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SPATIO-TEMPORAL DYNAMICS OF TOXIC CYANOBACTERIA IN AN ARTIFICIAL LAKE IN THE BRAZILIAN SEMI-ARID REGION[1]

FRANCISCO JOSIVAN DE OLIVEIRA LIMA[2]*, FERNANDO BEZERRA LOPES[2], EUNICE MAIA DE ANDRADE[2], FRANCISCO CLEITON DA ROCHA[3], ANA CÉLIA MAIA MEIRELES[4]

ABSTRACT - Intensification of the eutrophication process in surface water leads to an increase in the intensity and frequency of cyanobacterial blooms, compromising the availability of drinking water. Therefore, the aim of this study was to investigate the spatio-temporal dynamics of cyanobacteria and identify the most important nutrients for such dynamics in a semiarid artificial lake, the Orós reservoir, in north-eastern Brazil. Seventy-seven water samples were collected in 11 campaigns (six during the dry season and five during the rainy season) from seven points. The attributes under investigation were the Secchi transparency, turbidity, pH, apparent colour, electrical conductivity, total solids, total phosphorus, soluble orthophosphate content, total Kjeldahl nitrogen, ammonia content, nitrate content, and cyanobacteria dynamics, resulting in a total of 924 samples (number of campaigns × number of points × number of attributes). Principal component analysis and cluster analysis were used to investigate the significance and determinant attributes of the spatio-temporal dynamics of cyanobacteria. Of the 17 species of cyanobacteria identified, 10 accounted for 72.47% of the total accumulated variance. During the rainy season, four homogeneous groups of cyanobacteria formed, whereas during the dry season, only three groups formed. The greatest concentrations occurred during the dry season, notably for *Aphanocapsa* spp., *Cylindrospermopsis* sp., and *Geitlerinema* sp., which are potentially toxic and show a greater affinity to the physical attributes of water. Climate seasonality was decisive in the spatio-temporal dynamics of cyanobacteria, and high transparency values limited excessive proliferation of the dominant species.

Keywords: Phytoplankton. Water quality. Seasonality. Multivariate analysis.

DINÂMICA ESPAÇO-TEMPORAL DE CIANOBACTÉRIAS TÓXICAS EM LAGO ARTIFICIAL NO SEMIÁRIDO BRASILEIRO

RESUMO - A intensificação do processo de eutrofização nas águas superficiais leva a um aumento da intensidade e frequência de florações de cianobactérias comprometendo a disponibilidade hídrica para o uso consuntivo. Deste modo, objetivou-se estudar a dinâmica espaço-temporal das cianobactérias e a identificação dos nutrientes de maior peso nessa dinâmica em lago artificial semiárido, reservatório Orós (Nordeste do Brasil). Foram analisadas 77 amostras de água em 11 campanhas (seis no período seco e seis no chuvoso) em sete pontos. Os atributos investigados foram: Transparência de Secchi, Turbidez, pH, Cor Aparente, Condutividade Elétrica, sólidos totais, fósforo total, ortofosfato solúvel, NTK, Amônia, Nitrato e Cianobactérias, totalizando 924 (número de campanhas × número de pontos × número de atributos). Para investigar a significância e os atributos determinantes da dinâmica espaço-temporal das cianobactérias empregou-se análise da componente principal e análise de agrupamento. Das 17 espécies de cianobactérias identificadas, 10 espécies explicaram 72,47% da variância total acumulada. Durante a estação chuvosa foram formados 4 grupos homogêneos de cianobactérias enquanto no período seco formaram-se apenas três grupos. As maiores concentrações ocorreram no período seco com destaque para as espécies *Aphanocapsa* spp, *Cylindrospermopsis* sp e *Geitlerinema* sp, que são potencialmente tóxicas, e mostraram uma maior afinidade aos atributos físicos. A sazonalidade climática foi determinante na dinâmica espaço-temporal das cianobactérias, e que os altos valores de transparência limitaram a proliferação excessiva das espécies dominantes.

Palavras-chave: Fitoplâncton. Qualidade de água. Sazonalidade. Análise multivariada.

*Corresponding author
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[2]Department of Agricultural Engineering, Universidade Federal do Ceará, Fortaleza, CE, Brazil; josivan.lima1@gmail.com - ORCID: 0000-0002-6620-6381, lopesfb@ufc.br - ORCID: 0000-0001-8285-2925, eandrade.ufc@gmail.com – ORCID: 0000-0002-9750-0364.
[3]Centre of Education Science, Universidade Federal do Piaui, Teresina, PI, Brazil; biofcr@yahoo.com.br -ORCID: 0000-0002-6208-7434.
[4]Centre of Agricultural Sciences and Biodiversity, Universidade Federal do Cariri, Crato, CE, Brazil; ana.meireles@ufca.edu.br - ORCID: 0000-0002-8860-2043.

INTRODUCTION

The world has recently been going through a crisis in the water sector caused by a decrease in the quantity and quality of easily available water. What seemed to be an unlimited resource was proven to be fragile given the growth in population and the disorderly development of large urban centres without adequate sanitary infrastructure, which increased the demand for consumption of this resource and also resulted in the pollution of water bodies (VENANCIO et al., 2015).

In the semi-arid region of Brazil, the problem is worse because of the low availability of water. The region is characterised by irregular rainfall, with a high spatial and temporal variability and a high rate of evapotranspiration, in addition to having low annual rainfall depths (ANDRADE et al., 2020).

In these regions, in addition to the climate characteristics, the soils are mostly shallow or of moderate depth and are based on crystalline rock, thereby forming a dense network of ephemeral or intermittent rivers (ANDRADE et al., 2020). As a result, artificial reservoirs have emerged as the main form of storage and the principal source of water for various uses, such as human and industrial consumption, irrigation, and fish farming (ANA, 2016). However, during the past few decades, a serious problem of water quality, i.e., eutrophication, has intensified in various reservoirs of the semi-arid region of Brazil. Several studies have been conducted to understand this process (ROCHA JUNIOR et al., 2018; WIEGAND et al., 2021).

The increased intensity and frequency of cyanobacterial blooms in eutrophic reservoirs, whose water is not suitable for most of the uses for which they were planned, have been identified by different researchers (MEDEIROS et al., 2015). The eutrophic state of the reservoirs, together with the increase in the water surface temperature in a stable water column and the high residence time of the reservoirs, has fostered ecological conditions for the development of cyanobacteria (OLIVEIRA et al., 2015; MEDEIROS et al., 2015). The massive blooms of these micro-organisms represent a serious public health problem (AFFE; BARBONI, 2012).

Health problems related to cyanophyceae or cyanobacteria are due to the toxin producing ability of some species, which can affect human health and cause animal mortality (CARNEIRO et al., 2013). Furthermore, in addition to their toxic potential, under favourable conditions, the excessive development of cyanobacteria affects water use, such as the catchment and treatment of water, fishing practices, recreational activities, and water sports (SILVA et al., 2016).

Because these organisms disperse easily in the water column, given their small size and high abundance, it is reasonable to assume that local conditions and the availability of resources (such as nutrients, light, and high temperatures), among other factors, determine which species dominate at any given time and place (CHA et al., 2014; ZHANG et al., 2021). Oliveira et al. (2015) stated that spatial heterogeneity (vertical and horizontal of the source) and temporal heterogeneity (seasonality), even over a short period, affect the biological dynamics and limnological attributes of the reservoirs.

The above information leads to the hypothesis that the period of drought might be responsible for the dominance of certain groups of cyanophyceae in the reservoirs of the semi-arid region.

Therefore, the aim of this work was to study the spatio-temporal dynamics of cyanobacteria in an artificial lake in the semi-arid region of Brazil to identify the physical and chemical attributes that have the greatest influence on the formation of similar groups of cyanobacteria, as well as to identify the dominant species.

MATERIALS AND METHODS

Study area

The research was carried out in the Orós reservoir, located between 6°08'03″–6°20'26″ S and 38°54'56″–39°13'28″ W, in the basin of the Upper Jaguaribe in the state of Ceará, Brazil (Figure 1). The reservoir has a storage capacity of 1.94 billion cubic metres of water and a watershed of 35,000 ha. According to the Köppen classification, the climate in the region is type BSw'h'. The rainy season period comprises December to May and the dry season from June to November (FERREIRA et al., 2015).

The soils of the Upper Jaguaribe basin have the following distribution: Neosols and Argisols (61%), with the remaining 39% classified as Latosols, Luvisols, Vertisols, and Planosols. The predominant types of land use in the basin are related to agricultural activities (the cultivation of cotton, beans, cassava, maize, bananas, and rice) and other important activities, such as cattle and poultry farming (IPECE, 2015).

Collection points

For a better understanding of the distribution of phytoplankton in the reservoir, the water collection points were located at the entrance to six tributaries (Figure 1): P1, P2, P3, P4, P5, P6 and P7, with point P7 located close to the spillway. Collections were taken every two months, from April 2008 to February 2010.

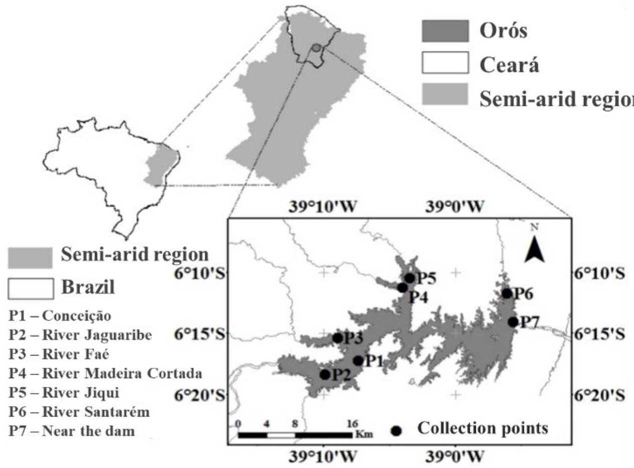

Figure 1. Location of the Orós reservoir and water collection points.

Monitoring the rainfall and accumulated volume in the reservoir

The series of daily rainfall data from meteorological station in the city of Iguatu and accumulated volume of the Orós reservoir (Figure 2) were obtained from the database of the Hydrological Information Site of the State of Ceará (COGERH, 2021), from 1 April 2008 to 28 February 2010.

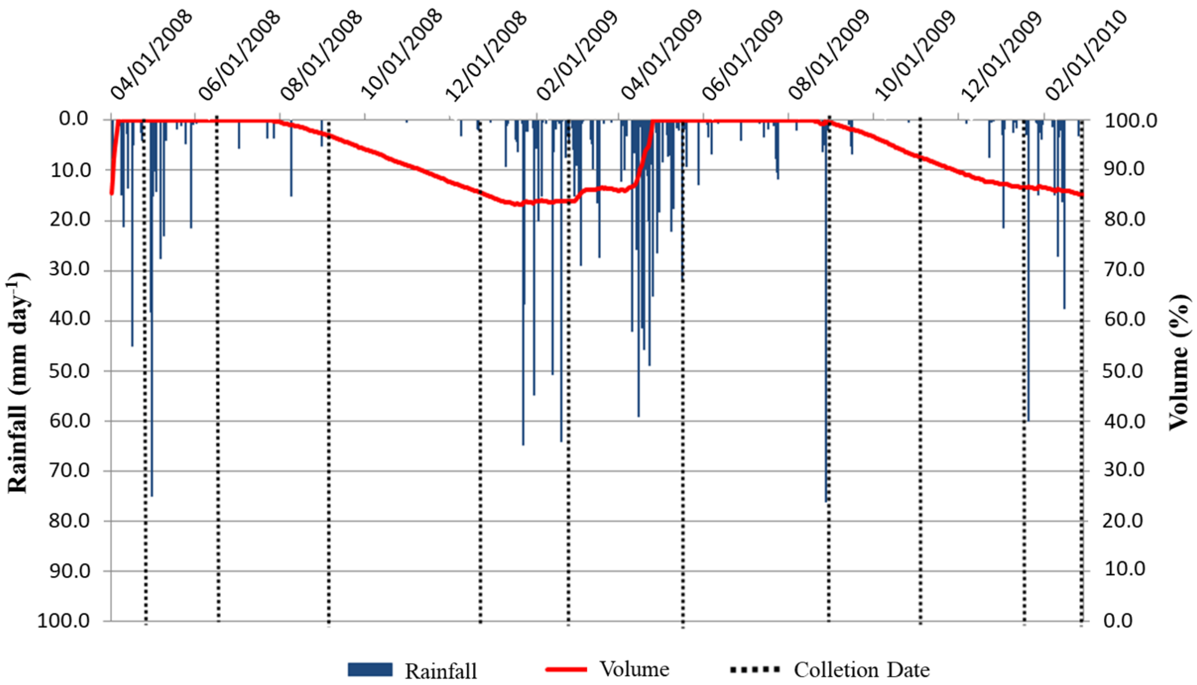

Figure 2. Daily rainfall data and volume in the reservoir.

Physical and chemical attributes

Physical and chemical attributes were evaluated to understand abiotic interference in the succession of phytoplankton species (Table 1). pH, temperature and Secchi transparency were determined on site. For other attributes, collections were taken at a depth of 30 cm from the surface of the water, using properly decontaminated bottles with a capacity of 1.5 L. The bottles were stored in thermal boxes and sent for analysis to the Water, Soil and Plant Tissue Analysis Laboratory of Federal Institute of Ceará (IFCE Campus Iguatu), and to the Integrated Fresh Water and Wastewater Laboratory of Federal Institute of Ceará (IFCE Campus Fortaleza).

The attributes were compared with the pertinent Brazilian legislation on the classification of water sources, which is provided for in Resolution No. 357 of 2005 of the National Environment

Council (CONAMA). This resolution classifies the fresh, brackish and salt waters of the National Territory, which are classified, according to the quality required for their predominant uses, into thirteen quality classes. Thus, freshwater is classified into special class (potable water supplies, with disinfection), class 1 (potable water supplies, after simplified treatment), class 2 (potable water supplies, after conventional treatment) and class 3 (potable water supplies, after conventional or advanced treatment).

Table 1. Evaluated physical and chemical attributes and respective analytical method.

Attribute	Analytical Method
Secchi Transparency (m)	Secchi Disk
Turbidity (NTU)	Turbidimetric
pH	Potentiometric
Apparent Colour (uH)	Colorimetric
Electrical Conductivity (dS m^{-1})	Conductivimetric
Total Solids — TS (mg L^{-1})	Drying at 103–105 °C
Total Phosphorous (mg L^{-1})	Spectrophotometric — Ascorbic acid
Soluble Orthophosphate (mg L^{-1})	
TKN (mg L^{-1})	Spectrometric — Macro-Kjeldahl distillation
Ammonia (mg L^{-1})	followed by Direct Nesslerisation
Nitrate (mg L^{-1})	Spectrophotometric — Sodium salicylate

Cyanobacteria

To analyse the phytoplankton, 500 mL of water was collected using a 20 µm plankton net and then placed in carefully washed amber flasks containing 20 mL of buffered formalin. The entire collection process was carried out as recommended by Apha, Awwa and Wef (2005) and Bicudo and Menezes (2006). The collected material was analysed at the IFCE Campus Fortaleza laboratory. Cyanobacteria were quantified by analysing the sediment in a Sedgewick–Rafter chamber using the Utermöhl method, which enables the organisms present in a known volume to be counted.

Statistical analysis

A descriptive analysis of the data was carried out to identify the distribution of physical and chemical attributes over space and time. Principal component analysis (PCA) was used to identify the species of cyanobacteria with the highest degree of explicability for total variance. Cluster analysis (CA) was used to classify similar groups of cyanobacteria. Similarity was estimated from the square of the Euclidean distance, and Ward's method was used for the clustering algorithm. For the above analysis, Statistical Package for the Social Sciences (SPSS) v.16.0 was used. Canonical correlation analysis (CCA) was used to observe the effects of the physical and chemical attributes of cyanobacteria species, and PAST software was used for this analysis.

RESULTS AND DISCUSSION

Physical and chemical attributes

The pH values were higher during the rainy season than during the dry season (Tables 2 and 3). This is related to the dissolution of carbonates and bicarbonates that occurs with the runoff process in alkaline soils; however, values during both periods remained within the range of 6.0 to 9.0, specified by CONAMA Resolution No. 357 of 2005, for all classes of freshwater (BRASIL, 2005).

Electrical conductivity (EC) also showed higher values during the rainy season, with extreme values recorded at the main intake of the Orós reservoir. This is related to an increase in the ionic strength of the salts formed from the weathering of rocks and transported by runoff. In a study of seven reservoirs in the state of Ceará, Sales et al. (2014) found EC values ranging from 0.51 to 2.15 dS m^{-1} for waters from reservoirs of the metropolitan basin of Ceará, while the mean values for the Orós reservoir did not exceed 0.32 and 0.34 dS m^{-1} during the rainy and dry seasons, respectively.

With the attributes of turbidity, apparent colour and total solids, the values were always higher during the rainy season, the opposite being found for transparency; it can be seen that these physical attributes express the effect of runoff in areas with a great potential for erosion and sediment generation (ROCHA; ANDRADE; LOPES, 2015). Point P2 presented the highest values for these attributes during both periods, demonstrating the influence of the River Jaguaribe as the main tributary, due to its large drainage area (22,969.06 km^2).

According to CONAMA Resolution No 357 of 2005, the mean values for turbidity during both periods were within the maximum permitted values for class 1 freshwater, which are less than 40 uT. The legislation determines maximum values for true colour, which is the colour of the filtered water (disregarding turbidity), and specifies values for class 2 freshwaters only, of up to 75 mg Pt/L or 75 uH. All points presented lower values than specified in the legislation, except for P2 during the rainy season; however, it should be noted that the attribute under evaluation was apparent colour, so that part of the colour is a result of turbidity. As for Total Solids, the legislation determines a maximum value of 500 mg.L^{-1} for class 1 freshwater, whereas the mean values at each point during both periods, were less than those specified by the legislation.

Table 2. Descriptive analysis of physical and chemical attributes during the rainy season by collection point (EC - electrical conductivity; TS - total solids; Transp. - transparency; TKN, -total Kjeldahl nitrogen; TP - total phosphorus; SO - soluble orthophosphate).

Attribute	Statistic	Collection Point						
		1	2	3	4	5	6	7
pH	Mean	8.20 ± 0.30	8.16 ± 0.32	8.20 ± 0.40	8.44 ± 0.60	8.40 ± 0.42	8.50 ± 0.37	8.67 ± 0.20
	Amplitude	7.70 - 8.47	7.70 - 8.60	7.50 - 8.50	7.90 - 9.40	7.70 - 8.80	8.20 - 9.10	8.45 - 9.00
	CV (%)	3.66	3.92	4.88	7.11	5.00	4.35	2.31
EC (µS m^{-1})	Mean	320 ± 9	300 ± 6	280 ± 6	280 ± 3	290 ± 3	280 ± 4	270 ± 4
	Amplitude	190 - 430	210 - 350	190 - 330	260 - 320	260 - 330	230 - 340	230 - 330
	CV (%)	27.78	19.87	21.66	10.56	10.49	14.18	14.65
Turbidity (uT)	Mean	11.66 ± 2.54	26.40 ± 8.96	12.34 ± 2.16	6.92 ± 2.70	6.32 ± 1.76	5.76 ± 1.57	6.96 ± 2.44
	Amplitude	8.00 - 14.20	17.00 - 36.00	10.00 -15.00	3.00 - 9.30	4.70 - 9.00	4.00 - 7.80	4.00 - 9.60
	CV (%)	21.78	32.92	17.50	39.02	27.85	27.26	35.06
Apparent Colour (uH)	Mean	62.6 ± 22.3	114.4 ± 15.1	65.8 ± 17.1	34.6 ± 14.2	33.4 ± 10.4	28.6 ± 12.7	40.6 ± 10.5
	Amplitude	39 - 95	94 - 136	46 - 92	19 - 56	17 - 45	12 - 40	33 - 59
	CV (%)	35.56	13.16	26.02	40.90	31.02	44.48	25.86
TS (mg L^{-1})	Mean	203.4 ± 56.4	211.6 ± 20.7	193.4 ± 34.5	177.4 ± 25.4	182 ± 14.9	185.6 ± 50.2	183.8 ± 19.2
	Amplitude	155 - 298	180 - 228	138 - 223	133 - 195	159 - 199	151 - 274	164 - 210
	CV (%)	27.74	9.78	17.82	14.32	8.18	27.04	10.45
Transp. (m)	Mean	0.79 ± 0.16	0.42 ± 0.17	0.72 ± 0.11	1.30 ± 0.53	1.11 ± 0.51	1.22 ± 0.61	1.40 ± 0.60
	Amplitude	0.68 - 1.08	0.18 - 0.60	0.60 - 0.85	0.88 - 2.20	0.67 - 2.00	0.67 - 2.20	0.85 - 2.30
	CV (%)	20.25	40.48	15.28	40.77	45.95	50.00	42.86
TKN (mg L^{-1})	Mean	0.78 ± 0.18	0.75 ± 0.24	0.87 ± 0.21	0.95 ± 0.27	0.96 ± 0.20	0.87 ± 0.23	0.83 ± 0.23
	Amplitude	0.61 - 1.06	0.49 - 1.10	0.62 - 1.19	0.66 - 1.26	0.69 - 1.21	0.50 - 1.10	0.53 - 1.16
	CV (%)	23.08	32.00	24.14	28.42	20.83	26.43	27.71
Total Ammonia (mg L^{-1})	Mean	0.11 ± 0.05	0.09 ± 0.06	0.14 ± 0.09	0.17 ± 0.08	0.19 ± 0.12	0.15 ± 0.09	0.17 ± 0.10
	Amplitude	0.05 - 0.17	0.03 - 0.18	0.07 - 0.24	0.08 - 0.29	0.06 - 0.35	0.05 - 0.23	0.07 - 0.28
	CV (%)	45.45	66.67	64.29	47.06	63.16	60.00	58.82
Nitrate (mg L^{-1})	Mean	0.08 ± 0.05	0.11 ± 0.08	0.07 ± 0.03	0.12 ± 0.07	0.12 ± 0.13	0.10 ± 0.06	0.09 ± 0.10
	Amplitude	0.02 - 0.13	0.01 - 0.19	0.05 - 0.11	0.08 - 0.22	0.03 - 0.3	0.04 - 0.15	0.01 - 0.24
	CV (%)	62.50	72.73	42.86	58.33	108.33	60.00	111.11
TP (mg L^{-1})	Mean	0.08 ± 0.02	0.09 ± 0.05	0.22 ± 0.27	0.08 ± 0.12	0.11 ± 0.14	0.16 ± 0.18	0.09 ± 0.06
	Amplitude	0.06 - 0.11	0.03 - 0.15	0.05 - 0.70	0.01 - 0.29	0.03 - 0.35	0.03 - 0.45	0.02 - 0.16
	CV (%)	25.00	55.56	122.73	150.00	127.27	112.50	66.67
SO (mg L^{-1})	Mean	0.05 ± 0.05	0.07 ± 0.05	0.06 ± 0.06	0.06 ± 0.08	0.04 ± 0.05	0.03 ± 0.03	0.03 ± 0.01
	Amplitude	0.01 - 0.13	0.04 - 0.15	0.01 - 0.17	0.01 - 0.15	0.01 - 0.12	0.00 - 0.05	0.01 - 0.04
	CV (%)	100.00	71.43	100.00	133.33	125.00	100.00	33.33

Regarding the nitrogen fractions (Tables 2 and 3), higher values for TKN and ammonia were found during the rainy season than in the dry season, with the opposite being found for nitrate (except P2). This is because of the greater supply of nitrogen from areas cultivated using nitrogen fertiliser and from areas of livestock activity. In addition to farming activity, the nitrogen content can be attributed to the low percentage of households (11.22%) connected to the sewage system in the Orós basin (LOPES et al., 2014). Despite the diffuse supply of nitrogen to the waters of the Orós reservoir, the mean values for total ammonia and nitrate during the dry and rainy seasons were below the standards for class I freshwater specified by CONAMA Resolution No. 357 of 2005.

Table 3. Descriptive analysis of physical and chemical attributes during the dry season by collection point (EC - Electrical Conductivity, TS - Total Solids, Transp. - Transparency, TKN - Total Kjeldahl Nitrogen, TP - Total Phosphorus, SO - Soluble Orthophosphate).

Attribute	Statistic	Collection Point						
		1	2	3	4	5	6	7
pH	Mean	8.09 ± 0.36	8.11 ± 0.42	8.22 ± 0.52	8.39 ± 0.46	8.44 ± 0.46	7.88 ± 0.31	7.95 ± 0.09
	Amplitude	7.58 - 8.44	7.44 - 8.57	7.37 - 8.76	7.70 - 8.92	7.76 - 9.01	8.40 - 8.15	7.81 - 8.03
	CV (%)	4.45	5.18	6.33	5.48	5.45	3.93	1.13
EC ($\mu S\ m^{-1}$)	Mean	280 ± 140	300 ± 8	220 ± 2	250 ± 5	320 ± 170	350 ± 190	250 ± 6
	Amplitude	200 - 530	250 - 430	200 - 260	190 - 300	190 - 620	190 - 690	180 - 290
	CV (%)	49.30	27.02	9.05	19.84	53.97	54.76	24.39
Turbidity (uT)	Mean	11.7 ± 8.6	21.9 ± 13.1	13.6 ± 10.4	5.2 ± 1.2	5.6 ± 2.0	3.1 ± 0.4	2.3 ± 0.8
	Amplitude	6.00 - 26.70	7.50 - 37.30	6.50 -31.70	3.30 - 6.40	3.20 - 7.90	2.70 - 3.50	1.10 - 3.20
	CV (%)	73.29	59.64	76.13	23.26	35.36	12.26	34.65
Apparent Colour (uH)	Mean	58.2 ± 28.7	67.5 ± 26.4	59.6 ± 28.4	35.1 ± 8.4	33.9 ± 5.5	25.7 ± 9.1	17.8 ± 5.7
	Amplitude	34.5 - 107	45.5 - 106	40 - 109	27.5 – 48	26 - 39	14.5 - 38	11 – 26
	CV (%)	49.33	39.10	47.67	23.93	16.11	35.33	31.97
TS ($mg\ L^{-1}$)	Mean	171.6 ± 17.3	190.2 ± 38.0	176.0 ± 26.0	161.6 ± 12.7	158.4 ± 26.9	182.2 ± 38.9	154.8 ± 13.5
	Amplitude	149 - 194	145- 240	135 - 203	147 - 176	132 - 189	151 - 249	133 - 167
	CV (%)	10.06	19.99	14.78	7.88	16.97	21.37	8.72
Transp. (m)	Mean	0.70 ± 0.18	0.49 ± 0.14	0.57 ± 0.20	0.82 ± 0.30	0.86 ± 0.26	1.82 ± 0.68	1.88 ± 0.38
	Amplitude	0.50 - 1.00	0.35 - 0.70	0.39 - 0.90	0.49 - 1.30	0.5 - 1.19	0.84 - 2.47	1.32 - 2.25
	CV (%)	25.71	28.57	35.09	36.59	30.23	37.36	20.21
TKN ($mg\ L^{-1}$)	Mean	0.49 ± 0.14	0.51 ± 0.19	0.60 ± 0.23	0.68 ± 0.11	0.65 ± 0.26	0.51 ± 0.16	0.48 ± 0.14
	Amplitude	0.31 - 0.70	0.31 - 0.76	0.31 - 0.95	0.57 - 0.82	0.23 - 0.93	0.26 - 0.70	0.31 - 0.61
	CV (%)	28.57	37.25	38.33	16.18	40.00	31.37	29.17
Total Ammonia ($mg\ L^{-1}$)	Mean	0.08 ± 0.05	0.07 ± 0.04	0.07 ± 0.07	0.12 ± 0.10	0.05 ± 0.03	0.06 ± 0.04	0.07 ± 0.04
	Amplitude	0.01 - 0.15	0.02 - 0.12	0.01 - 0.17	0.01 - 0.29	0.01 - 0.08	0.02 - 0.10	0.01 - 0.12
	CV (%)	62.50	57.14	100.00	83.33	60.00	66.67	57.14
Nitrate ($mg\ L^{-1}$)	Mean	0.19 ± 0.11	0.08 ± 0.04	0.27 ± 0.46	0.20 ± 0.16	0.13 ± 0.09	0.17 ± 0.10	0.12 ± 0.06
	Amplitude	0.08 - 0.35	0.03 - 0.11	0.01 - 1.06	0.05 - 0.45	0.03 - 0.24	0.08 - 0.32	0.08 - 0.22
	CV (%)	57.89	50.00	170.37	80.00	69.23	58.82	50.00
TP ($mg\ L^{-1}$)	Mean	0.10 ± 0.05	0.08 ± 0.01	0.09 ± 0.06	0.07 ± 0.03	0.07 ± 0.05	0.06 ± 0.02	0.06 ± 0.03
	Amplitude	0.06 - 0.16	0.06 - 0.09	0.02 - 0.17	0.04 - 0.10	0.01 - 0.15	0.04 - 0.08	0.04 - 0.09
	CV (%)	50.00	12.50	66.67	42.86	71.43	33.33	50.00
SO ($mg\ L^{-1}$)	Mean	0.05 ± 0.05	0.04 ± 0.04	0.05 ± 0.04	0.02 ± 0.01	0.02 ± 0.02	0.02 ± 0.02	0.03 ± 0.03
	Amplitude	0.01 - 0.13	0.01 - 0.10	0.01 - 0.10	0.01 - 0.03	0.01 - 0.05	0.01 - 0.04	0.01 - 0.07
	CV (%)	100.00	100.00	80.00	45.00	100.00	100.00	100.00

The values for TP and SO were higher during the rainy season, except at P1 for TP. These higher values are related to the input of nutrients from surface runoff (MOLISANI et al., 2013). The mean values for TP during both periods were greater than the value specified by CONAMA Resolution 357 of 0.02 mg L^{-1} for class II water.

Cyanobacteria

Of the 17 species of cyanobacteria under investigation, it was found that only ten, distributed over five components, explained 72.47% of the data (Table 4). The Kaiser-Meyer-Olkin test (KMO) showed a value of 0.54, and Bartlett's test of sphericity was significant ($p<0.05$), indicating that the data adjusted well to the model.

The species of cyanobacteria that make up the first component, C1, are typical of the functional groups S1/R (*Planktothrix* sp.) and Tc (*Gloethece* sp.), whose shared characteristics include the eutrophic environments of slowly flowing stable waters (PADISÁK; CROSSETTI; NASELLI-FLORES, 2009). The species of cyanobacteria that form the C2 component are exclusive to the functional groups Sn (*Cylindrospermopsis* spp.) and S1 (*Geitlerinema* spp.), and are typical of mixed environments; they can occur in the deeper layers of tropical lakes, and can therefore tolerate dark environmental conditions and are sensitive to the current (REYNOLDS et al., 2002; PADISÁK; CROSSETTI; NASELLI-FLORES, 2009).

The species with the highest weighting in components C3 and C5 comprise the functional groups Reynolds Lm and M (*Microcystis* sp.) and K (*Aphanocapsa* spp.), which are of the same order, *Chroococcales*, and M (*Microcystis* sp.) and H1 (*Aphanizomenon* sp.), respectively, and occur in eutrophic or hypereutrophic environments of small and medium-sized lakes. They are sensitive to the current, mixed deep waters and low total light (REYNOLDS et al., 2002; RANGEL et al., 2016). Finally, the functional groups Tc (*Phormidium* sp.) and Lm (*Coelomoron* sp.) are found in the fourth component, originating in eutrophic to hypereutrophic waters, slowly flowing small or medium-sized aquatic environments, sensitive to current and to low total light (PADISÁK; CROSSETTI; NASELLI-FLORES, 2009).

Table 4. Factorial load matrix of transformed variables using the varimax algorithm for the selected principal components of cyanobacteria species in the Orós reservoir.

No	Variable	Component					C*
		C1	C2	C3	C4	C5	
1	*Planktothrix sp.*	0.892	0.071	-0.014	0.048	-0.027	0.804
2	*Gloeothece sp.*	0.883	-0.062	0.037	-0.016	0.006	0.786
3	*Cylindrospermopsis spp.*	-0.101	0.890	-0.096	0.010	-0.042	0.814
4	*Geitlerinema spp.*	0.151	0.830	0.303	-0.028	-0.007	0.805
5	*Microcystis sp.*	-0.127	0.010	0.891	-0.089	-0.006	0.818
6	*Aphanocapsa spp.*	0.429	0.243	0.643	0.158	-0.175	0.712
7	*Phormidium sp.*	-0.148	0.088	-0.012	0.746	0.198	0.626
8	*Coelomoron sp.*	0.267	-0.125	0.013	0.681	-0.193	0.588
9	*Aphanizomenon sp.*	0.024	-0.082	0.007	-0.161	0.832	0.725
10	*Microcystis aeruginosa*	-0.070	0.042	-0.133	0.366	0.641	0.570
	Total	1.908	1.582	1.328	1.217	1.212	
	variance (%)	19.079	15.819	13.280	12.171	12.121	
	accumulated variance (%)	19.079	34.898	48.178	60.349	72.470	

According to the Ministry of Health (Brazil), the above-mentioned species that constitute the genera *Aphanizomenon*, *Phormidium*, *Planktothrix*, and *Cylindrospermopsis*, are neurotoxin producers. However, no human deaths related to this toxin have been reported. The most common type of poisoning involving cyanobacteria is related to hepatotoxins, with the best-known case of hepatotoxin poisoning occurring in a dialysis clinic in the city of Caruaru. Of the above-mentioned species, those with the ability to synthesise the toxin belong to the genera *Aphanocapsa*, *Microcystis*, *Phormidium*, *Planktothrix*, *Cylindrospermopsis*, and *Aphanizomenon*; however, all cyanobacteria are potential toxin producers (BRASIL, 2015).

Based on the species obtained through PCA, a CA of the data for the rainy and dry seasons was performed (Figure 3). Four groups formed in the rainy season (Figure 3A), with three groups forming during the dry season (Figure 3B). The cutoff point that defined the number of groups was calculated based on the first big jump between the differences in consecutive clustering coefficients. The distance value of the cutoff point during the rainy season was greater than 3.17, while, during the dry season, the distance was greater than 4.68.

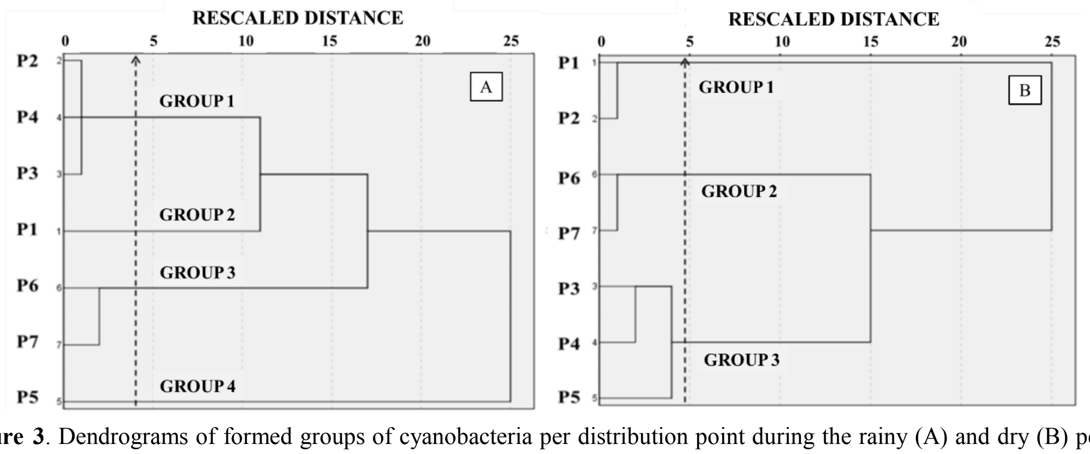

Figure 3. Dendrograms of formed groups of cyanobacteria per distribution point during the rainy (A) and dry (B) periods in the Orós reservoir.

Formation of the groups was influenced by climate seasonality, given that the groups formed were different for the two periods, with the exception of points P6 and P7; this is related to the stability of these points, a result of their proximity to the dam. According to Reynolds et al. (2002), separation of the algae (among them, cyanobacteria) occurs because of their morphology and to a great extent coincides with their distribution across the different types of habitats, which are distinguished by accessibility to light and to all nutrient resources.

The distribution of functional groups reflects the physical, chemical, and hydrological differences related to the seasonal and spatial variability of the system. According to Rangel et al. (2016), the lentic environments created by dams promote differences in turbulence and in the availability of light and nutrients, with a consequent heterogeneous distribution of biological communities.

The concentration of cyanobacteria was higher during the dry season compared to the rainy season (Tables 5 and 6). Concentrations of these organisms are higher during the dry season due to greater availability of sunlight and the greater transparency of the water column. Lopes et al. (2014) stated that primary productivity depends not only on the availability of nutrients, but also on other factors such as the amount of sunlight penetrating the water.

It can also be seen from Table 5, that group 1 from the rainy season is formed by the main tributaries (points P2, P3, and P4) of the Orós, which is characterised by waters with a high concentration of solids and nutrients (characterising them as eutrophic to hypereutrophic), and greater turbulence (due to the supply of rainwater).

Group 1 is composed of *Phormidium* sp. (Tc) and *Coelomoron* sp. (Lm), which have the highest weightings in component C4 (Table 4), and by *Gloeothece* sp. (Tc), which is part of the same functional group as *Phormidium* sp. They showed a higher concentration than other groups from the same species, but lower concentrations than some of the species in their own group. This is because of turbulence at the points that form the group.

Table 5. Composition of cyanobacteria (ind/mL) by group during the rainy season.

Variable	Statistic	Group			
		1	2	3	4
Aphanizomenon sp.	Mean	70.2 ± 136.9	12.2 ± 29.8	190.2 ± 428.0	22.0 ± 53.9
	Amplitude	0 – 344	0 – 73	0 - 1062	0 - 132
	CV (%)	195.0	244.3	225.0	245.0
Aphanocapsa spp.	Mean	3039.2 ± 2402.2	3964.5 ± 2739.3	2421.0 ± 2685.4	1502 ± 1185.2
	Amplitude	489 – 7512	1749 - 8832	172 - 7396	318 - 3754
	CV (%)	79.04	69.1	110.9	78.9
Coelomoron sp.	Mean	4.8 ± 9.2	2.8 ± 6.9	1.5 ± 3.7	1.83 ± 4.5
	Amplitude	0 – 23	0 – 17	0 - 9	0 - 11
	CV (%)	191.7	246.4	246.6	245.9
Cylindrospermopsis sp	Mean	36.3 ± 41.1	35.8 ± 66.4	1021.7 ± 1492.2	383.2 ± 745.7
	Amplitude	0 – 101	0 – 165	0 - 3993	0 - 1863
	CV (%)	113.2	185.5	146.1	194.6
Geitlerinema sp.	Mean	80.3 ± 88.6	249.8 ± 439.9	443.7 ± 591.3	31.3 ± 76.8
	Amplitude	0 – 216	0 – 1104	0 - 1573	0 - 188
	CV (%)	110.3	176.1	133.3	245.4
Gloeothece sp.	Mean	3.2 ± 7.8	2.8 ± 7.0	2.5 ± 4.0	ND
	Amplitude	0 – 19	0 – 17	0 - 9	ND
	CV (%)	243.8	250.0	160.0	ND
Microcystis sp.	Mean	20.0 ± 36.1	205.0 ± 482.2	23.3 ± 48.5	5.8 ± 9.9
	Amplitude	0 – 93	0 – 1189	0 - 122	0 - 24
	CV (%)	180.5	235.2	208.2	170.7
Microcystis aeruginosa	Mean	8.8 ± 12.3	9.67 ± 16.8	3.5 ± 8.6	5.3 ± 9.4
	Amplitude	0 – 29	0 – 41	0 - 21	0 - 23
	CV (%)	139.8	173.7	245.7	177.4
Phormidium sp.	Mean	2.0 ± 4.9	ND	1.5 ± 3.7	ND
	Amplitude	0 – 12	ND	0 - 9	ND
	CV (%)	245.0	ND	246.7	ND
Planktothrix sp	Mean	ND	ND	ND	ND
	Amplitude	ND	ND	ND	ND
	CV (%)	ND	ND	ND	ND

Group 2 from the rainy season is formed by point P1, which is located downstream of point P2 (River Jaguaribe) and consequently receives an input of nutrients from P2, which, together with less turbulence (compared with P2), favours *Aphanocapsa* spp. (functional group K) and *Microcystis* sp. (functional group M), which constitute C3, and *Microcystis aeruginosa* (functional group M), which is part of the same functional group as *Microcystis* sp.

Group 3 from the rainy season is governed by species from the functional groups Sn (*Cylindrospermopsis* spp.) and S1 (*Geitlerinema* spp.) that formed C2, and from H1 (*Aphanizomenon* sp.), which presented the highest concentrations in relation to the other groups of the same species because it is favoured by the conditions promoted by points P6 and P7, which are located near the dam, where the water is deeper with little current.

However, Group 4 from the rainy season is characterised by a low absolute concentration of organisms, with the lack of development of three species, a result of greater water flow caused by the rainfall, and by predation from fish farming.

Group 1 from the dry season (Table 6) is formed by points P1 and P2, where P2 is the River Jaguaribe, which is the main tributary of the Orós and contributes to a high concentration of nutrients. This group was governed by *Gloeothece* sp. (Tc) and *Planktothrix* sp. (S1/R), the species that formed C1, *Phormidium* sp. (Tc), and *M. aeruginosa* (M). *Gloeothece* sp. and *Phormidium* sp. are part of the same functional group and have a tendency toward the environmental characteristics of point P2, as was seen in group 1 from the rainy season. The species *M. aeruginosa* is related to the characteristics of point P1, which is also seen in group 2 from the rainy season.

Group 2 from the dry season was governed by *Cylindrospermopsis* sp. from the functional group Sn, which occurs in the deepest layers of tropical lakes and is sensitive to currents. These characteristics are found at points P6 and P7 (Figure 1), which are located close to the dam and consequently have greater depths and smaller currents.

Finally, group 3 from the dry season consisted of points P3, P4, and P5. In this group the main species were: *Aphanocapsa* spp. (K), *Microcystis* sp. (M), *Coelomoron* sp. (Lm) and *Geitlerinema* sp. (S1). *Aphanocapsa* spp. and *Microcystis* sp. formed component 3 in the PCA, demonstrating the strong link between these species, since they were also together in group 2 from the rainy season. *Coelomoron* sp, was seen at point P4 during the rainy season, which demonstrates that this species has a bias towards this environment. However, *Geitlerinema* sp. tended to move toward these points because of the conditions afforded by the dry season, which corresponds to functional group S1 of a tropical lake with little current.

Table 6. Composition of cyanobacteria (ind/mL) by group during the dry season.

Variable	Statistic	Group		
		1	2	3
Aphanizomenon sp.	Mean	ND	ND	ND
	Amplitude	ND	ND	ND
	CV (%)	ND	ND	ND
Aphanocapsa spp.	Mean	5154.0 ± 4161.2	2867.4 ± 691.9	6385.8 ± 5218.2
	Amplitude	2252 – 12331	2149 - 3916	1261 – 13493
	CV (%)	80.7	24.1	81.7
Coelomoron sp.	Mean	37.0 ± 33.68	19.8 ± 26.23	37.4 ± 60.6
	Amplitude	0 – 81	0 – 64	0 – 144
	CV (%)	91.0	132.5	162.0
Cylindrospermopsis sp.	Mean	67.6 ± 95.1	732.4 ± 1135.8	471.4 ± 1004.8
	Amplitude	0 – 200	0 – 2716	0 – 2268
	CV (%)	140.7	155.1	213.2
Geitlerinema sp.	Mean	258.6 ± 319.2	246.0 ± 418.89	1273.6 ± 1022.0
	Amplitude	19 – 813	0 – 987	189 – 2325
	CV (%)	123.5	170.3	80.2
Gloeothece sp.	Mean	18.2 ± 26.2	ND	11.8 ± 13.9
	Amplitude	0 – 63	ND	0 – 34
	CV (%)	144.0	ND	117.8
Microcystis sp.	Mean	17.2 ± 30.3	12.8 ± 9.2	51.2 ± 31.3
	Amplitude	0 – 70	0 – 25	24 – 87
	CV (%)	176.2	71.9	61.1
Microcystis aeruginosa	Mean	16.8 ± 17.4	11.2 ± 18.7	7.6 ± 11.0
	Amplitude	0 – 41	0 – 43	0 - 24
	CV (%)	103.6	167.0	144.7
Phormidium sp.	Mean	9.8 ± 21.9	3.3 ± 7.2	ND
	Amplitude	0 – 49	0 – 16	ND
	CV (%)	223.5	218.2	ND
Planktothrix sp.	Mean	77.8 ± 160.4	23.2 ± 23.4	4.8 ± 10.7
	Amplitude	0 – 364	0 – 53	0 – 24
	CV (%)	206.2	100.9	223.0

Among the species that contributed to forming the groups and showed the highest absolute population density were *Aphanocapsa* spp., *Cylindrospermopsis* sp., and *Geitlerinema* sp. during the rainy and dry seasons. The highest concentrations of cyanobacteria occurred in group 2 (P1, Conceição Bay) during the rainy season, and in group 3 (P3, River Faé; P4, River Madeira Cortada; P5, Giqui) during the dry season. The genera showing the greatest abundance are represented by three functional groups, which are typical of eutrophic environments, shallow water, and/or mixed and warm-water zones: K (*Aphanocapsa* spp.), S1 (*Cylindrospermopsis* sp.), and SN (*Geitlerinema* sp.) (REYNOLDS et al., 2002).

Canonical correlation analysis between cyanobacteria and physical and chemical attributes

Based on the CCA for the rainy season (Figure 4), the formation of four groups can be seen, confirming the result of the cluster analysis (Figure 3A). Points P2, P3 and P4 formed one group. Point P1 formed another group, which showed a slight difference from the first group. Points P6 and P7 formed the third group, and point P5 was isolated from the others due to its dissimilarity.

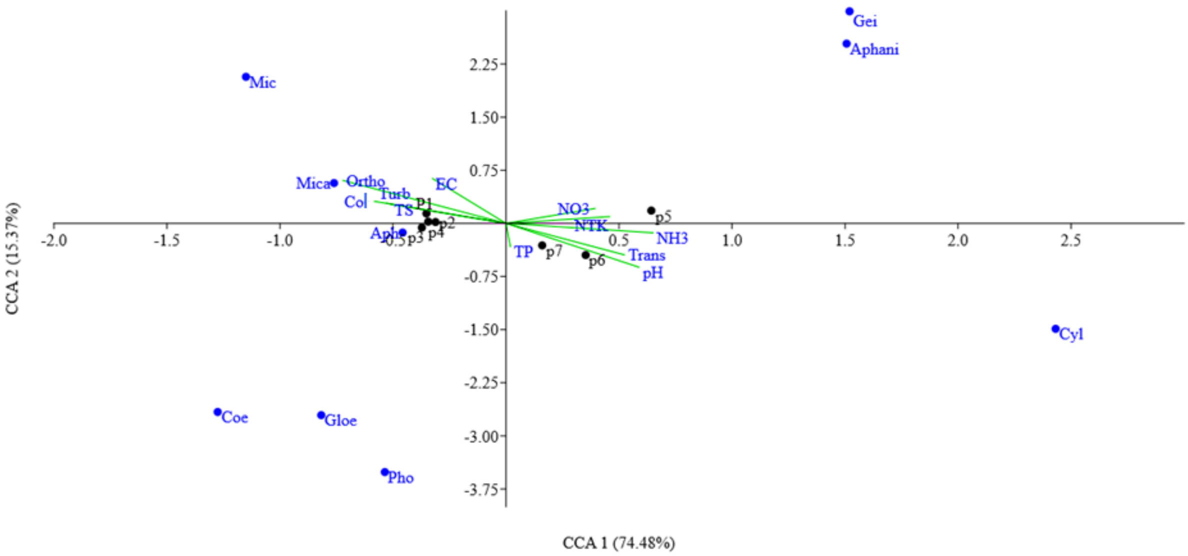

Figure 4. Canonical correlation analysis for the rainy season (EC, electrical conductivity; Turb, turbidity; Col, colour; TS, total solids; Trans, transparency; NTK, total Kjeldahl nitrogen; NH3, total ammonia; NO3, nitrate; TP, total phosphorus; Ortho, soluble orthophosphate; Aphani, *Aphanizomenon* sp.; Aph, *Aphanocapsa* spp.; Coe, *Coelomoron* sp.; Cyl, *Cylindrospermopsis* sp.; Gei, *Geitlerinema* sp.; Gloe, *Gloeothece* sp.; Mic, *Microcystis* sp.; Mica, *M. aeruginosa*; Pho, *Phormidium* sp.).

The environmental variables that determine the dynamics at points P1, P2, P3 and P4 are colour, turbidity, TS, EC and orthophosphate, which favoured the development of species *Microcystis* sp., *M. aeruginosa* and *Aphanocapsa* spp. At point P5, the variables total nitrogen and nitrate were responsible for the response of *Geitlerinema* sp. and *Aphanizomenon* sp. At points P6 and P7, the transparency, pH and ammonia had a greater influence on species *Cylindrospermopsis* sp. None of the water quality attributes used in the CCA for the rainy season were able to explain the distribution of *Phormidium* sp., *Coelomoron* sp., and *Gloeothece* sp.

For the dry period (Figure 5), the group comprising points P1 and P2 was formed, as seen in the cluster analysis (Figure 3B). Another group was formed by points P5, P6 and P7; however, the same was not found for P3 and P4, which showed dissimilarities to the other points.

The water quality that directed the dynamics at points P1 and P2 was mainly TS, which favoured the development of species *Aphanocapsa* spp., *Phormidium* sp., *Coelomoron* sp., *M. aeruginosa* and *Planktothrix* sp. For point P3, the variables pH, colour, turbidity, TP and orthophosphate created conditions for the development of species *Coelomoron* sp. At point P4, it was the influence of the nitrogenous fractions TKN, ammonia and nitrate on species Microcystis sp. and Geitlerinema sp. At points P5, P6, and P7, the high transparency and EC were responsible for the response of species *Cylindrospermopsis* sp.

Livestock activity is carried out close to points P3 and P4, while agriculture is practiced near points P2, P3, P4, P5 and P6, with fish-farming at points P1 and P5 (SILVA, 2013). Furthermore, the rainy season saw high rainfall (Figure 2), which contributed to a greater number of runoff events that helped recharge the reservoir. According to Rocha, Andrade and Lopes (2015), surface runoff is responsible for the high erosion potential and the generation of sediment. Point P2, at the inflow of the River Jaguaribe, was responsible for introducing a high suspended-sediment load from the erosive processes that occurred in the catchment basin of the Orós reservoir. According to Chaves et al. (2019), the presence of suspended sediments is related to the anthropogenic process in the upper Jaguaribe basin, which is drained by the River Jaguaribe.

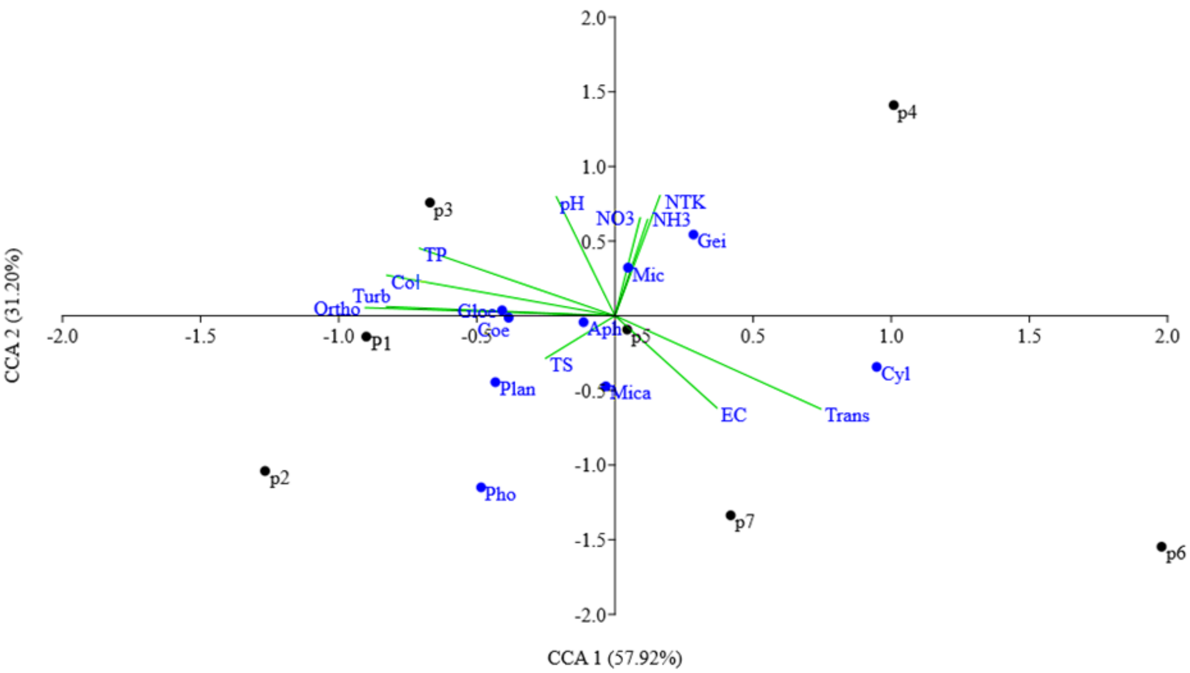

Figure 5. Canonical correlation analysis for the dry season (EC, electrical conductivity; Turb, turbidity; Col, colour; TS, total solids; Trans, transparency; NTK, total Kjeldahl nitrogen; NH3, total ammonia; NO3, nitrate; TP, total phosphorus; Ortho, soluble orthophosphate; Aphani, *Aphanizomenon* sp.; Aph, *Aphanocapsa* spp.; Coe, *Coelomoron* sp.; Cyl, *Cylindrospermopsis* sp.; Gei, *Geitlerinema* sp.; Gloe, *Gloeothece* sp.; Mic, *Microcystis* sp.; Mica, *M. aeruginosa*; Pho, *Phormidium* sp.; Plan, *Planktothrix* sp.).

CONCLUSIONS

Seasonality had a strong influence on the physical and chemical attributes of the water, creating different environmental conditions in the same reservoir. This reflected directly on the spatial distribution of the cyanobacteria, which formed groups based on three principal characteristics: total variance, functional groups, and environmental conditions.

The total nitrogen had a positive influence on the increase in population density, especially during the dry season; the reduction in this nutrient and the increase in cyanobacteria indicating that nitrogen limited the reactions that culminate in the proliferation of these organisms. This was not seen during the rainy season due to the greater supply of nitrogen from surface runoff.

The high values of physical attributes, mainly in the groups formed by points P1 and P2 in both periods, was a limiting factor for species proliferation, strengthening the impact of suspended solids from the waters of the River Jaguaribe on the dominant species.

The high transparency limited the proliferation of most species of cyanobacteria, with the exception of *Cylindrospermopsis* sp., which has a predilection for environments with a higher incidence of sunlight.

Finally, during both periods, the concentrations of cyanobacteria were high, especially in individuals with the potential to produce hepatotoxins, thereby leading to the risk of poisoning the users who collect and consume these waters directly from the Orós reservoir, which may become a public health problem.

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