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Seasonal dynamics and diversity of cyanobacteria in a eutrophied Urban River in Brazil

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ABSTRACT

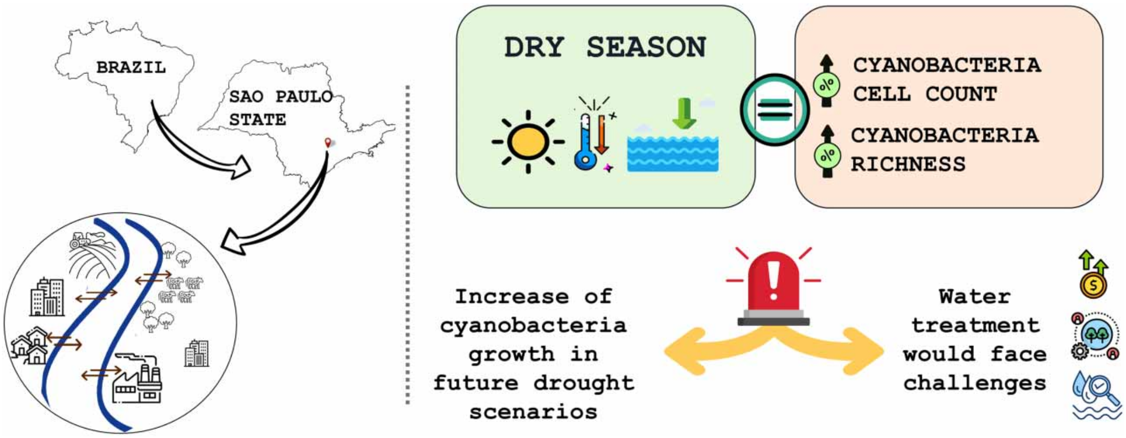
Surface water bodies are vulnerable to cyanobacteria overgrowth, primarily owing to nutrient enrichment, rising temperatures, and recurrent droughts. Regular cyanobacteria monitoring in water systems is crucial to prevent and manage health risks associated with toxin exposure. Surface water samples were collected from the Jundiai River in São Paulo State, Brazil for 3 years (2018–2022) to study the seasonal changes and species diversity of cyanobacteria. The study also aimed to understand the relationship between cyanobacteria abundance, climate, water quality, and hydrological parameters. Data analyses revealed a pattern of significantly elevated cyanobacterial cell counts during the dry season (DS), accompanied by an increase in the cyanobacterial species. The identified species poses a threat to water safety owing to the potential production of toxins, as well as causing unpleasant taste and odor. The DS is marked by higher nutrient concentrations and lower water flow. Phosphorus levels remain high, allowing cyanobacteria to grow without being limited by nutrients. In future scenarios, the primary concern for the Jundiai River is not temperature rise but droughts that create a stable environment for cyanobacteria proliferation. This research provides valuable data for river water users and contributes to a broader understanding of the global cyanobacterial dispersion.

Key words: cyanobacteria bloom, surface water bodies, tropical source water, urban water supply, water quality, water security

HIGHLIGHTS

- This pioneering Jundiai River study uncovers cyanobacterial diversity and count.
- Toxin-producing, taste and odor-causing species were identified.
- Investigation explores also cyanobacteria-environment links in Jundiai River.
- Temperature increase is not an issue for the cyanobacteria growth in Jundiai River.
- Cyanobacteria data warn of droughts in the tropics and implications for water utilities.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The Jundiai River, located in the Brazilian State of São Paulo, is environmentally and historically significant to the region. The intense development of anthropic activities (i.e., urbanization, industry, and agriculture), municipal and industrial effluent discharge, urban and rural runoff, and lack of proper vegetative protection of the banks have caused deterioration in the water quality. As a result of water pollution, the presence of cyanobacteria has been observed next to the Jundiai River basin outlet. In a regional context of water scarcity, the Jundiai River has become a strategic source for several municipal water supply systems; therefore, the knowledge of the seasonal dynamics of cyanobacteria is essential for proper water treatment and water safety.

Massive cyanobacterial development in water is associated with organoleptic concerns, toxicological issues (Newcombe *et al.* 2010), and poor water quality (Kuo *et al.* 2018). Nutrient availability, although directly related to cyanobacterial development, does not act in isolation for biomass growth, as other factors such as light, temperature, and water velocity are also essential in the growth process (Cunha *et al.* 2017). Tropical water bodies experience certain peculiarities, such as intense solar radiation and high water temperatures, which encourage phytoplankton nutrition absorption and enable high nutrient assimilation (Ludolf Gomes *et al.* 2012).

Cyanobacteria proliferation in rivers is a warning sign because it indicates deterioration in water quality. Evidence indicates an exponential increase in the abundance of cyanobacteria in subtropical aquatic ecosystems of South America, primarily driven by nutrient enrichment associated with the change in land-use patterns (Kruk *et al.* 2023). Increased nutrient concentrations associated with watershed fertilizer runoff, sewage discharge, reduced flow due to the installation of artificial structures, and increased water temperatures are often the causes of this disturbance (Park *et al.* 2021). Particularly in the subtropics, for example, the State of São Paulo, Brazil, riverine ecosystems are becoming increasingly susceptible to cyanobacterial development as temperatures rise owing to climate change (Haakonsson *et al.* 2017).

Periodic monitoring of cyanobacteria levels in water systems is critical to prevent and manage potential health risks associated with toxin exposure. This is particularly important in Brazil, where a large section of the population depends on surface water sources for water supply. In addition, currently, insufficient emphasis is being placed on monitoring and counting cyanobacterial diversity in river water systems that possess the potential to serve as a public water supply source. Therefore, this study aims to identify the seasonal dynamics and species diversity of cyanobacteria on Jundiai River (São Paulo, Brazil) and explore the relation of climate, water quality, and hydrological parameters with cyanobacteria abundance. This research provides valuable data for current and future users of the water of the Jundiai River, as well as contributes to a broader understanding of cyanobacterial dispersion globally.

2. METHODS

2.1. Study area and data collection

Surface water samples were collected for 3 years at a sampling site on the Jundiai River (23°11′42″ S and 47°16′0″ W), located in Salto City, São Paulo State, Brazil (Figure 1). Because the river course is surrounded by urbanized areas and it receives and concentrates pollution loads from the watershed before they flow through the outlet, the river course is characterized by a high trophic state. The Jundiai River study point is situated in a region that is suffering from a severe shortage of water supply. The public water supply in this area is under threat because of multiple factors, including the poor quality of ground and surface waters and the limited capacity of reservoirs.

The data on freshwater variables were collected from December 2018 to December 2022, according to the schedule in Table 1. The water sampling procedure followed rigorous guidelines, including laboratory internal Standard Operating Procedures (SOP 238, 230, and 239), Brazilian technical standards (ABNT NBR 9898/1987), and the Standard Methods for Examination of Water and Wastewater (23rd Edition 2017, Methods 1060 and 9060). These procedures were selected based on specific analysis objectives. The sampling was conducted at a similar schedule, approximately around noon, to ensure the reliability and consistency of the collection process.

The water quality parameters included one monthly sampling of cyanobacterial species diversity and total cell counting (CYAN cell mL^{-1}), chlorophyll-*a* (Chl-a), and other relevant parameters (such as ammoniacal nitrogen, biochemical oxygen demand ($BOD_{5,20}$), chemical oxygen demand (COD), color, dissolved oxygen (DO), nitrogen-nitrate, nitrogen-nitrite, pH, total dissolved solids, total phosphorus (TP), turbidity, thermotolerant coliforms, and water temperature). All analyses

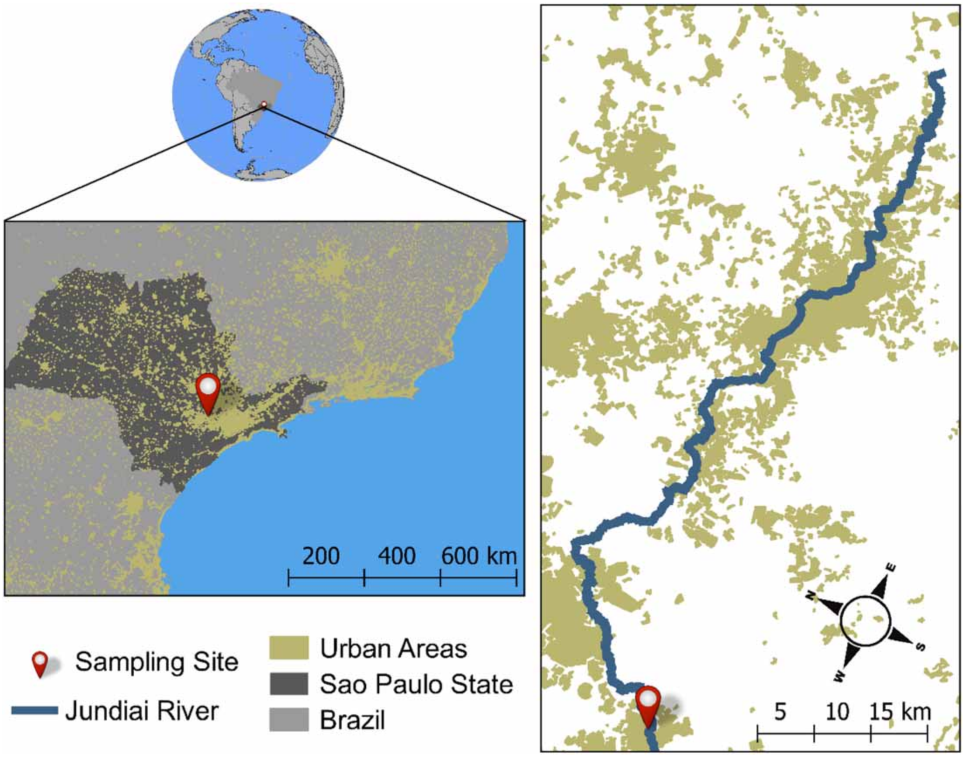


Figure 1 | Location of the sampling site on the Jundiai River.

were performed in an ISO/IEC 17025 accredited laboratory that conforms to the general standards for testing and calibration laboratory competence. The laboratory methods for all the analyses can be found in the Supplementary Material.

Summers in the studied area are hot and humid (Figure 2), while winters are moderate and dry. January is the rainiest month registering an average rainfall of 212 mm. The driest month has been August with average rainfall of 29 mm. For seasonal assessment, the year was divided into two main periods based on geographical characteristics: dry season (DS, April–October) and wet season (WS, November–March). The total accumulated rainfall for the given period was 4,307.6 mm, with 3,143.4 mm observed during the WS (averaging 149.69 mm per month) and 1,164.2 mm during the DS (averaging 43.11 mm per month).

The total number of samples obtained for each parameter were as follows: 35 (DS: 23; WS: 12) for cyanobacterial diversity, 41 (DS: 26; WS: 15) for cell counting, 43 (DS: 26; WS: 17) for chlorophyll-*a*, and 15 (DS: 10; WS: 5) for other water quality parameters. Furthermore, climatological variables including daily maximum, minimum, and mean temperatures, monthly precipitation, precipitation within the last 24 and 72 h, and hydrological parameters (i.e., flow rate) were collected. The climatic data were obtained from CIIAGRO (2023), while the hydrological data were acquired from DAEE (2023).

2.2. Statistical analysis

Descriptive statistics tools were used to organize, summarize, and characterize the data set. The seasonal variations were represented by box-and-whisker plots for the cyanobacteria cell counting and physicochemical parameters. The analysis of variance (ANOVA) was used to study the statistical significance of water quality metrics and cyanobacteria indicators across seasonal assessment (i.e., dry and wet seasons). Based on the data features and aiming to explore the correlation between the environmental factors (such as water quality parameters, climate variables, and flow rate) and cyanobacteria abundance, Spearman's rank correlation coefficient (ρ) was calculated. Univariate linear regression analysis with a confidence level limit of 95% (p-value < 0.05) was used to determine statistically significant relationships. For discussion purposes, p-values up to a confidence level of 10% (p-value < 0.1) are supplied. To minimize leverage in correlation and significance analyses, the outliers identified during preliminary data analysis were excluded. Outliers were identified through visual analysis of the data distribution and creation of scatter plots while considering the use of z-scores and modified

Table 1 | Sampling schedule by freshwater variable (2018–2022)

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Cyanobacteria count												•	2018
Cyanobacteria diversity													
Chlorophyll-*a*											•	•	
Other water quality parameters*											•		
Cyanobacteria count	•		•	•	•			•	•	•	•	•	2019
Cyanobacteria diversity									•	•	•	•	
Chlorophyll-*a*	•		•	•	•			•	•	•	•	•	
Other water quality parameters*													
Cyanobacteria count		•	•	•	•	•	•	•	•	•	•	•	2020
Cyanobacteria diversity		•	•	•	•	•	•	•	•	•	•	•	
Chlorophyll-*a*	•	•	•	•	•	•	•	•	•	•	•	•	
Other water quality parameters*						•	•						
Cyanobacteria count	•	•	•	•	•	•	•	•	•	•			2021
Cyanobacteria diversity	•	•	•	•	•	•	•	•	•	•			
Chlorophyll-*a*	•	•	•	•	•	•	•	•	•	•			
Other water quality parameters*	•						•						
Cyanobacteria count			•	•	•	•	•	•	•	•	•	•	2022
Cyanobacteria diversity			•	•	•	•	•	•	•	•	•	•	
Chlorophyll-*a*			•	•	•	•	•	•	•	•	•	•	
Other water quality parameters*			•	•	•	•	•	•	•	•	•	•	

[a]Ammoniacal nitrogen, biochemical oxygen demand ($BOD_{5,20}$), chemical oxygen demand (COD), color, dissolved oxygen, dissolved aluminum, nitrogen-nitrate, nitrogen-nitrite, pH, total dissolved solids, total phosphorus, turbidity, thermotolerant coliforms, total zinc, water temperature.

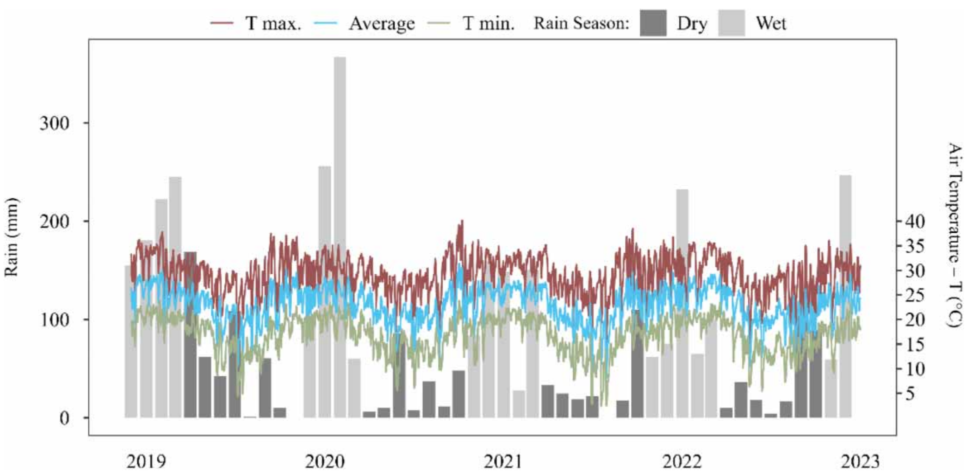


Figure 2 | Monthly precipitation averages and daily temperature ranges for the study area were recorded from December 2018 to 2022. Temperature data from the Integrated Center for Agrometeorological Information of the State of São Paulo (CIIAGRO 2023); precipitation data from the Department of Water and Electricity of the State of São Paulo (DAEE 2023).

z-scores, which were ultimately deemed unnecessary given the prominent deviations discernible through visual examination. All data visualization and statistical analyses were executed using the R programming language on RStudio (© 2009–2022 RStudio, PBC).

3. RESULTS AND DISCUSSION

The count of cyanobacteria cells in the Jundiai River, in Salto, SP reached the maximum levels throughout the dry months over the entire period monitored (Figure 3), reaching 21,190 cells mL^{-1} in May 2020, 15,537 cells mL^{-1} in October 2019, 13,371 cells mL^{-1} in June 2022, and 12,495 cells mL^{-1} in July 2021. In general, the WS showed lower concentrations of cyanobacteria cells, reaching maximums of 10,010 cells mL^{-1} in December 2018, 6,534 cells mL^{-1} in December 2022, and 5,332 cells mL^{-1} in November 2019.

The presence of cyanobacteria cells was detected in all samples; however, the months of January and February had the lowest cell counts, with 339 cells mL^{-1} in January 2021, 215 cells mL^{-1} in February 2021, and 370 cells mL^{-1} in February 2020. The cyanobacteria cell counts showed a clear tendency for cell growth throughout the DS of the year, particularly between May and August (Figure 3). A significant difference (p-value < 0.05) in the concentration of cells is observed between the DS and WS, with averages of 5,722 and 2,486 cells mL^{-1}, respectively.

The diversity of cyanobacteria showed temporal variation, a total of 17 distinct species identified over the course of the study period in the Jundiai River (Figure 4). January and February consistently exhibited the lowest species diversity among the samples. During January, *Pseudanabaena* sp. (34.51%) and *Oscillatoria* sp. (32.45%) were the predominant species, whereas *Aphanocapsa* sp. (47.86%) and *Pseudanabaena* sp. (40.17%) were the dominant species in February. The month of October exhibited the highest species richness, with a total of 13 distinct species identified. Furthermore, *Aphanocapsa* sp. accounted for the highest proportionate cell count (46.17%).

Throughout the year, *Pseudanabaena* sp. was consistently detected in the Jundiai River, while in nine other months, *Raphidiopsis* sp. (renaming from *Cylindropermopsis*) (March–August and October–December), *Aphanocapsa* sp. (February–May and July–November), and *Geitlerinema* sp. were also identified.

In general, at least 10 of all 17 reported species are potential producers of a wide range of toxins. Among those, *Aphanocapsa*, *Dolichospermum*, *Oscillatoria*, *Phormidium*, *Pseudanabaena*, *Merismopedia*, and *Microcystis* are microcystin-genera-producers (Chorus & Welker 2021). Furthermore, *Dolichospermum* and *Raphidiopsis* produce cylindrospermopsin (Chorus & Welker 2021). *Dolichospermum, Phormidium, Planktothrix*, and *Cuspidothrix* are producers of anatoxin-a (Chorus & Welker 2021). In addition, *Raphidiopsis* and *Planktothrix* also produce saxitoxin (Chorus & Welker 2021). Nevertheless, all cyanotoxin samples collected during the entire monitoring period exhibited concentrations below the detection limit (<0.1 μg L^{-1} for microcystin and cylindrospermopsin; < 0.08 μg L^{-1} for saxitoxin). Consequently, despite the presence of cyanotoxin-producing strains, the water of the Jundiai River did not exhibit detectable levels of microcystin, saxitoxin, or cylindrospermopsin.

During December and August, *Raphidiopsis* sp. was the dominant species, comprising >50% of the total number of cells in the monthly samples analyzed (77.05 and 58.35%, respectively). Notably, in the samplings conducted in October and December of 2022, this species accounted for 100% of the cells detected. *Raphidiopsis* sp., a cylindrospermopsin-producing cyanobacteria, was the most prevalent species during both sampling periods, accounting for 23.49 and 33.68% of total cell abundance during the DS and WS, respectively (Table 2).

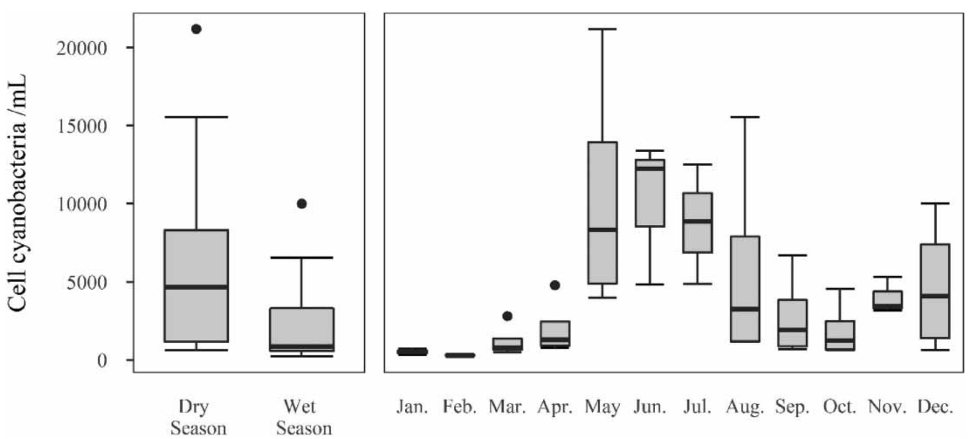


Figure 3 | Boxplot of seasonal and annual counting of cyanobacterial cells on the Jundiai River (Salto, São Paulo, Brazil).

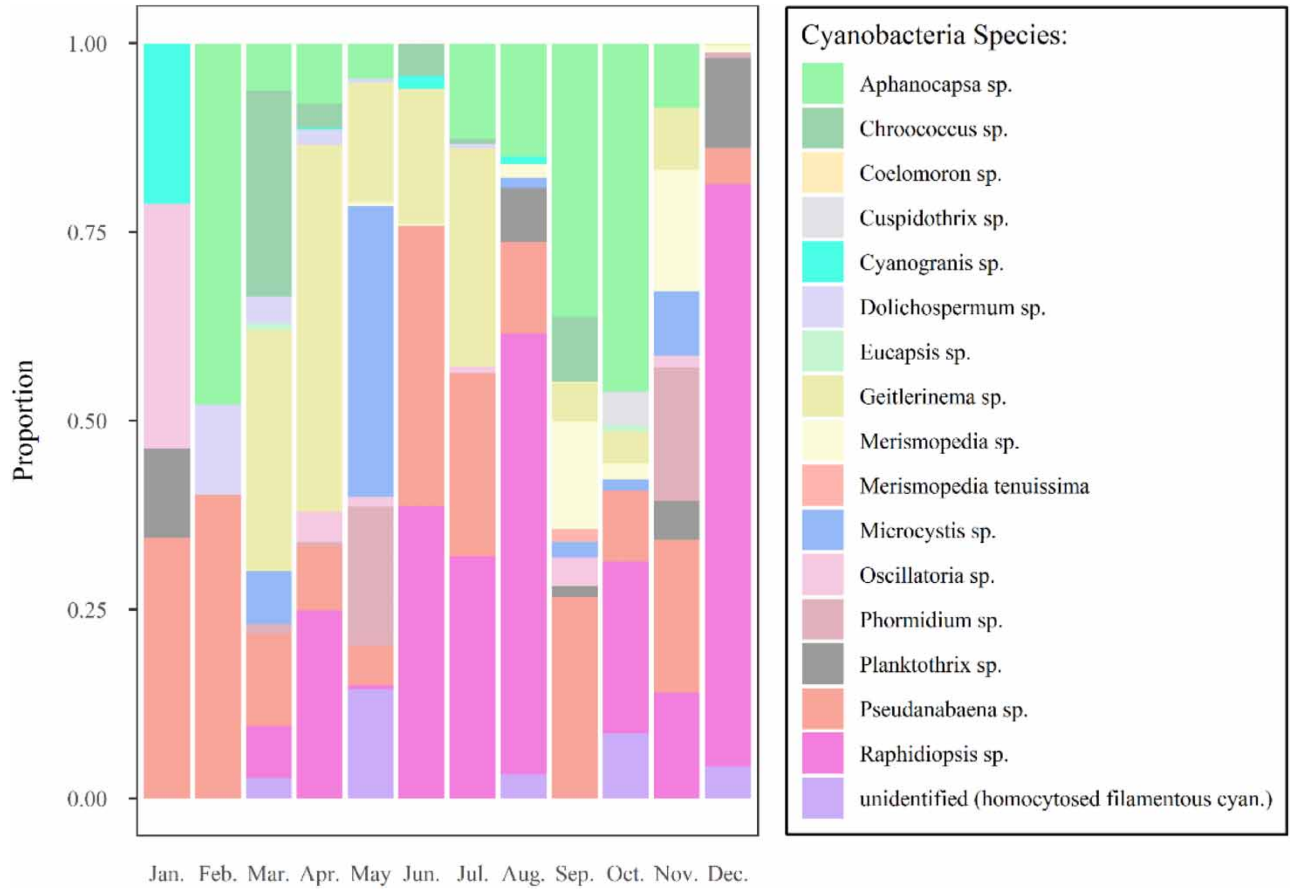


Figure 4 | Relative abundances of cyanobacteria species observed in sampled point on the Jundiai River (Salto, São Paulo, Brazil).

On the DS, the *Pseudanabaena* sp. cells constituted 20.39% of the total cell count, while in the WS, this percentage decreased to 14.31%. *Pseudanabaena* organisms, which were the second most abundant cyanobacteria during both DS and WS, are able to synthesize toxins (Chorus & Welker 2021) and are geosmin and 2-methylisoborneol (MIB)-producing species (Chorus & Welker 2021).

Geosmin and MIB are odorous compounds, which can be perceived even at concentrations as low as nanograms per liter (ng L^{-1}) (Chorus & Welker 2021) and detected in small numbers (~500 cells mL^{-1}) of cyanobacteria cells (Newcombe *et al.* 2010). In contrast to cyanotoxins, taste and odor compounds are not directly associated with human health risks (Chorus & Welker 2021). However, the sensory perception of water by the population can lead to complaints (Newcombe *et al.* 2010) and a loss of confidence in the delivered water quality.

Raphidiopsis sp., *Pseudanabaena* sp., and *Geitlerinema* sp. collectively constitute >57% of the total cyanobacterial cells during both seasons. Notably, during the DS, these species contribute even more, accounting for 62.08% of the total cyanobacterial population. Notably, certain species were exclusively present during the DS, such as *Cuspidothrix* sp., *Merismopedia tenuissima*, and *Coelomoron* sp., which were found in October 2019, September 2021, and September 2020, respectively.

During the WS, not only fewer cells but also lesser species richness was observed. *Raphidiopsis* showed higher abundance during the WS, suggesting a greater tolerance to less favorable flow and ammonia nitrogen conditions. Other species that increased in abundance during this season include *Merismopedia* sp., *Phormidium* sp., *Planktothrix* sp., and *Chroococcus* sp. Particularly, *Raphidiopsis racibiorskii* is an invasive species in Brazil, known for its ability to fix atmospheric nitrogen and high adaptability to various environmental conditions (Padisák 1997). This species occurs in numerous riverine environments and poses a risk to public health by producing toxic compounds (Padisák 1997).

The range of concentrations of several key nutrients, including ammonia nitrogen, nitrogen-nitrite (N-NO_2), nitrogen-nitrate (N-NO_3), and TP, was wider during the DS compared to the WS (Figure 5). Further, as expected during the WS,

Table 2 | Seasonal diversity in cyanobacterial organism richness and abundance on the Jundiai River (sampled point in Salto, Sao Paulo, Brazil, September 2019–December 2022)

Species	Dry season ($n = 23$)		Wet season ($n = 12$)		Total ($n = 35$)	
	Cell mL^{-1}	%	Cell mL^{-1}	%	Cell mL^{-1}	%
Pseudanabaena sp.	24,475	20.39	3,729	14.31	28,204	19.30
Aphanocapsa sp.	14,000	11.66	1,584	6.08	15,584	10.67
Raphidiopsis sp.	28,204	23.49	8,777	33.68	36,981	25.31
Geitlerinema sp.	21,855	18.20	2,408	9.24	24,263	16.60
Merismopedia sp.	2,141	1.78	2,001	7.68	4,142	2.83
Microcystis sp.	12,121	10.10	1,325	5.08	13,446	9.20
Oscillatoria sp.	1,305	1.09	296	1.14	1,601	1.10
Phormidium sp.	5,601	4.67	2,216	8.50	7,817	5.35
Planktothrix sp.	713	0.59	1,703	6.53	2,416	1.65
Chroococcus sp.	2,682	2.23	1,190	4.57	3,872	2.65
Dolichospermum sp.	468	0.39	228	0.87	696	0.48
Cyanogranis sp.	590	0.49	72	0.28	662	0.45
Eucapsis sp.	60	0.05	40	0.15	100	0.07
Coelomoron sp.	28	0.02	0	0.00	28	0.02
Cuspidothrix sp.	338	0.28	0	0.00	338	0.23
Merismopedia tenuissima	200	0.17	0	0.00	200	0.14
unidentified (Homocytosed filamentous cyan.)	5,277	4.40	493	1.89	5,770	3.95
Total	**120,058**	**100**	**26,062**	**100**	**146,120**	**100**

n – number of samples.

the highest values of water temperature, flow, and turbidity were recorded. The average concentration of ammonia nitrogen was 5.83 mg L^{-1} during the DS and 2.51 mg L^{-1} during the rainy season (p-value < 0.05). Average concentrations of TP and nitrogen-nitrite were also higher in the DS (1.27 and 0.34 mg L^{-1}, respectively) compared to the WS (TP: 0.84 mg L^{-1} and N-NO_2: 0.13 mg L^{-1}). Notably, the average flow rate was 22.71 m^3 s^{-1} during the WS and 6.42 m^3 s^{-1} during the DS (p-value $<$ 0.001). The inverse relationship between higher flow volumes and lower nutrient concentrations suggests the presence of a nutrient dilution effect, although this is not strongly evident in the correlation analyses (Figure 6).

TP concentrations were assorted, within the range of 0.37–2.62 mg L^{-1} over the study period, and with no statistically significant difference between the dry and wet seasons. According to the phosphorous concentration-based trophic state assessment for river systems used by the Environmental Company of the São Paulo State (CETESB 2013), the Jundiai River can be categorized as supereutrophic and hypereutrophic based on the aforementioned threshold values. In this context, phosphorus concentration in the Jundiai River does not appear to be a limiting factor for the growth of phytoplankton species. Nitrogen forms also exhibit similar behavior.

Studies have suggested optimal nutrient values for increased biomass and bloom development, including TP $>$ 0.175 mg L^{-1} and ammoniacal nitrogen $>$ 0.5 mg L^{-1} (Zhao *et al.* 2019), TP $>$ 0.10 mg L^{-1} (Kuo *et al.* 2018), and TP $\geq$ 0.14 mg L^{-1} and total nitrogen $<$ 1.34 mg L^{-1}, which are associated with potentially toxic cyanobacteria (Giblin & Gerrish 2020).

Phosphorus is widely considered to be the most limiting nutrient for cyanobacterial growth (Loewen *et al.* 2020). However, in several environments, including the one investigated in this study ($\rho = 0.068$; p-value > 0.05), TP and its constituents do not exhibit a statistically significant correlation with the cyanobacterial biomass, likely because of the already high nutrient loading and eutrophication (Li *et al.* 2018; Kim *et al.* 2019; Zhao *et al.* 2019).

The high nutrient content of the Jundiai River is attributed to its land-use and land-cover features. Water resources in anthropized areas are exposed to significant pollution loads from urban, industrial (Yang *et al.* 2019), and agricultural sources

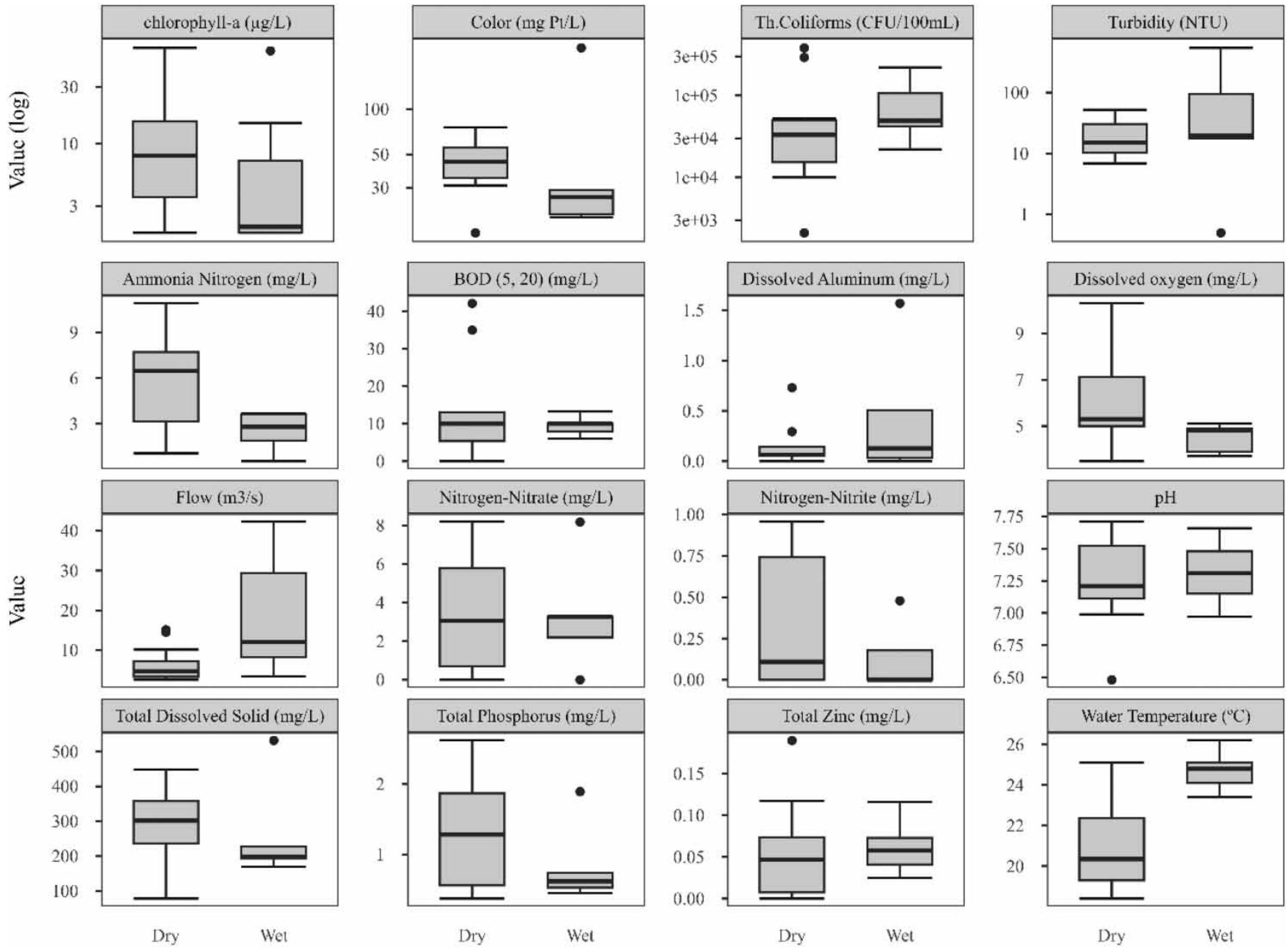


Figure 5 | Boxplots of measured water parameters during the dry and wet seasons in the Jundiai River [mg Pt L^{-1}, milligram of Platinum–Cobalt scale; Th.Coliforms, thermotolerant coliforms; CFU, colony-forming units; NTU, nephelometric turbidity unit; $BOD_{(5,20)}$, biochemical oxygen demand; COD, chemical oxygen demand].

(Loewen *et al.* 2020). For example, the direct discharge of untreated wastewater and microbial degradation of organic compounds increase ammonia nitrogen concentrations in the water (Xing *et al.* 2007). Surface runoff from agricultural areas and discharge from domestic and industrial sewage are the primary sources of phosphorus (Xing *et al.* 2007; Kuo *et al.* 2018; Kim *et al.* 2019).

Previous investigations conducted in Brazilian rivers have revealed a positive correlation between cyanobacterial density and the occurrence of point sources of pollution, while the presence of riverbank protective vegetation has been associated with a reduction in cyanobacterial abundance (Cunha *et al.* 2017). Therefore, to mitigate the exacerbation of cyanobacteria proliferation in water resources, particularly in the Jundiai River, it is essential to minimize nutrient inputs.

The Jundiai River exhibited water temperatures in the range of 18.2–26.2 °C over the entire data collection period. The average water temperature in the DS (20.9 °C) was lower than that in the WS (24.7 °C), consistent with the DS occurring in the winter months and WS in the summer months. The number of cyanobacteria cells was more during the DS with temperatures in the range of 18.4–25.1 °C, despite the higher water temperatures observed during the WS (within the range of 23.4–26.2 °C). Water temperature is directly affected by air temperature (p-value < 0.05). This trend of high cyanobacteria cell counts at lower temperatures was statistically significant (p-value < 0.05) and exhibited a negative correlation with the daily maximum ($\rho = -0.39$), minimum ($\rho = -0.46$), and average air temperatures ($\rho = -0.45$) (Figure 6).

Moreover, the region's climatic conditions result in only a few days per year with minimum air temperatures <10 °C. As previously mentioned, the climate characteristics of the region where the Jundiai River is located consist of mild to hot

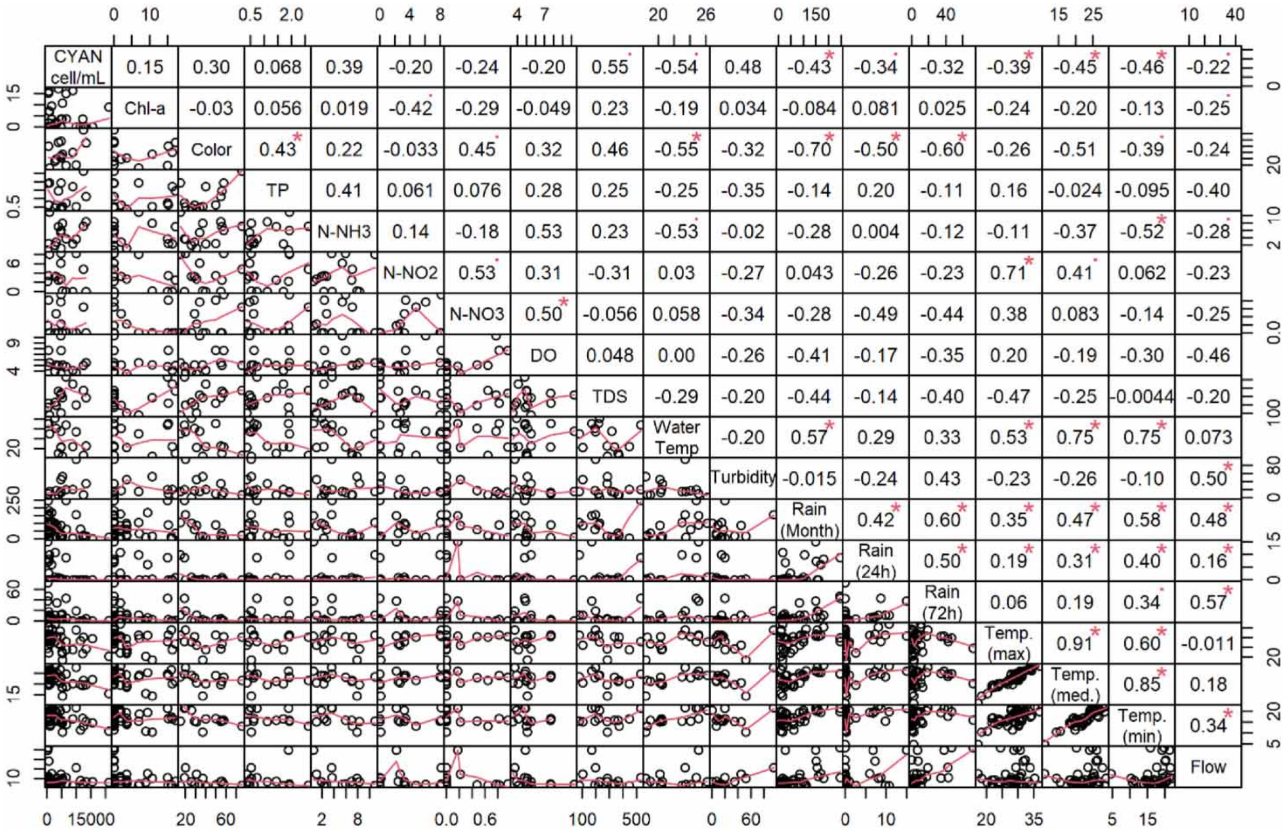


Figure 6 | Spearman's correlation coefficient (ρ) and significance of univariate linear regression (* for p-value < 0.05; · for p-value < 0.1) examining the relationships between cyanobacteria counts, water quality parameters, climate, and hydrological variables.

winters, with minimum daily air temperatures recorded during DS sampling days ranging from 10 to 20 °C and maximum daily air temperatures ranging from 18 to 37 °C. Additionally, the region experiences predominantly sunny days. Consequently, the water temperature, which remained between 18 and 25 °C, still fits into the range supported by cyanobacteria species. Certain cyanobacterial species exhibit varying degrees of thermal tolerance. For instance, select species within the *Aphanizomenonaceae* family have been shown to prefer mild temperatures (Park *et al.* 2021) and thrive in temperatures as low as 14 °C (Xing *et al.* 2007). In addition, *Pseudanabaena* sp., a highly adaptable species, can withstand a broader range of temperatures within 15–35 °C (Gao *et al.* 2018).

Research conducted in a prominent South American river reveals that the impact of climate and hydrological factors on cyanobacterial abundance is minimal when compared to the nutrient influence caused by land-use change (Kruk *et al.* 2023). Water resources located in tropical regions are particularly prone to cyanobacteria abundance owing to the region's climatic characteristics, intense solar radiation, and high temperatures that accelerate the consumption and assimilation of nutrients by primary producers (Ludolf Gomes *et al.* 2012). This phenomenon results in the consequent dominance of cyanobacteria over other phytoplankton species (Li *et al.* 2018). Furthermore, these environments typically lack significant temperature oscillations throughout the year (Dao *et al.* 2016), thus enabling blooms to persist.

During the WS, which encompasses the summer months, the recorded minimum daily air temperatures ranged from 14 to 23 °C, with maximum daily air temperatures between 21 and 36 °C. The water temperature remained between 23 and 26 °C, conditions that closely resemble those observed during the DS. Therefore, similarly to TP, we can assume that the pattern of values recorded during the monitoring period remained within a range of non-critical or limiting values for cyanobacteria development.

A negative correlation was observed between cyanobacteria cell counts and flow ($\rho = -0.22$), which, despite its weak magnitude, was statistically significant at a confidence level of 10% (Figure 6). The increased flow rates associated with greater precipitation (p-value < 0.05 for monthly, 24-h, and 72-h rain) during the hot and humid months likely led to a more turbulent and unstable environment for cyanobacteria cells, in addition to nutrient depletion. Consequently, less favorable conditions for cell reproduction are enforced during the WS. The findings of this study align with the previous research in the field, which has shown that flow is the hydrological factor that most frequently compromises the development of cyanobacteria proliferation and is among the most significant factors triggering and affecting the cyanobacteria abundance (Nelson *et al.* 2018). Indeed, rivers exhibit a higher degree of sensitivity to precipitation than that of lentic ecosystems (Haakonsson *et al.* 2017).

During periods of low flow in this river ecosystem, the growth of cyanobacterial cells can be attributed to two main synergistic relationships. Firstly, the diminished flow results in the accumulation of crucial nutrients, such as nitrogen and phosphorus, due to the restricted dilution of pollutants discharged into the Jundiai River. This observation is supported by data, which demonstrate a negative association between water flow and TP ($\rho = -0.40$) and, although weak, a significant correlation at the 10% confidence level with ammonia nitrogen ($\rho = -0.23$). Thus, the reduction in the volume of water available for nutrient dilution allows cyanobacteria to have greater access to essential nutrients, promoting their growth. Additionally, during the WS, higher water flow associated with increased water turbidity ($\rho = 0.50$ and p-value < 0.05) reduces access to sunlight and indicates increased hydraulic turbulence. Under these conditions, cyanobacterial cells, which typically prefer still waters, are carried away by the river current. Therefore, the combination of these factors – the positive relationship between flow and turbidity and the negative relationship between flow and nutrients – creates favorable conditions for cyanobacterial growth during periods of low river flow.

High flow generally leads to intense agitation, which prevents blooms by increasing water turbidity and reducing light availability at deeper layers, ultimately disrupting populations (Cha *et al.* 2017). This disruption causes the cells to dissipate before the proliferation process is initiated (Cha *et al.* 2017). Alterations to the flow profile can impact the distribution of cyanobacterial genera and lead to changes in their composition (Giblin & Gerrish 2020). Some species of the genera *Anabaena*, *Microcystis*, *Aphanizomenon*, and *Dolichospermum* are dominant in low-discharge waters (Nelson *et al.* 2018; Giblin & Gerrish 2020; Park *et al.* 2021). By contrast, other phytoplankton groups are more resilient under high flow conditions, dominating the environment (Giblin & Gerrish 2020). Nonetheless, the implementation of efficient phosphorus control measures can mitigate the risk of cyanobacterial proliferation, even in situations characterized by lower flow rates and higher temperatures (Haakonsson *et al.* 2017).

Each aquatic ecosystem has unique characteristics, and the growth of cyanobacteria is influenced by a complex interrelationship of diverse environmental factors. The development of cyanobacteria in a river experiencing its lower flows may be specific to the context and should not be extrapolated as a universal trend applicable to all low flow environments. Thorough investigations and continuous monitoring are essential to comprehensively understand the dynamics of cyanobacterial growth.

3.1. Future scenarios and water supply implications

Overall, air temperature is strongly and positively correlated with cyanobacteria cell growth, and global warming will result in more incidences of such episodes (Yan *et al.* 2020). However, as revealed by the current results, the temperature increase is not the primary issue for the Jundiai River, as water temperature remained above 18 °C. The growth of cyanobacteria in the studied location of the Jundiai River is associated with high concentrations of nutrients, primarily phosphorus, and reduced flow that is observed during drought periods.

Future climate projections emphasize, in addition to warming, the expansion of drought-affected areas in South America and other regions (Feng & Fu 2013). Notably, when comparing the 2010–2020 data with the 1980–2010 data, a 3.68% reduction in flow was observed in the Jundiai River (ANA 2021). The scenario was even more severe in other nearby regions, with an average flow reduction of >30% (ANA 2021). In recent years, the population increase in the region, coupled with the reduction of surface water flows, has contributed to water insecurity that is exacerbated by the degradation of surface source water. The impact of urbanization on water resource quality depends, among other factors, on the effectiveness of public sanitation services, which are still deficient in many regions of Brazil, particularly in terms of tertiary treatment.

In general, unregulated changes in human activities have the greatest impact on the onset of cyanobacterial proliferation, significantly affecting the protection of water quality, aquatic ecosystem balance, and human health (Loewen *et al.* 2020). The scarcity of riverbank protective vegetation due to unregulated urban development along riverbanks significantly affects the water resource conditions in terms of temperature, solar radiation, as well as the retention of nutrients and sediments from runoff (Cunha *et al.* 2017). Therefore, water resources in anthropized watersheds that are inherently vulnerable to cyanobacteria because of the physical and hydrological characteristics of the system (Burford *et al.* 2007) are likely to experience even more severe blooms in accordance with climate change projections (Paerl & Paul 2012).

The occurrence of algae and cyanobacteria in water treatment for public supply can have significant implications for various aspects of the treatment process, including coagulant dosage, performance of the clarification stage, filter clogging and performance, generation of toxins, release of taste and odor compounds in the water, and disinfection demand. To meet regulatory standards, upgrades to the water treatment systems are often necessary, such as the use of activated carbon, oxidant readjustment, or the implementation of additional processes like nanofiltration and reverse osmosis to establish multiple barriers for effective contaminant removal (Merel *et al.* 2013).

In the context of water safety, a strategy to minimize the release of intracellular compounds into the water treatment train leads to the removal of preserved cyanobacteria cells (Newcombe *et al.* 2010); without membrane damage during clarification. The effective removal of cyanobacterial cells during the DS poses a critical challenge in the treatment of water from the Jundiai River. This season not only witnesses the highest concentration of cells but also exhibits the lowest levels of turbidity. The limited presence of inert particles in the water avoids the generation of sufficiently heavy flocs for sedimentation during the clarifying step. As an alternative solution, flotation could be employed.

Source water quality fluctuations threaten the treatability of water for human consumption. The design and operation of a water treatment plant must be efficient to deal with different matrices over time, such as treating water having low turbidity and high concentration of organic matter and nutrients, favoring the proliferation of cyanobacteria, which is the object of this study. Thus, seasonal periodic variations in quality, as well as the variations resulting from increasing anthropogenic pressure and climate changes over the years of operation of a municipal water supply system (usually two or three decades), must be considered when selecting treatment technologies. Efficient and effective treatment plant operation will thus depend on refined monitoring. Protection and recovery of sources, multiple green and gray barriers, and the combination of all these management practices are essential to guarantee the safety of water for human consumption.

Lakes and reservoirs are characterized by hydrological conditions that are conducive to phytoplankton growth and are vital sources of water for human populations. Consequently, concerns over the safety of these water resources have intensified, and most studies on cyanobacterial proliferation have been conducted in lakes and reservoirs. Over time, the quality of riverine water resources that serve as vital sources of water for populations worldwide as well as in Brazil has declined, leading to a growing cyanobacterial proliferation in these environments.

In the context of this exploratory study, it is important to highlight the limitations associated with the statistical correlations. These limitations include a small sample size, diminishing the statistical power of the analysis and restricting the generalizability of the results to a broader population. Furthermore, the absence of multivariate analysis may result in overlooking potential interactions and complex relationships among multiple independent variables. In addition, the limited precision stemming from a smaller number of observations contributes to wider confidence intervals, making it more challenging to draw definitive conclusions regarding the strength and direction of the associations.

4. CONCLUSION

Over the course of 3 years of the Jundiai River (Salto, São Paulo State, Brazil) water monitoring, a consistent pattern of significantly elevated cyanobacterial cell counts during the DS was identified, which also coincided with the presence of the highest number of species. Furthermore, most of the species identified in the river can produce toxins and generate unpleasant taste and odor in the water, posing a threat to water safety. *Raphidiopsis* sp., *Pseudanabaena* sp., and *Geitlerinema* sp. were the dominant species throughout the dry and wet seasons.

The DS is characterized by higher average nutrient concentrations and lower water flow. The finding of the current study provides evidence that the reduction in river flow creates the primary precursor condition to the cyanobacteria cell growth. Because the Jundiai River is highly eutrophic, phosphorus is not a limiting factor.

Effective management of the Jundiai River basin requires control of points and diffuse pollution sources to improve water quality. The main challenges include the control of pollution of Brazilian rivers through the implementation of tertiary treatment of effluents and increased riparian protection of streams. Therefore, monitoring the presence of cyanobacteria in the river sources of drinking water, such as the Jundiai River, is essential for ensuring water safety and implementing effective management measures.

Notably, the current study adopted an exploratory approach. Therefore, the obtained findings should be interpreted with caution, as they do not aim to establish definitive conclusions or generalize the insights. Further research, encompassing larger sample sizes and more comprehensive analyses, is imperative to validate and reinforce the results, leading to broader inferences.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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