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Cyanobacterial bloom monitoring and assessment in Latin America

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ABSTRACT

Cyanobacterial blooms have serious adverse effects on human and environmental health. In Latin America, one of the main world's freshwater reserves, information on this phenomenon remains sparse. To assess the current situation, we gathered reports of cyanobacterial blooms and associated cyanotoxins in freshwater bodies from South America and the Caribbean (Latitude 22° N to 45° S) and compiled the regulation and monitoring procedures implemented in each country. As the operational definition of what is a cyanobacterial bloom remains controversial, we also analyzed the criteria used to determine the phenomena in the region. From 2000 to 2019, blooms were reported in 295 water bodies distributed in 14 countries, including shallow and deep lakes, reservoirs, and rivers. Cyanotoxins were found in nine countries and high concentrations of microcystins were reported in all types of water bodies. Blooms were defined according to different, and sometimes arbitrary criteria including qualitative (changes in water color, scum presence), quantitative (abundance), or both. We found 13 different cell abundance thresholds defining bloom events, from 2×10^3 to 1×10^7 cells mL^{-1}. The use of different criteria hampers the estimation of bloom occurrence, and consequently the associated risks and economic impacts. The large differences between countries in terms of number of studies, monitoring efforts, public access to the data and regulations regarding cyanobacteria and cyanotoxins highlights the need to rethink cyanobacterial bloom monitoring, seeking common criteria. General policies leading to solid frameworks based on defined criteria are needed to improve the assessment of cyanobacterial blooms in Latin America. This review represents a starting point toward common approaches for cyanobacterial monitoring and risk assessment, needed to improve regional environmental policies.

1. Introduction

Cyanobacterial blooms degrade water quality for recreation, drinking water and fisheries, threatening global water security and resulting in high economic costs (Chorus and Welker, 2021; Dodds et al., 2009; Ibelings et al., 2021; Steffensen, 2008). More than 80 cyanobacterial taxa are currently associated with the production of harmful toxins (cyanotoxins) to wild life and humans (Bernard et al., 2016; Sivonen and Jones, 1999), and over 75% of cyanobacterial blooms are toxic (Chorus, 2001). Blooms have increased on a global scale during recent decades, and projected to keep this trend due to eutrophication and global warming (Ho et al., 2019; Huisman et al., 2018; O' Neil et al., 2012; Reichwaldt and Ghadouani, 2011). Notably, to date, the definition of cyanobacterial blooms remains controversial being defined according to visual observations (water discoloration), numerical thresholds, or even subjective criteria (Erratt et al., 2022; Huisman et al., 2018). Cyanobacterial bloom management differs greatly between regions, probably associated with the large inequities in scientific development, gender

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Table 1
Summarized WHO guidelines followed in this article. Information compiled from (Chorus and Welker, 2021). *Guideline levels are defined based on biovolume. The number of cells is given for reference only. ** For recreational waters, Guidance Level 1 are the same as Level 2 for drinking waters. Potential human health risk in drinking and recreational waters is considered moderate at Guidance Level 1, and high when cyanobacterial biovolume exceeds 4 mm^3L^{-1}.

Water use	Guideline	Biovolume ($mm^3\ L^{-1}$)	Chlorophyll *a* concentration (μgL^{-1})	Equivalent to abundance (Cells mL^{-1}) *	Microcystin LR (μgL^{-1})
Drinking	Vigilance level	<0.3	<1	<5000	<1
	Level 1	0.3 – 4	1 - 12	5000 - 60,000	1
	Level 2**	4 - 8	12 –24	60,000 - 120,000	12
Recreational	Vigilance level	1 - 4	3 - 12		
	Level 1**	4 - 8	12 –24	60,000 – 120,000	
	Level 2	>8	>24	>120,000	24

biases, funding access, and technical capabilities between countries (Tundisi and Matsumura, 2011; Valenzuela-Toro and Viglino, 2021). Differences in the perception of blooms and monitoring capabilities can potentially lead to misestimations of their occurrence and their potential health effects.

Latin America is inhabited by nearly 650 million people and has the 31% of the freshwater world resources. The countries face great environmental challenges and conflicts of interest between environmental protection and human activities (Grill et al., 2019; Tundisi and Matsumura, 2011; Zabel et al., 2019). Economies are dependent on agricultural commodities, river damming, and extraction of natural resources, main factors leading to freshwater eutrophication and consequent algae blooms (Heisler et al., 2008). Latin American countries invest on average 0.3% of the gross domestic product (GDP) in science and technology (Bolaños-Villegas et al., 2020), which results in severe limitations to develop and implement strategies to protect surface water quality.

Cyanobacterial blooms are frequent in South America and the Caribbean, sometimes flowing by the rivers through several countries along hundreds of kilometers, posing serious health concerns for drinking water sources (Aubriot et al., 2020; IANAS, 2019; Mowe et al., 2015; O'Farrell et al., 2019). Intoxications and deaths of animals, and even tragic human fatalities associated with toxic cyanobacteria have been reported since the 1980 decade (Azevedo et al. 2002; Dörr et al. 2010; Aguilera et al. 2018). Regulations for drinking sources and recreational waters largely vary across Latin American countries (Chorus, 2012; IANAS, 2019), and the risk assessment of harmful cyanobacteria is still missing in the region.

As global predictions forecast scarcity in access to clean water in the future (Boretti and Rosa, 2019), assessing cyanobacterial blooms and their toxins becomes a task of high priority in the region. This work compiled reports on cyanobacterial blooms and associated cyanotoxins in lentic freshwater bodies in South America and the Caribbean. We analyzed how this phenomenon is perceived in terms of identification and quantification, the most frequent taxa associated with blooms and the type of water bodies affected, and their human use. Based on this literature survey, we provide a set of recommendations to improve the assessment of harmful cyanobacterial blooms in Latin America.

2. Methods

2.1. Database

An extensive literature review was performed (January 2018 to June 2020) to investigate the occurrence of cyanobacterial blooms and associated cyanotoxins in freshwater ecosystems in South America and

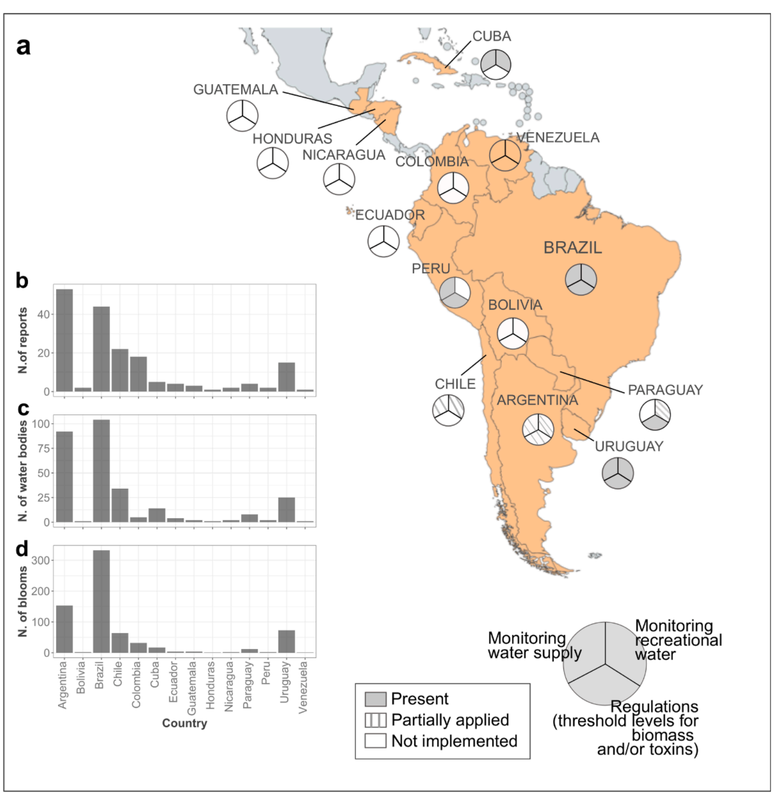

Fig. 1. Occurrence of cyanobacterial blooms in South America and the Caribbean. A, Countries were blooms were registered, and regulations regarding cyanobacteria (pie chart); B, Number of information sources included in the dataset; C, Number of affected water bodies; D, number of blooms reported per country. Occurrence was determined through literature searches (January 2018 to June 2020) for records of blooms (or "floración", or "floração") from the year 2000. In the pie charts, gray indicates the presence of legislation regarding cyanobacteria for drinking (right), recreational waters (left) and microcystins (lower third), shaded areas indicate that some regulations are followed, and white indicates absence of regulation. For more information, see Table 2. The map was created in MapChart (https://www.mapchart.net).

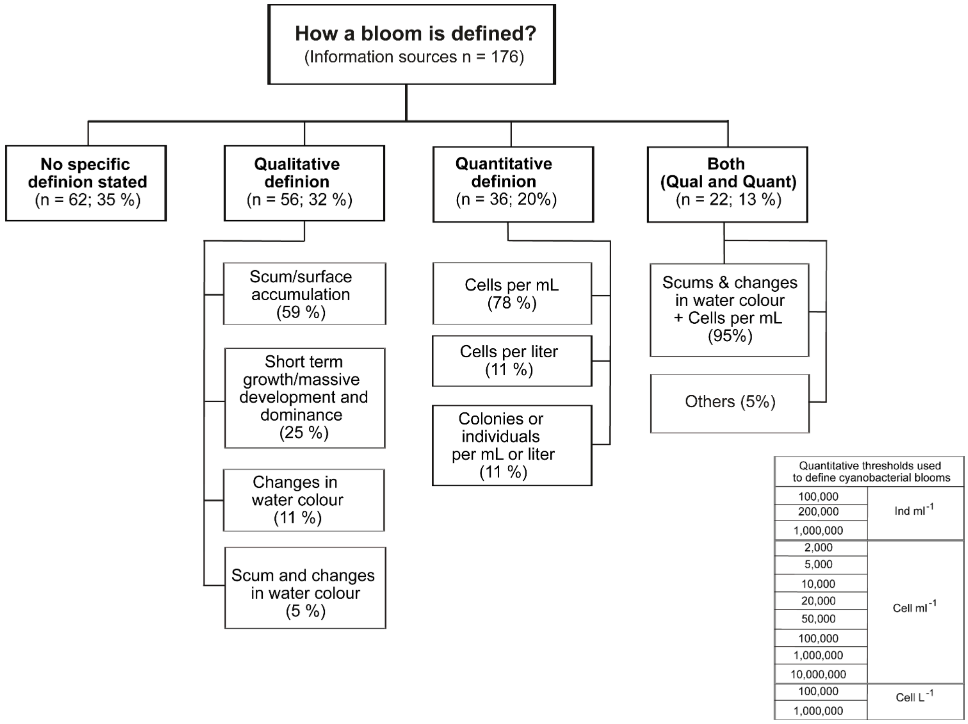

Fig. 2. Flowchart summarizing the criteria used to determine and quantify a cyanobacterial bloom in South America and the Caribbean. Bottom right: Insert showing the threshold levels used to define a bloom, based on individuals or cells.

the Caribbean. We performed a search using the keywords "bloom" (or "floración", or "floração", Spanish and Portuguese, respectively). Scientific literature was retrieved from Scopus, Google Scholar, and SciELO. Each article was analyzed, discarding those that did not report blooms in their results. The final database includes 176 publications (118 scientific articles; 40 technical reports; 5 conference presentations; 2 book chapters; 4 undergraduate and postgraduate theses, and 7 unpublished set data) from 14 countries. Each data source was screened for the following information: *i)* The definition of bloom, first classified as quantitative (indicators such as cyanobacterial cell counts, cyanobacterial biovolume or chlorophyll *a*, qualitative (non-quantitative variables such as visual aspects including watercolor and scums presence), or both criteria; *ii)* the environmental and physicochemical parameters measured when monitoring the blooms; *iii*) the type of water body and characteristic (geographic location, surface area, depth, origin (natural/man-made), trophic state), *iv)* the use of the water,

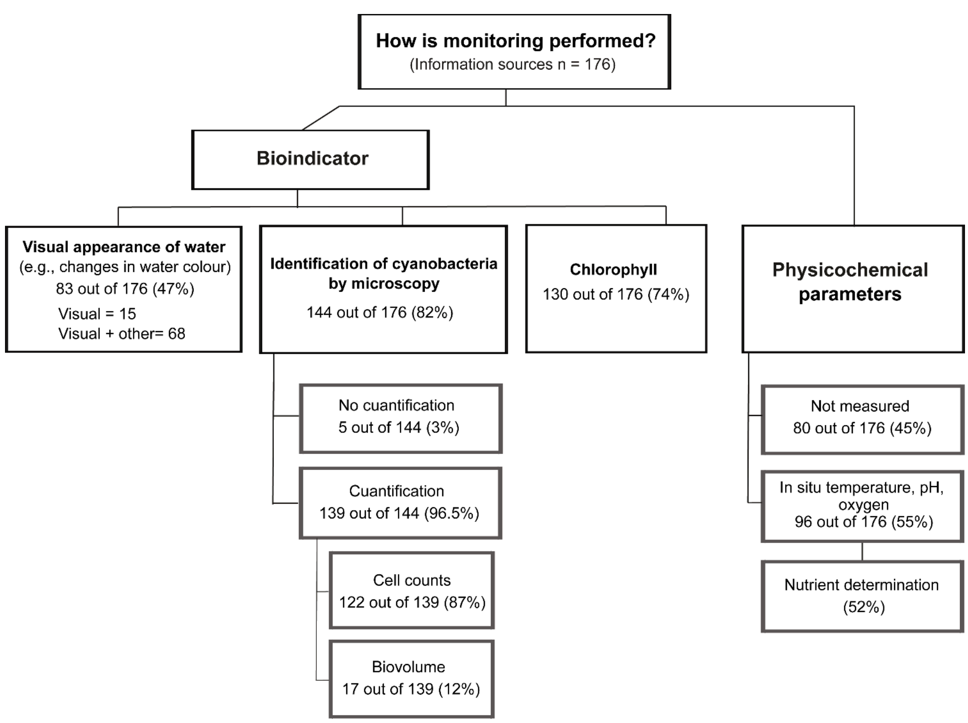

Fig. 3. flowchart summarizing cyanobacterial bioindicators and environmental variables found in the survey for South America and the Caribbean.

summarized in three large categories: recreation (Recre), water supply (Ws), and other uses (e.g., fishery, aquaculture, irrigation, hydropower, livestock), *v)* taxa and cyanotoxin associated with the bloom, and the methodology employed for their quantification. When available, information on the bloom-forming species were obtained and grouped at the genera level. We compiled the regulatory and monitoring plans for cyanobacteria in South America and the Caribbean to determine the current situation in the region.

2.2. Data analysis

Quantitative data were classified into categories considering the Alert Levels Framework and the Guidance Levels for drinking and recreational waters, respectively, recently modified by WHO (Chorus and Welker, 2021) (summarized in Table 1). Criteria used for bloom definition and monitoring (environmental variables, biological indicators) were summarized in two flowcharts. Differences in the biovolume, cell abundance, and microcystin concentration between water bodies used for different purposes were analyzed with the Kruskal-Wallis test (K-W), followed by Dunn`s post hoc pairwise test (D-test) (Dinno, 2017) since data failed the normality and homoscedasticity prior verifications. To explore the potential effect of the number of reports on the number of cyanobacterial genera detected, we used the non-parametric local weighted (Loess) regression, commonly applied for scarce data and/or data exploration (Cleveland and Devlin, 1988). The relationship between the number of blooms and the number the information sources was analyzed using Spearman's correlation in GraphPad Prism version 9.3.0 for Mac Os. Plots and tests were built in R with the magrittr, ggpubr, PMCMRplus, FSA, and ggplot2 packages (R Core Team, 2020; Wickham, 2016).

3. Results and discussion

3.1. Criteria to define cyanobacterial blooms

As of June 2020, a total of 699 cyanobacterial bloom events were retrieved from the database (176 data sources, in 14 countries) (Fig. 1), with a positive correlation between the number of blooms and the number of information sources ($\rho = 0.979$; $p < 0.001$). Differences in the number sources and cases found per country could be attributed to contrasting realities in scientific profiles and specialized technicians rather than the lack of cyanobacterial blooms (Aguilera et al., 2018b; Bonilla et al., 2015, 2023; Soares et al., 2013; Svirčev et al., 2019). The term "bloom" was defined based on qualitative criteria (32% of the total number of cases), quantitative criteria (20%), or both, and no definition was found in 35% of the cases (13%) (Fig. 2). Our results clearly show the variety in the criteria used to define a bloom, which may respond to different subjective perceptions of the events, highlighting the need to establish a more harmonized criterion.

3.2. Methods for bloom detection and quantification

Visual inspection, cell counting under the microscope, and chlorophyll *a* (Chl *a*) were the main methods to assess cyanobacterial blooms (Fig. 3). Microscopic identification and cell counting were the most common quantitative techniques (n = 144 out of 176), complemented with Chl *a* concentration ($n = 130$) or visual inspection ($n = 68$) (Fig. 3). The classic methods for phytoplankton quantification (Chorus and Welker, 2021; Sournia, 1978) were commonly used: the Utermöhl's method (cell, individual or colonies) (63% of 137 reports) was followed by counting in 1 mL chambers under direct microscope (Sedgewick Rafter and Neubauer chambers, 12% and 4%, respectively). In 17% of the cases the methodology employed was not mentioned. Phytoplankton taxonomy based on morphological traits has a long tradition among limnologists of Latin America (Pedroche, 2016), still resulting in the dominant method to identify bloom-forming cyanobacteria. Counting phytoplankton to the species or genus level has high costs as it is time consuming and requires highly trained technicians (Edler and Elbrächter, 2010). The limited budget allocated to science and technology in Latin America likely prevent the incorporation of molecular techniques that have become increasingly popular to detect potential toxic cyanobacteria in monitoring programs (Moreira et al., 2014; Rosa et al., 2011; Salazar-Alcaraz et al., 2021; Salmaso et al., 2017).

In our survey, 74% of the reports included Chl *a* concentration, a robust, yet indirect proxy for phytoplankton biomass widely used in water quality programs (Chorus and Welker, 2021). New methods based on in vivo fluorescence of photosynthetic pigments are promising tools to complement efforts in cyanobacterial monitoring (Ahn et al., 2007; Bertone et al., 2018; Gitelson, 1992). Fluorometers are easy to use, provide quantitative results in real time, and some of them are small and low-cost handheld instruments easy to be incorporated in monitoring programs (Cremella et al., 2018). Remote sensing applied to retrieve Chl *a* represents a low-cost tool to provide high-frequency quantitative data to monitor cyanobacteria in Latin America. Remote sensing can be particularly useful to cover large regions or inaccessible sites (e.g., private lands, remote sites) (Aubriot et al., 2020; Maciel et al., 2022; Zabaleta et al., 2023).

Cell abundance or density was the most used quantitative indicator for cyanobacteria (per mL or per liter, 11% and 78% of the cases, respectively), but we also found reports of colonies or individuals per volume unit (11%). We identified 13 threshold levels to define a bloom (Fig. 2) but no report defined bloom based on biovolume. Cell abundances most frequently chosen to define a bloom were between 2000 and 50,000 cells mL^{-1} (47% and 26%, respectively). Cell size can vary two orders of magnitude and poorly correlates with biomass (biovolume) or pigment concentrations (Reynolds, 2006). For instance, in our study, four threshold levels associated with blooms were below 60.000 cells mL^{-1}. Those abundances are low and can correspond to a cyanobacterial biovolume of ≤ 4 mm^3 L^{-1} and ≤ 12 μgL^{-1} of chlorophyll *a* concentration (Alert 1 and Surveillance for drinking and recreational waters, respectively) (Chorus and Welker, 2021), indicating a strong disagreement with the presence of a bloom. More importantly, the use of numerical thresholds can be problematic given differences in toxin content per cell among different cyanobacterial species (Merel et al. 2013b). Therefore, in order to reduce health risks, numerical thresholds require specific knowledge regarding cyanotoxin production (e.g., concentration per cell) in the bloom-forming cyanobacteria present in the affected water body. "Individuals" per volume (unicells, filaments, and colonies, altogether), was also used to report blooms found in our survey. This estimator can lead to large errors and misinterpretations, being conceptually wrong and has to be eradicated from ecological studies and from regulations. Biovolume is the most precise proxy for phytoplankton biomass and, according to the WHO, it is the recommended estimator to implement in alert systems concerning cyanobacteria (Chorus and Welker, 2021). According to our survey, only a small fraction of studies determines biovolume (12%). This could be due to the effort needed to process the samples to calculate biovolume, which is a highly time-consuming and specialized task (Edler and Elbrächter, 2010). The availability of free access software for microscopic image processing or even on line biovolume calculators can make the cell measurements easier and quicker (Borics et al., 2021).

3.3. Associated environmental parameters

A total of 132 reports (72% of the total) included environmental variables such as water temperature, salinity and pH, while 52% had nutrient determinations (Fig. 3, Table S1). Much of the available information comes from studies carried out in cold temperate lakes, this highlight the need to increase efforts to study freshwaters in warmer regions (Barros et al., 2019; De Senerpont Domis et al., 2013; Haakonsson et al., 2017). The environmental characterization of ecosystems affected by blooms is essential to better understand the conditions that

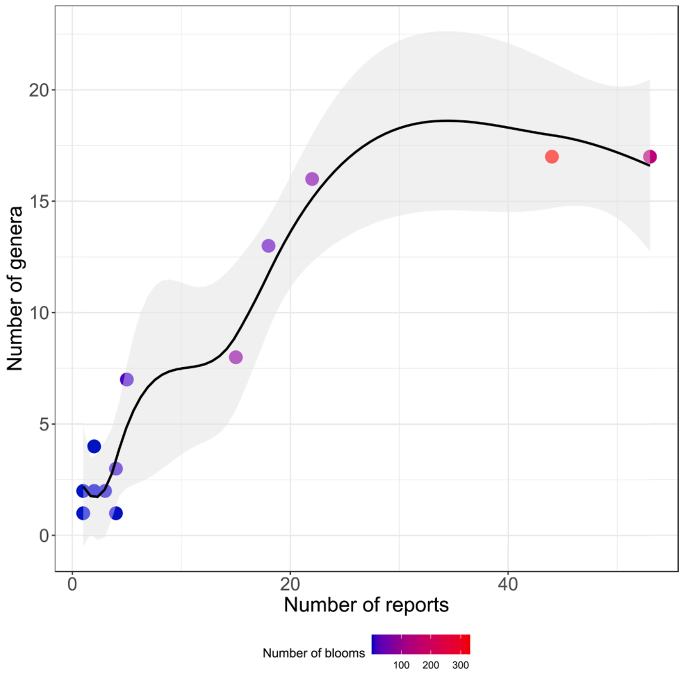

Fig. 4. Distribution of the number of genera reported (circles) in relation to the number of reports found in the survey. The number of blooms is indicated in color (gradient blue to red). The solid line is the Loess fitted curve and the shaded area is the 95% confidence level interval.

promote the phenomenon and to improve management measures (Chorus and Welker, 2021). Adding the measurement of physical-chemical variables in environmental monitoring programs can be a challenge in conditions of limited human and instrumental resources, however, some variables of simple measurement, such as water temperature, can provide key information to develop simple predictive models for cyanobacterial occurrence (Haakonsson et al., 2020).

3.4. Bloom composition

Most of the reports included taxonomic information (96%). Eighty-six taxa (32 genera; 58 species, Table S2) were associated with blooms and distributed between Nostocales (10 genera and 31 morphospecies), Synechococcales (11 genera, 11 morphospecies), Oscillatoriales (7 genera, 7 morphospecies), and Chroococcales (4 genera, 9 morphospecies). Blooms were formed by a single taxon (46%), or more taxa (54%), mostly dominated by Nostocales. The number of detected genera positively correlated with the number of studies (Fig. 4). Argentina, Brazil, Chile and Uruguay were the countries with the highest number of bloom-forming taxa (Table S2), in correspondence with the number of reports per country (Fig.1 and 4). These findings suggest that the increased number of studies and intensified monitoring efforts could have led to more effective detection of blooms and harmful cyanobacterial taxa.

At least 57 of the reported taxa in our study are potentially toxic (Table S2). *Microcystis, Raphidiopsis, Planktothrix, Dolichospermum, Pseudanabaena* and *Aphanizomenon* were the most frequent genera (Fig. 5) including multiple known toxic species (Bernard et al., 2016; Svirčev et al., 2019). Blooms of the hepatotoxic *Microcystis* spp. complex have been reported in at least 79 countries, seven located in Latin America (Harke et al., 2016). Among the *Raphidiopsis* species found in our survey, *R. raciborskii* (formerly *Cylindrospermopsis raciborskii,* Aguilera et al., 2018a) is increasingly being reported in Europe, North and South America (Bonilla et al., 2012; Venegas et al., 2018; Vico et al., 2020), but all South American strains produce highly potent neurotoxins (saxitoxins and gonyautoxins) (Fabre et al., 2017; Vico et al., 2020, 2016). *R. mediterranea*, a subtropical species known to produce cylindrospermopsin and anatoxin-a (Namikoshi et al., 2003; Rzymski and Poniedzia, 2014) has been associated with blooms in water bodies used for recreation in Argentina and Uruguay (Aguilera et al., 2018b; Aubriot and Bonilla, 2018), in some cases together with *R. curvata*, known to produce cylindrospermopsin (Jiang et al., 2012). A variety of toxins (microcystins, saxitoxins and cylindrospermopsin) have been reported in the literature for *Dolichospermum* and *Aphanizomenon* species found in our survey (Table S2) (Cirés and Ballot, 2016; Li et al., 2016). The taxonomic composition then provides a valuable first orientation of the potential cyanotoxins present in a bloom and our results warn about a potential wide variety of cyanotoxins present in Latin American blooms.

3.5. Cyanotoxins associated with blooms

We mapped the available data about cyanotoxins associated with cyanobacterial blooms, which were reported in 67% of bloom cases ($n =$ 514, 141 water bodies, 9 countries). No published information was found for Bolivia, Cuba, Honduras, Peru and Venezuela (Fig. S1). Microcystin was the most frequently reported and widespread

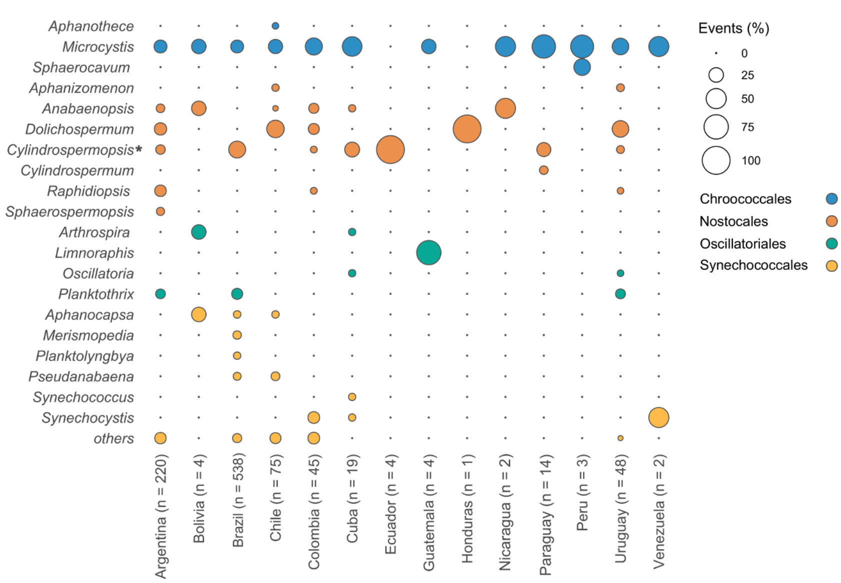

Fig. 5. Dominant genera reported in cyanobacterial bloom events in the studied countries. The size of the bubble represents the percentage of each genus out of the total number of cases per genus per country. Others: Genera contributing less than 4% of the cases, data per country is shown between brackets (n). Colors indicate the taxonomical order. * Refers to the percentage of cases where the *Cylindrospermopsis* was dominant. The original name found in the reports was kept despite the genera being transferred to *Raphidiopsis* (Aguilera et al., 2018a).

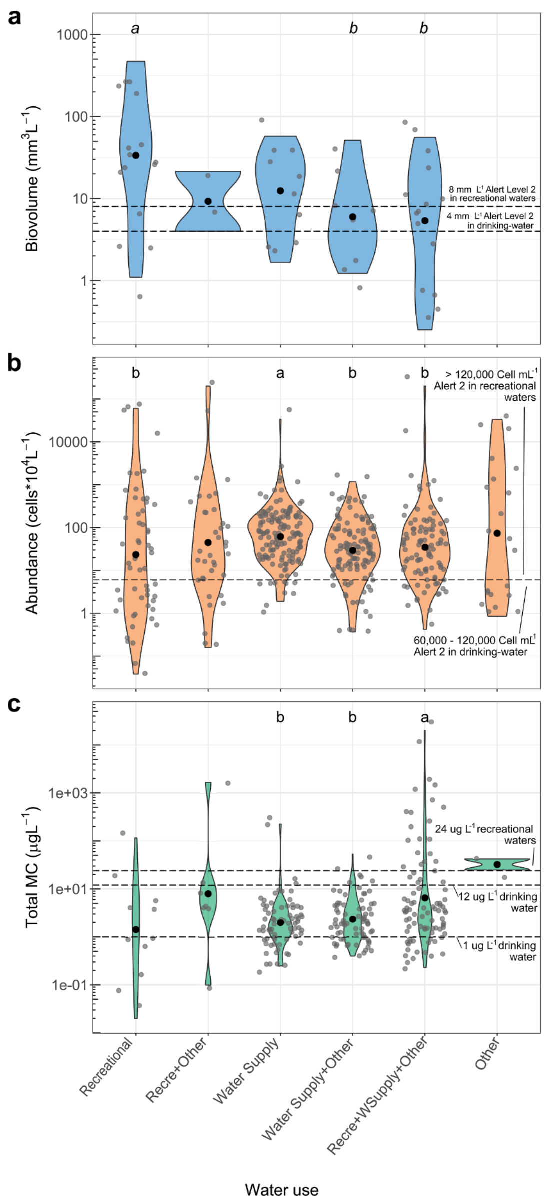

Fig. 6. Cyanobacterial biovolume (a), cell abundance (b), and total microcystin concentrations (c) reported in blooms discriminated by water body use and summarized in violin plots. The width of the violin represents the data density or how frequently the value occurs in the dataset. Black circles represent mean values and gray dots represent individual data. All y axes are in $\log_{10}$. Letters indicate statistically significant differences between categories ($p < 0.05$, italic letters, marginal significance $p = 0.06$ was found between biovolume categories). Data: cyanobacterial biovolume ($n = 50$), cell abundance ($n = 554$), total microcystin concentrations ($n = 258$). Dotted lines indicate provisional WHO alert levels and guideline values for drinking and recreational waters (Chorus and Welker, 2021). MC, microcystin; Recre, recreational; WSupply, water supply; other, uses other than recreation or water supply.

cyanotoxin (61%; 316 out of 514; eight out of nine countries with toxin reports), with seven variants (LA, LR, RR, YR, LF, LF, D-Asp^3, (E)-Dhb^7]-Microcystin-RR). Saxitoxins (27% of the total) were mostly found in Brazil but also in Argentina and Guatemala; cylindrospermopsin (10%) in Brazil, Ecuador, and Guatemala; anatoxin-a in Argentina and Brazil while nodularin was quantified in one water body in Chile (Fig. S1). Microcystins were found in water bodies used for drinking water, followed by saxitoxins and cylindrospermopsin, and microcystins were mostly detected in artificial reservoirs built on rivers (84%). The most common analytical tool used for cyanotoxin determination was the enzyme-linked immunosorbent assay (ELISA, 85% of cases) (Fig. S3). Other methods were high-performance liquid chromatography (HPLC and HPLC-UV: 10%), liquid chromatography-mass spectrometry (LC-MS and LC-MS/MS: 3%; matrix-assisted laser desorption ionization-TOF MS - MALDI-TOF-MS: 1%), and mouse bioassay (1%). ELISA results were confirmed with HPLC in less than 10% of the reports. Cyanotoxin detection can be expensive, and some methods require sophisticated equipment hardly available in most laboratories. In addition, simple and rapid methods that allow the processing of a large number of samples in a short time, such as ELISA or molecular methods to detect toxin genes, should be prioritized (Brena et al., 2021; Martínez de la Escalera et al., 2017; Pírez et al., 2013). Following the global trend, toxin analysis in Latin America is mainly focused on the detection and quantification of microcystins, and consequently other toxins could be potentially overlooked (Merel et al., 2013a; Pineda-Mendoza et al., 2012). Our results highlight the need to expand the variety of cyanotoxins that are monitored in the region, in particular the potent neurotoxins and cytotoxins produced by Nostocales (Nowruzi and Porzani, 2021).

3.6. *Water resources affected by cyanobacterial blooms*

Cyanobacterial blooms ($n = 699$) were reported in 295 water bodies distributed in 14 countries covering the Caribbean ($n = 1$), Central ($n = 3$) and South America ($n = 10$) (Fig. 1) (Latitude range: 22° N to 45° S). Blooms develop in either natural (41%) or man-made (58%) water bodies. The former includes shallow lakes (22%), lakes (< 3 m, 12%), lagoons (3%), rivers and streams (8%), and one estuary (0.3%) (Fig. S4a). Man-made systems are mainly reservoirs built in rivers (148 out of 172), but also artificial shallow lakes, water storage facilities and sewage treatment plants. Fifty-two percent of cyanobacterial blooms were reported in freshwater sources for drinking water (exclusively or in combination with other uses) and 30% were found in water bodies mainly used for recreational activities (Fig. S4b). Water bodies were located from 0 to 3809 m a.s.l, covering areas between 1 and 4290,000 ha, with maximum depths ranging from 0.9 to 350 m (Table S1).

Cyanobacterial biomass (biovolume) in recreational waters was higher than in water supply and mix uses (K-W, D-test, $p = 0.06$) (Fig. 6a). Mean values of biovolume were above the WHO Alert Level 2 for drinking water sources (4 mm^{3}L^{-1}) and recreational waters (>8 mm^{3}L^{-1}) in freshwaters for all type of uses (Fig. 6a). The highest biovolumes were reported in recreational waters (~400 mm^{3}L^{-1}), and up to 57 mm^{3}L^{-1} were registered in drinking water sources. Cell abundances found in drinking water sources were significantly lower than in recreational and sources with multiple uses (K-W, D-test, $p< 0.05$) (Fig. 6b). The highest concentrations of total microcystin were recorded in water bodies with mixed uses (K-W, D-test, $p<0.05$)(max 20,000 µg L^{-1}; mean 499.58 ± 2769.6) (Fig. 6c). In water bodies used for drinking water, mean values of total microcystin were above surveillance level of 1 µg L^{-1} suggested by WHO (mean ± SD: 8.6 µg L^{-1} ± 36.4 for water supply only; 4.28 µg L^{-1} ± 6.9 for water supply and other uses). Mean values of total microcystin in water bodies used for recreation and other purposes (245. 51 µg L^{-1} ± 632.6) were above Alert 2 for drinking water sources and recreational waters suggested by WHO (Fig. 6c).

Information about the trophic state was presented for three quarters of the water bodies ($n = 225$). Overall, 45% of them were eutrophic, 41% hypereutrophic, 6% mesotrophic and 7% oligotrophic (Table S3). Most of the sources used for drinking water supply and recreation were eutrophic or hypereutrophic. Cyanobacterial blooms, one of the most evident consequences of eutrophication, are widespread in lentic and but also lotic eutrophic ecosystems around the globe (Chorus and Welker, 2021; Davis and Koop, 2006; Huisman et al., 2018). South America stands out with a rich network of large rivers crossing several countries where toxic blooms can be transported by the river flow limiting or impeding ecosystem services hundreds of kilometers away from where they generated (Aubriot et al., 2020; O'Farrell et al., 2019). Threats on superficial freshwaters include hydrological alterations of

Table 2
Current status on regulations and monitoring plans regarding cyanobacteria and cyanotoxins in South America and the Caribbean, summarized and compiled from (Chorus and Welker, 2021), otherwise indicated.

Country	Main causes of freshwater deterioration (*)	Cyanobacterial intoxication events (on humans or animals)	CyanobacteriaRegulations Parameter regulated	Values	Monitoring plans
Argentina	Eutrophication	Birds (Wild-life) mortality in Piedras Moras reservoir (Mancini et al., 2010). 2011: Human acute intoxication by an MC-producing cyanobacterial bloom, Salto Grande reservoir (Argentina-Uruguay) (Giannuzzi et al., 2011). 1984: Acute poisoning and mass mortality of livestock (cows) probably due to blooms of *Microcystis aeruginosa* (Odriozola et al., 1984).	No regulations. Some water utilities follow the provisional guideline by WHO for Microcystin-LR of 1 μg/L (Aguilera et al., 2018b).		From 2011: Surveillance Program for the Uruguay River beaches by the Administration Commission of the Argentinean-Uruguayan Binational Commission, (CARU). Reports on the presence of cyanobacterial blooms in public beaches are posted on the CARU web page (https://www.caru.org.uy) on a weekly basis during summers or monthly during the rest of the year. 2021: The Water Resources sub secretary of Buenos Aires province launched an early warning system for cyanobacteria in recreative waters (https://www.gba.gob.ar/cianobacterias).
Bolivia	Eutrophication, urban contamination, heavy metals (Gossweiler et al., 2019; Guédron et al., 2017)	Not reported.	No regulations.	–	–
Brazil	Eutrophication from domestic and industrial waste, from agriculture; prolonged droughts, mining, floods and other major pollution disasters, deforestation (Azevedo, 2005).	1988: 88 human fatalities from intoxication and 2000 people were poisoned after drinking water from the Itaparica reservoir (Bahia) (Texeira et al., 1993). 1996: 130 patients poisoned and 76 fatalities, at a hemodialysis clinic, Caruaru (Azevedo et al., 2002; Carmichael, 2001) 2001: sublethal exposure, 44 patients poisoned with cyanotoxins at a dialysis clinic, Rio de Janeiro, (Soares et al. 2006). Skin irritation, Los Patos Lagoon (Yunes, 2009) 2003: Mass fish mortality Marechal Dutra Reservoir (Chellappa et al., 2008)	Cyanobacterial cell densities (PORTARIA GM/MS N° 888, DE 4 DE MAIO DE 2021), available in https://www.in.gov.br/en/web/dou/-/portaria-gm/ms-n-888-de-4-de-maio-de-2021–318461562 Cyanotoxins: Microcystins Cylindrospermopsin Saxitoxin	In Raw water (water body). When the results of the analysis reveal that the concentration of chlorophyll-*a* ≥ 10 μg/L, a new sample collection must be carried out for phytoplankton analysis ≤10 000 cells/ml (quarterly cells monitoring) >10 000 cells/ml (weekly Cells monitoring). When the cyanobacterial cell count ≥ 20,000 cells/mL, analysis of microcystins, saxitoxins and cylindrospermopsins should be performed at the point of uptake at least weekly. Weekly Monitoring of cyanotoxins in treated water when cell densities in raw water ≥ 20,000 cells/mL Limits: Microcystin-LR equivalent ≤ 1,0 μg/L Cylindrospermopsin ≤ 1,0 μg/L Saxitoxin ≤ 3,0 μg/L (STX equiv.)	Environmental monitoring and warning system and actions for cyanobacteria and cyanotoxins implemented: at >10 000 cells/ml weekly monitoring is required; at > 20 000 cells/ml toxicity testing and/or quantitative (Brazil, 2017, 2000) Cyanotoxins analysis in drinking-water is required. From 2000: Drinking Water Quality Surveillance Information System (SISAGUA), implemented by the Ministry of Health, with open data access about water quality, cyanobacteria and cyanotoxins in drinking water sources (http://sisagua.saude.gov.br/sisagua/paginaExterna.jsf) (Chorus, 2012; Cybis et al., 2006; Oliveira Júnior et al., 2019)
			For recreation waters: Visual monitoring in beaches. (Brazil 2000)	Two levels: Absence and presence of “algal” bloom.	
Chile	Eutrophication from agriculture, aquaculture and urban development. Most of the water bodies in the central and southern areas of the country are affected.	1985: Mass fish mortality Laguna Redonda (Parra et al., 1986).	No regulations. Cyanobacterial and microcystin quantification in sources used for drinking water is carried out by companies. WHOs guideline for microcystin LR in drinking water is followed (Almanza com. pers).	–	Monitoring water quality of country aquatic ecosystems (Lakes Control Network of General Directorate of Water, DGA). Phytoplankton and cyanobacteria are included as a parameter of water quality. Reports available at: https://snia.mop.gob.cl/repositoriodga/handle/20.500.13000/1/discover?query=fit

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Table 2 (*continued*)

Country	Main causes of freshwater deterioration (*)	Cyanobacterial intoxication events (on humans or animals)	CyanobacteriaRegulations Parameter regulated	Values	Monitoring plans
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Colombia	Eutrophication from domestic, industrial wastewaters, agriculture and aquaculture. Mining, misuse of pesticides, deforestation (Roldán, 2020).	Numerous cases of fish mortality (Magdalena River, reservoir of Betania (Comba, 2009), the Ciénaga Grande de Santa Marta and the Porce River).	No regulations. Some public service companies follow the WHO guidelines for microcystin in drinking water.	–	Information of harmful algal blooms is scarce. Decision trees, based on cyanobacterial cell abundance, are occasionally implemented (not published) (Palacio com. pers.).
Cuba	Eutrophication, waste water (Rodríguez-Tito and Gómez Luna, 2020)	Not reported.	No regulations.	–	Local surveillance system for drinking and recreational waters, with three levels based on phytoplankton and cyanobacterial densities. These levels support a decision chart framework proposed for cyanobacterial risk management. The procedure also includes establishing an adequate strategy to communicate with local authorities and the public.
Ecuador	Eutrophication, deforestation, poor agricultural practices (Steinitz-Kannan et al., 2020).	Not reported.	No regulations.	–	–
Guatemala	Eutrophication, urban and agro-industrial wastewater. 25 years with precipitation below the historical annual average.	Not reported.	No regulations.	–	–
Honduras	Eutrophication, deforestation, forest fires, raw sewage discharges.	Not reported.	No regulations.	–	Monitoring is very limited, lack of continuity. Phytoplankton and cyanobacteria are not analysed.
Nicaragua	Eutrophication.	Not reported.	No regulations.	–	Monitoring system of water quality not including phytoplankton or cyanobacteria.
Paraguay	Freshwaters contamination by nutrients, industrial pig manure and domestic wastewater (Benítez Rodas et al., 2017).	2020: fish mortality, bad smell of water (Dos Santos et al., 2021).	Microcystin-LR in drinking water, recreation, irrigation (Decree_N222/02. 2002).	1 μg/L for all types of uses	Monitoring of water quality from 2012 to 2021 in the eutrophic lake Ypacarai (Universidad Nacional de Asunción e Itaipú Binacional). Some data are available at: https://geohidroinformatica.itaipu.gov.py/documents/?keywords_slug_in=Ypacarai&limit=5&offset=25
Peru	Eutrophication, mining, aquaculture.	Not reported.	Microcystin-LR. Cyanobacterial abundance and biovolume. Recent reports use WHOs updated guides based on biovolume (website AUTODEMA)	1 μg/L for drinking water. Water for drinking process or recreation, threshold: 5×10^6 organisms/L.	The SUNASS (National Superintendence of Sanitary Services) has guidelines for raw water including cyanobacteria, odor, taste and microcystins for drinking water (drinking water regulation DS No. 031–2010-SA). (Munoz et al., 2020) Some other monitoring initiatives of drinking water sources, especially in the Arequipa region. Reports are available at the website of the institution (AUTODEMA):

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Table 2 (*continued*)

Country	Main causes of freshwater deterioration (*)	Cyanobacterial intoxication events (on humans or animals)	CyanobacteriaRegulations Parameter regulated	Values	Monitoring plans
					https://www.autodema.gob.pe/resultados-laboratorio-de-calidad-de-agua/
Uruguay	Eutrophication mainly from agriculture (Bonilla et al., 2015; Conde and Sommaruga, 1999; Goyenola et al., 2021).	2011: Human acute intoxication by an MC-producing cyanobacterial bloom, Salto Grande reservoir (Argentina-Uruguay) (Giannuzzi et al. 2011). 2015: A case of acute liver failure in a baby, probably related with an exposure to cyanobacterial scum on a beach (Vidal et al. 2017). 2014–2016: Detection of microcystins in serum of livestock (drinking from sources with toxic cyanobacterial blooms), ranches on Río Negro river (Brena et al., 2021).	For drinking waters: Microcystin-LR (UNIT, 2010) For recreation waters: Visual monitoring in beaches.	1 µg/L: followed by the national drinking water facility. Three levels: Absence, presence and scums.	Alert system of the national drinking water facility (OSE): When potentially toxic cyanobacteria > 2000 cell/mL or 0.2 mm^3/L in treated water, or when dense blooms are observed in raw water: Microcystin analyses (ELISA) are carried out. Saxitoxin and cylindrospermopsin (by ELISA) are also analysed (Chorus and Welker, 2021). Information and reports are available at the institutional website. Data available upon request). From 2000: Visual monitoring program for in recreational waters of Montevideo (by the Municipality of Montevideo). From 2010: alert sanitary flag display on the beach for avoiding swimming and contact with the water when scums are present (Chorus and Welker, 2021). Weekly reports are available at the institutional website. Interactive maps with real time information are also available. https://montevideo.gub.uy/areas-tematicas/cultura-y-tiempo-libre/playas The Ministry of Environment implemented a national protocol for the monitoring of recreational waters based on visual inspection (three levels of cyanobateria). A program for monitoring cyanobacterial blooms based on satellite images is under evaluation. Data are open and available at: https://www.gub.uy/ministerio-ambiente/cianobacterias.
Venezuela	Eutrophication.	Not reported.	No regulations.	–	Limited monitoring systems for drinking water sources, not specifically including cyanobacteria.

rivers by dam constructions, eutrophication as a consequence of agriculture, and the lack of adequate sanitation service, which are forecasted to be intensified in the future (González Rivas et al., 2020; Grill et al., 2019; IANAS, 2019; Zabel et al., 2019). Climate predictions include modifications in the precipitation pattern with an increase in high rainfall or in duration of drought periods in different regions of South and Central America (Rodell et al., 2018; Torremorell et al., 2021). Due to long droughts, countries such as Argentina, Chile and Brazil are already facing challenges regarding clean water scarcity (Rodell et al., 2018). Current climate change and human impacts in the region can trigger the magnitude and frequency of cyanobacterial blooms in the future, compromising the access to clean water for Latin American inhabitants.

3.7. *Current monitoring policies and regulations*

Results in the present work suggest that the risk of being exposed to toxic cyanobacteria and their toxins is high in the region. However, this is not translated in monitoring plans and regulations, which are still limited or absent in several Latin American countries (Fig. 1, Table 2). Argentina, Brazil and Uruguay have, so far, comprehensive studies evaluating the distribution of bloom forming species and bloom events (Aguilera et al., 2018b; Barros et al., 2019; Bonilla et al., 2015; Haakonsson et al., 2017; O'Farrell et al., 2019; Sant'Anna et al., 2008; Soares et al., 2013). For the other countries (e.g., Peru, Chile, Colombia and Venezuela), the information is fragmented or limited to specific ecosystems or watersheds (Almanza et al., 2019; Moreira et al., 2018; Rodas-Pernillo and Vasquez-Moscoso, 2020; Rodríguez-Tito et al., 2022; Rodríguez-Tito and Gómez Luna, 2020; Salomon et al., 2020; Steinitz-Kannan et al., 2020; Venegas et al., 2018).

Another critical aspect for improving bloom management is the open access to the data (Rashidi et al., 2021) which is still limited in many countries of the region (Dörr et al., 2010; IANAS, 2019; Merel et al., 2013a, 2013b). In Argentina, Chile, Paraguay and Colombia, where monitoring of drinking water sources is responsibility of local authorities or private companies, the information about cyanobacterial presence and abundances is not always available via publications, reports or internet sites. Brazil and Uruguay have taken public policies to increase the quantity and quality of available information on water quality, including cyanobacteria (Table 2).

Several countries lack national regulations regarding cyanotoxins (Fig 1, Table 2). Most countries define limits for cyanotoxin concentrations in drinking water but not in water used for recreational purposes. While such limits are defined for microcystins, other cyanotoxins are rarely explicitly regulated. The levels of microcystin LR are regulated in some countries (e.g., Peru and Paraguay) or regulations are under evaluation (e,g., México, Munoz et al., 2020). In some countries (e.g., Argentina and Chile), few drinking water treatment plants follow the provisional guidelines for microcystin LR suggested by WHO. The national drinking water facility of Uruguay follows the WHOs guidelines for microcystins in drinking water, but saxitoxins and cylindrospermopsin are also tested (Vidal and Britos, 2012). Reports are periodically available on the website, and databases are publicly available upon request. Brazil has the most exhaustive regulation and surveillance system for cyanobacteria and cyanotoxins in drinking and recreational water sources (Azevedo, 2005; Bittencourt-Oliveira et al., 2014) which includes mandatory standard values for microcystins, saxitoxins, and cylindrospermopsin (Brazil, 2021). Most of the information is available online since 2000 due to the initiative of the ministry of health (Drinking Water Quality Surveillance Information System, SISAGUA) (Oliveira Júnior et al. 2019).

Large freshwater basins are transnationals, and management decisions at a country level affect neighboring ones. The binational monitoring program between Argentina and Uruguay on the Uruguay River based on WHO Alert Levels for recreational waters is one of the few good examples of regional cooperation (Table 2). However, the current lack of common regional agreements, information exchange between policy makers and stakeholders, and restrict access to data are clear limitations to develop regional effective management plans to control blooms with a cross-border perspective.

4. Recommendations for the future and conclusions

- The use of different criteria to define a cyanobacterial bloom hampers the estimation of their occurrence, and consequently the associated risks and economic impacts. This highlights the urgent need to stablish a standard operational definition.
- Synoptic studies in Latin American countries are needed to further understand, predict and mitigate cyanobacterial blooms.
- Long-term monitoring plans must be implemented. In countries with severe technical and economical limitations, visual inspection may represent the first step to filling up information gaps about blooms (Bazán et al., 2020; Kotovirta et al., 2014; Mitroi et al., 2020). The incorporation of other new methodologies, such as satellite-based remote sensing tools or in vivo pigment fluorescence, could also provide consistent, low-cost data for the development of large geographical monitoring programs (Maciel et al., 2022).
- Policies leading to solid frameworks are needed to improve cyanobacterial bloom management and cyanotoxin risk assessment. Regulations should also address the presence of other cyanotoxins, for which no guideline values can be derived due to insufficient toxicological data. – In equipment and human resources training, large investments are necessary to increase the detection capacity of different toxins, and cyanobacterial identification and quantification.

Unlike the situation in other developing regions, Latin America has a political and historical context of good understanding of freshwater issues and information exchange, being a favorable scenario to generate international regulations to ensure water quality (Biswas, 2011). Given the adverse effects of economic pressures on the environment, possibly aggravated by climate change, cyanobacterial blooms are here to stay and intensify. This is a call for Latin American societies to unify efforts toward cyanobacterial bloom management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hal.2023.102429.

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