolichospermum* increased by high concentrations of phosphorus, while nitrogen dramatically increased that of non-azotrophic genera such as *Planktothrix* (Jankowiak et al. 2019).

These results also agree with results obtained in Lake Tanganyika (East African Rift Valley), which show that the combined addition of iron, phosphorus and nitrogen to lake water samples stimulates the cyanobacteria growth but not of chlorophytes or diatoms (Wever et al. 2007). In addition, the relationships between total concentrations of microcystin-LR and limnological factors at Foum-Gleita reservoir are in agreement with the study of Pan et al. (2019).

Table 2

Correlations between environmental factors of Foum-Gleita reservoir (T = water temperature; pH = water hydrogen potential; DO = dissolved oxygen; $N\text{-}NO_3^-$ = 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 = ir *Dolichospermum* = *Dolichospermum flos-aquae*; *Microcystis* = *Microcystis aeruginosa*: MC-LR = microcystin-LR). Significance of correlation coefficients (Pe *0.01 < p < 0.05, **0.001 < p < 0.01, and ***p < 0.001.

	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
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
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*
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*
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*

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

	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	$F_{2, 33} = 9.724$	$F_{2, 33} = 72.470$	$F_{2, 33} = 55.150$

4 Conclusions

First conclusion of this study is that Foum-Gleita reservoir is a hypereutrophic 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 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 need for regular monitoring of cyanobacteria and cyanotoxins in the waters of this reservoir.

Declarations

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Declaration of competing interest

The authors agree there is no conflict of interest with regard to this work.

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.

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Authors' contributions

A.S. Sadegh planned and carried out the experiment, analysis and interpretation of the results, writing-original draft. Z. Sidoumou involved in planning and supervised the project, review and editing. M. Dia helped supervise the project, review & editing. 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 analysis of the results and to the writing- review and editing.

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Figures

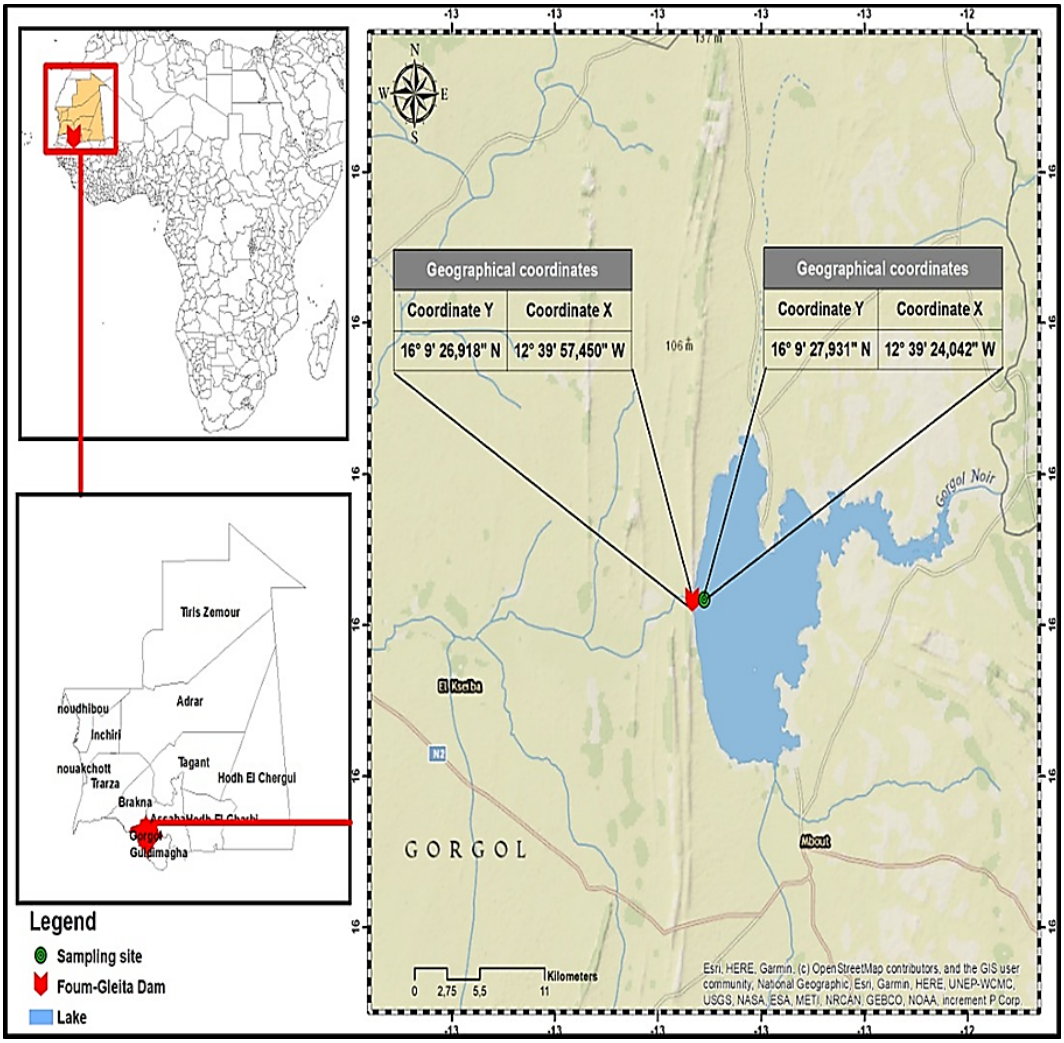

Figure 1

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

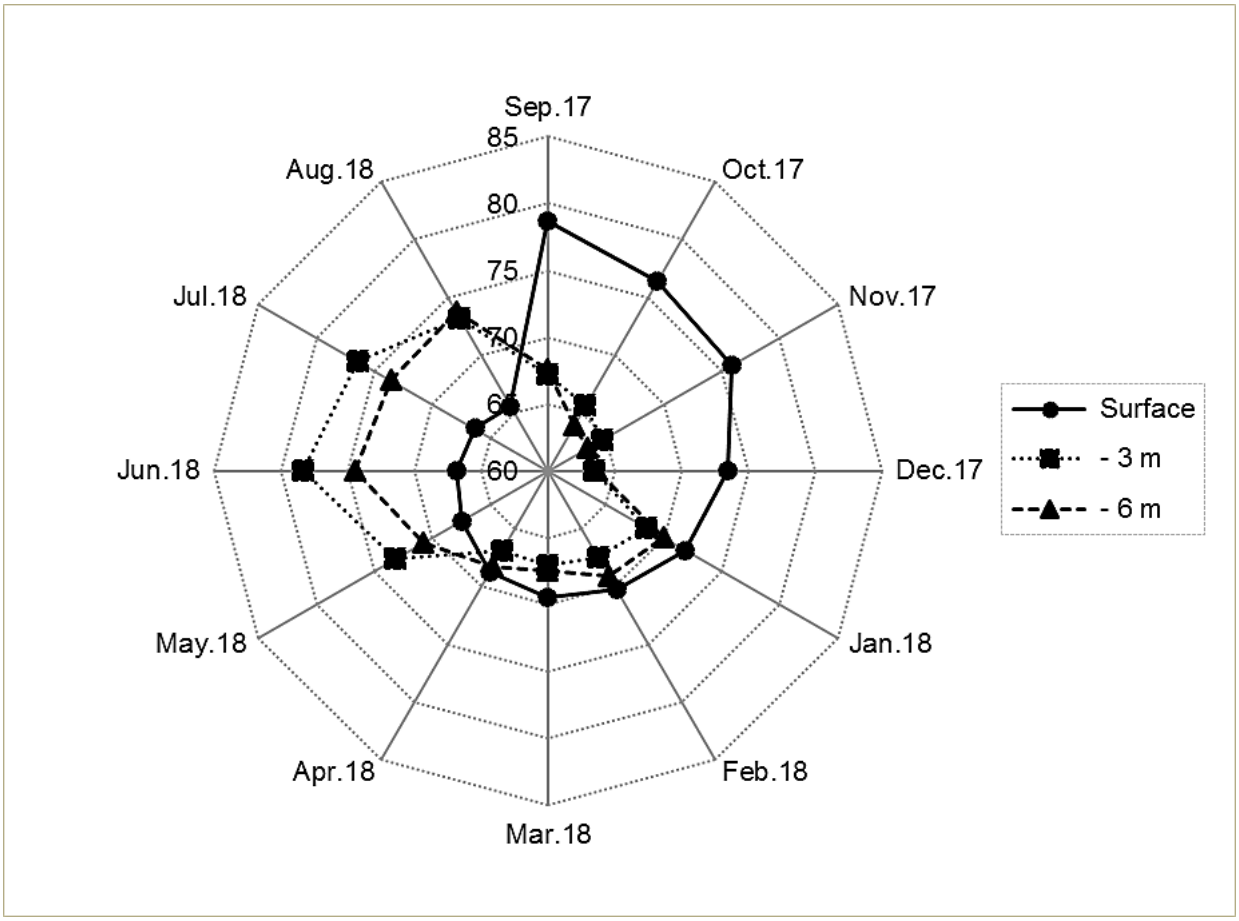

Figure 2

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

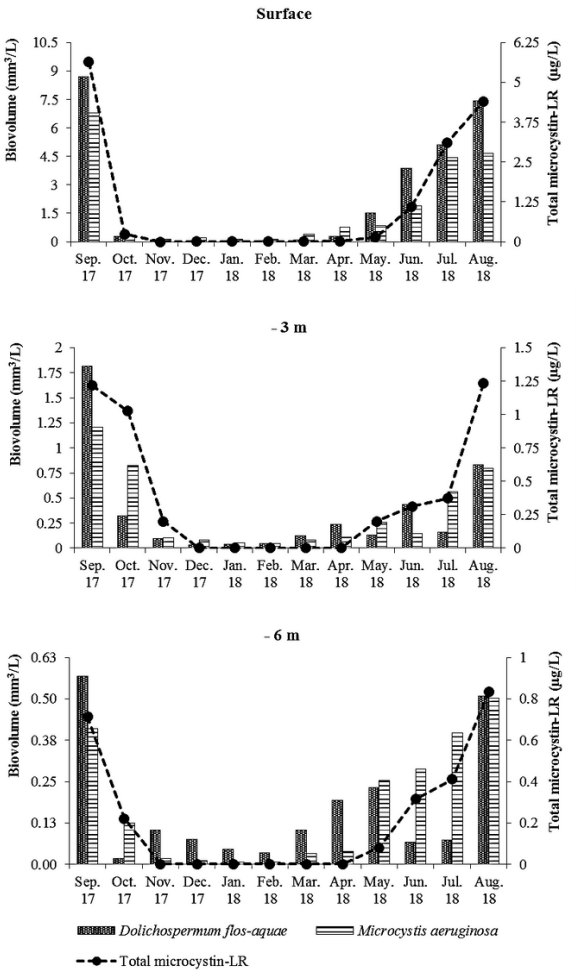

Figure 3

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.

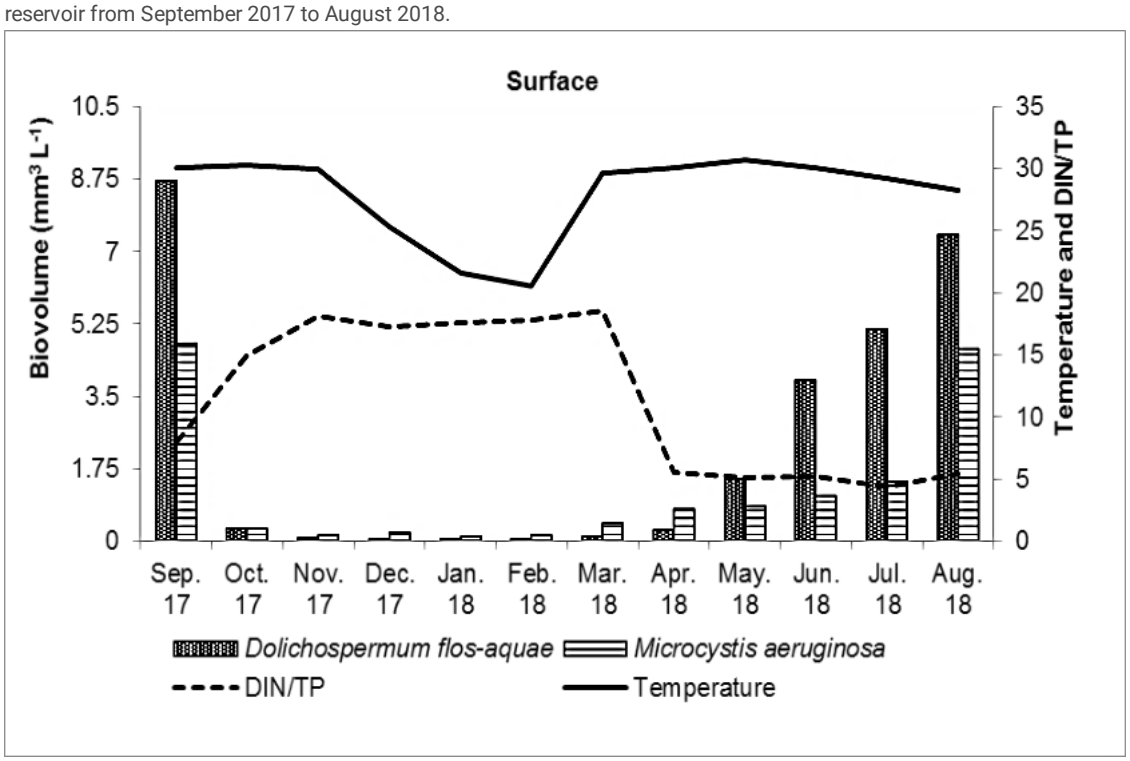

Figure 4

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

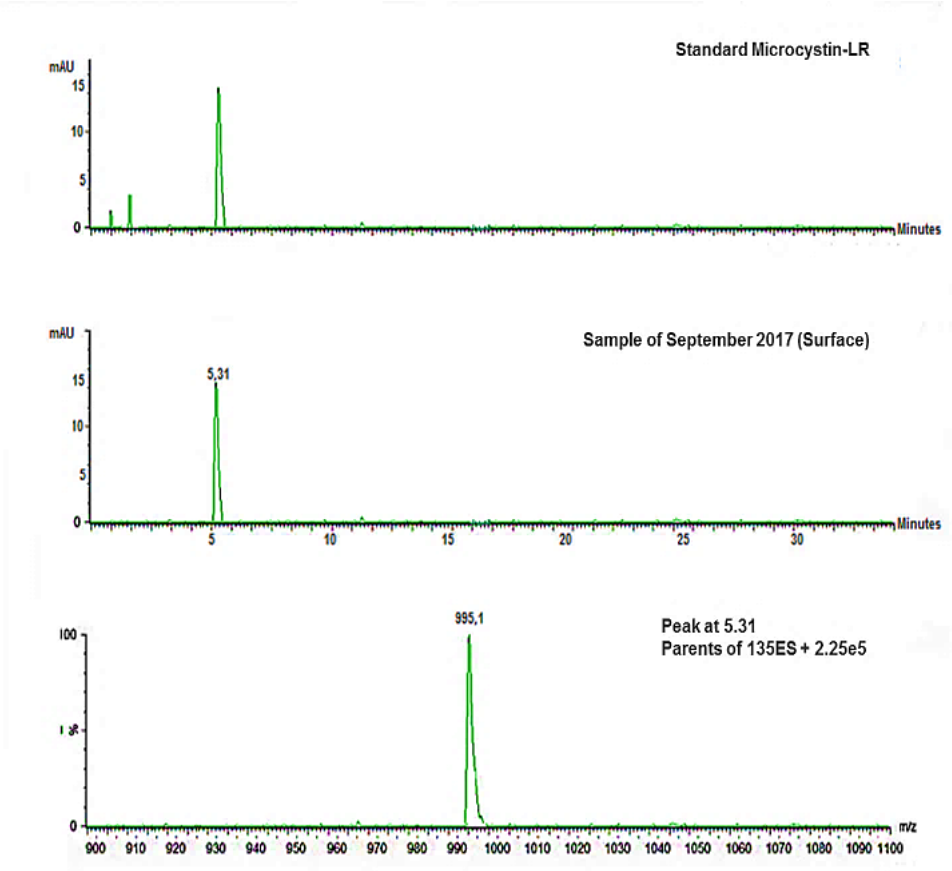

Figure 5

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] (down) 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).