Cyanobacterial Problems in South American Reservoirs: Historical Background, Current Status and Prospects for Countermeasures

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1. Historical Background

The incidence and intensity of cyanobacterial blooms are on the rise worldwide, and it has been suggested that global changes might aggravate the frequency, intensity, and spreading of such blooms, promoting an increase in cyanobacteria occurrence, even in higher latitudes (O'Neil et al. 2012; Huisman et al. 2018). Altered precipitation patterns which increase both external nutrient loadings and water residence time, elevated atmospheric carbon dioxide concentration, high pH and salinity/conductivity as well as temperature effects are all expected to drive cyanobacterial growth and consequently its dominance in aquatic ecosystems.

Bloom-forming cyanobacteria are a natural component of phytoplankton in most surface waters around the world. However, once they reach a high biomass (blooms) it contributes to aesthetic problems, impairs recreational use and might result in the development of obnoxious taste and odour in water supplies. In addition to these harmful effects, the freshwater cyanobacteria have received increasing attention due to their ability to produce toxins named cyanotoxins **(Figure 1)**.

Cyanobacteria comprise about 369 genera among which some species can produce a wide range of bioactive metabolites (named as cyanotoxins and other metabolites). Based on their chemical structure, the most studied cyanotoxins are divided into three main groups: cyclic peptides (microcystins and nodularins), alkaloids (anatoxin-a, guanitoxin (formerly anatoxin-a(s)), saxitoxins, cylindrospermopsin, aplysiatoxin and lyngbiatoxins), and cell-wall lipopolysaccharides – LPSs (Haider et al., 2003; Funari and Testai, 2008; Kaebernick and Neilan, 2001; Fiori et al. 2020). However, based on biological effects, the cyanobacterial toxins can be classified into five functional groups such as hepatotoxins, neurotoxins, cytotoxins, dermatotoxins and irritant toxins (Chorus and Bartram, 1999; Codd et al., 2005).

Harmful effects of cyanobacterial blooms include potential intoxication of humans and animals, crop contamination by irrigation with contaminated water, fish mortality, oxygen depletion, odour and taste provided by volatile compounds (e.g. geosmin and MIB – 2-Methylisoborneol) and aesthetic signs (pea soup-like color – **Figure 2**) which restrict water use. These phenomena also affect social and economic conditions. However, the actual impact of various climate change scenarios on bloom development, composition and toxicity has not been widely studied. Although eutrophication has been recognized globally as a growing concern since the 1950s, only in the last four decades, the proliferation of toxic cyanobacterial blooms has become recognized as a human health problem and is increasing its occurrence nowadays.

While the cyanobacteria are natural components of any aquatic ecosystem, warning to the occurrence of these microorganisms in public water supply is relatively new. The cultural eutrophication of rivers, natural lakes and reservoirs has been produced mainly by the discharge of domestic and industrial sewage from urban centres and by the diffuse pollution from agricultural regions. This artificial eutrophication produces changes in the water quality, including the increase of the incidence of blooms of microalgae and cyanobacteria, with negative consequences on the efficiency and the cost of water treatment. In tropical countries, the problem of blooms is intensified by the fact that the majority of the water supplies present a proper water temperature for the intense growth of cyanobacteria throughout the year resulting in perennial blooms.

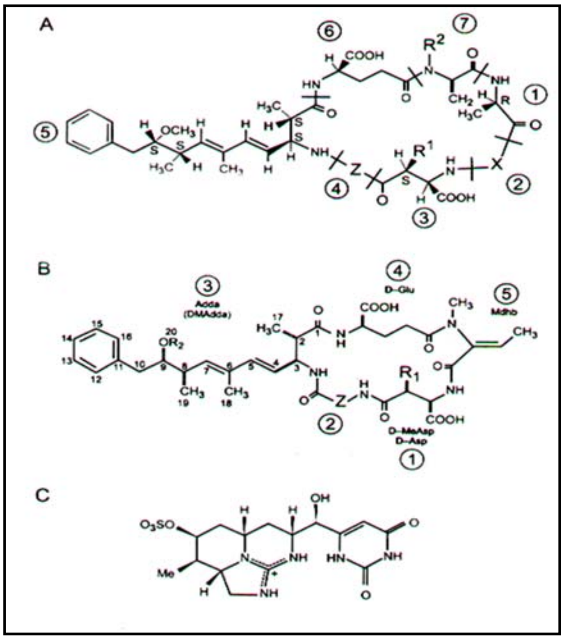

Figure 1.1. Chemical structure of hepatotoxins:
A: Microcystins (general structure); B: Nodularin; C: Cylindrospermopsin

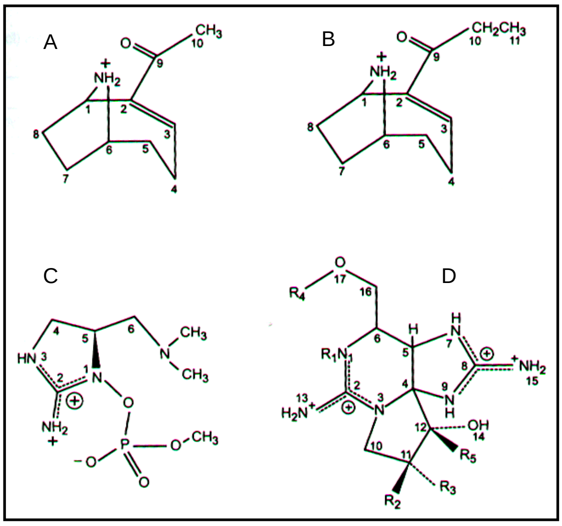

Figure 1.2. Chemical Structure of neurotoxins:
A: Anatoxin-a; B: homoanatoxin-a; C: guanitoxin; D: saxitoxins (general structure)

Moreover, it is impossible to consider cyanobacteria as pathogenic microorganisms in the classical sense, because although several strains of different species can produce bioactive and toxic secondary metabolites for cells of several animal groups (cyanotoxins), a large part of these compounds is only released into the water after cell lysis. The quality of water may be more compromised by the presence of dissolved cyanotoxins than by viable forms of cyanobacterial cells which should be removed during the conventional treatment of water. In turn, this procedure can lead to the rupture of the cells of these microorganisms due to the use of chemicals during this treatment process.

Cyanobacteria are also often associated with the production of compounds that provide taste and odour to drinking water. Although these compounds cannot be considered toxic as cyanotoxins, their presence cause concern to health authorities, seeing that frequently it results in the population rejecting the potable water, leading them to seek alternative sources of water supply. It can promote an additional risk to public health. In many of these cases, the cyanobacterial bloom can disappear from the reservoir before health authorities consider the bloom as a possible risk. It happens because these authorities are usually unaware of the potential damages that result from the occurrence of cyanobacteria blooms and, therefore, they assume that conventional water treatments are able of removing any potential problem.

The chronic or episodic exposure to cyanobacterial toxins is the leading cause of human exposure to these compounds, especially orally, through water supplies. On the other hand, studies undertaken in Brazil by Magalhães et al. (2001) and Magalhães et al. (2003) demonstrated that fish (tilapias) and crustaceans are also capable of accumulating microcystins in their muscle tissues, sometimes even at levels way above the limit recommended by WHO, which represents a severe risk to the population that consumes those fish. Also, fish farming activities mainly by using tank networks, which promote a rapid and intensive eutrophication process, can intensify the impacts caused by toxic cyanobacteria in aquatic environments.

Figure 2. Pea-soup like aspect of water during a *Microcystis* spp. bloom in Mundaú reservoir, Pernambuco – Northeastern Brazil. Photo: Vilar, M. C. P. (2012)

2. The occurrence of cyanobacterial blooms and cyanotoxins in Latin America

A recent survey done in the Thomson Reuters Web of Science database showed that the data on cyanobacteria blooms and cyanotoxins issues were registered in worldwide publications for more than 70 years. During the last decade (2009 – 2019), the number of published papers about these topics is still high. But, when we consider publications related to studies done in Latin America, it is possible to observe that it represents around 10% of global scientific publications **(Figure 3)**. This finding is coherent when we realize that Latin America represents a territory of 13% of the global territorial land, and its population is 7.8% of the world population.

To focus on the causes and consequences of toxic cyanobacterial blooms in Latin America it is necessary to consider the anthropogenic impacts on aquatic ecosystems and their relationship with water quality and public health. As observed in other continents, in Latin America, human activities lead to the multiple uses of water resources such as the supply for public provisioning, irrigation, industrial use, navigation, recreation, and aquaculture. Maybe the most aggravating difference is the complex mosaic of water uses that lack public management. Although these activities vary according to the occupation and use of the watershed and with local economic and social organization, they often generate impacts that cause deterioration in water quality and interfere with its availability. As consequence of these impacts, it is common to observe the accelerated artificial eutrophication of inland and coastal water bodies through anthropogenic disposal of organic pollutants. Eutrophication has become widespread, mainly in regions where the growth of the agro-industry and urbanization has undergone a rapid rate of increase without a corresponding improvement in wastewater treatment.

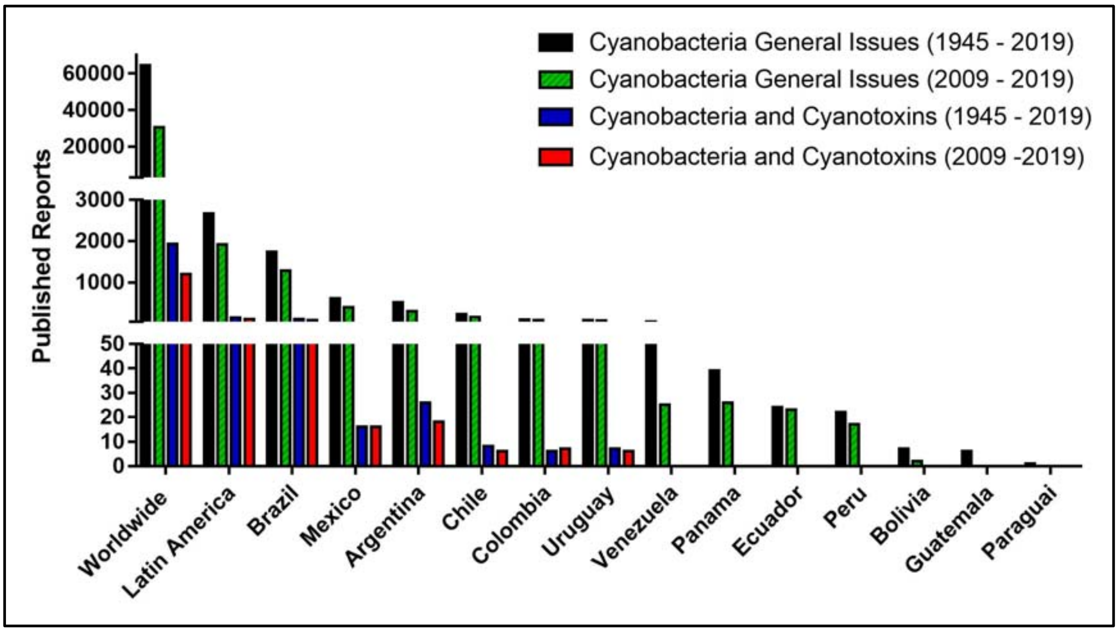

Figure 3.1. Total number of published studies on cyanobacteria blooms and cyanotoxins. Source: Thomson Reuters Web of Science database accessed on October 2019.

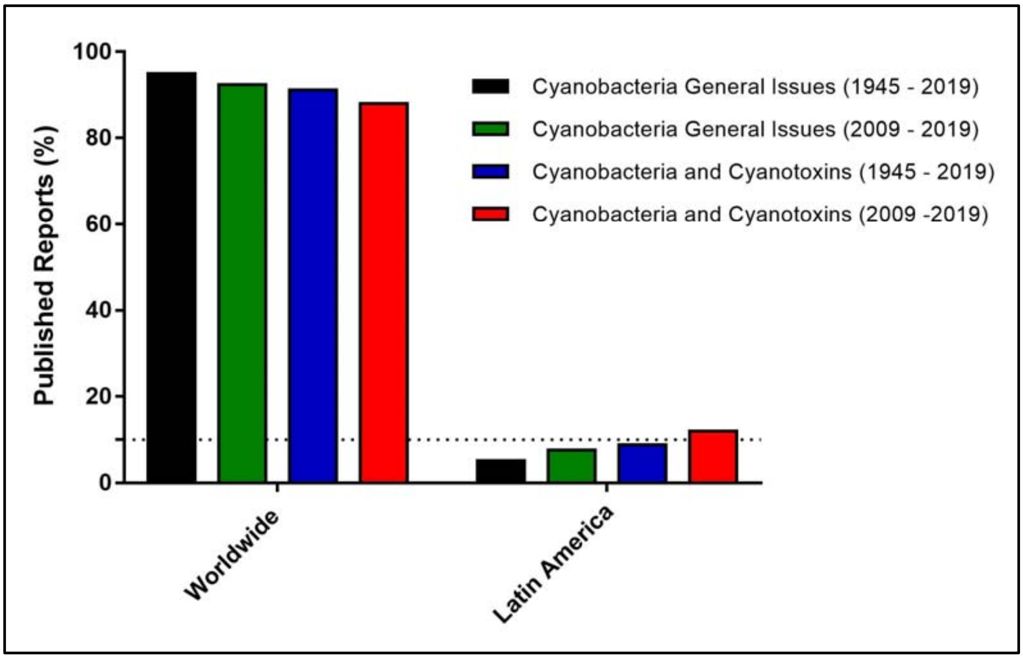

Figure 3.2. Percentage of published studies on cyanobacteria blooms and cyanotoxins. Source: Thomson Reuters Web of Science database accessed on October 2019.

According to a recent report of WHO (2017), this situation is found in all Latin America since only 22% of wastewater is safely managed. This problem is particularly relevant because, according to that report, about 23 million people are living without clean, safe drinking water.

Based on those data, it is clear that public health in Latin America is at high risk from the degradation of aquatic ecosystems due to the contamination of water resources and drinking water supplies. The disposal of sewage in waterbodies is not only a problem of eutrophication due to nutrient input, but also acts as an inoculum of several pathogenic microorganisms in water, once most of the disposed effluents are not treated. Thus, in this region, the most well recognized relationship is the transmission of waterborne diseases (e.g. cholera, hepatitis A, giardiasis) through the consumption of water. It is already known that, besides compromising water quality due to toxins availability and the production of odour and taste compounds, cyanobacterial blooms also can host antibiotic resistance genes (antibiotic resistome) (see Dias et al. 2018 and Guo et al. 2018) which increase the frequency of antibiotic resistant bacterial strains in water.

Cyanotoxin-producing cyanobacterial species are globally distributed. Therefore, the lack of effective responses to solve problems related to the harmful effects of toxic cyanobacteria is the same for developed or developing countries. However, in developing countries, the occurrence and consequence of cyanotoxins are usually underestimated by critical gaps in knowledge about ecology and physiology of harmful cyanobacterial species, management actions, and analytical methods for toxin detection**.**

Regarding cyanobacterial bloom occurrence and cyanotoxins analysis, it is clear that the phenomenon is well known in several countries, but there are few official reports and published data for the majority of countries in Latin America. In the **Figure 3-1**, as showed in the number of publications since 1945, it is evident that reports about toxic cyanobacteria are concentrated in six countries: Argentina, Brazil, Chile, Colombia, Mexico, and Uruguay.

In general, there is little information about cyanotoxins analysis or toxicity assessments done with cyanobacterial bloom material. The most common cyanotoxin detected is the cyclic heptapeptide microcystin (MC) which is currently distributed in more than 100 variants. These hepatotoxic heptapeptides were already confirmed in samples from Argentina, Brazil, Chile, Colombia, Mexico, and Uruguay (Ruibal, 2003; Azevedo et al. 1994; Campos et al. 1999; De Leon & Yunes, 2001; Vasconcelos et al. 2010; Nimptsch et al. 2016 and León & Peñuela, 2019). Besides, there are reports about microcystins in water supplies from Argentina, Brazil, Chile, and Uruguay and even in treated water from Argentina, Brazil, and Uruguay. Most of the analyzes were done by HPLC (*high performance liquid chromatography*) or ELISA (*enzyme-linked immunosorbent assay*) techniques, but there are references for the use of LC-MS (*liquid chromatography coupled to mass spectrometry*) in Argentina, Brazil, and Chile. The situation in each of the countries in Latin America is described below.

Argentina: The occurrence of toxic cyanobacterial blooms has been observed since 1947, according to Ringuelet et al. (1955). The authors described massive fish mortality in a lagoon caused by *Anabaena inaequalis, Anabaena circinalis* (currently *Dolichospermum circinale*), and *Polycystis flos-aquae* (currently *Microcystis flosaquae*). Since the 1980s, several blooms have been observed in rivers, reservoirs, lakes, coastal lagoons and estuaries from North to South Argentina (25º - 55ºS). More recently, reports of toxic cyanobacteria from different orders such as Nostocales, Chroococcales, Synechococcales, and Oscillatoriales have been presented. *Microcystis* and *Dolichospermum* are still the most predominant genera among different freshwater bodies (reservoirs, lakes, and rivers). About 60% of blooms occurrence in rivers is related to *the Microcystis* genus. In reservoirs, about 45% of blooms are represented by *Microcystis* and *Dolichospermum* (Aguilera et al., 2018). Previous studies showed values of microcystins in rivers between 0.6 µg/L to 37.7 µg/L and in reservoirs 0.17 µg/L to 48.6 µg/L. Detection of saxitoxins is also reported with values in rivers between 0.31 µg/L to 105.33 µg/L (Aguilera et al., 2018; Otaño et al., 2009). There is a report of an intoxication case of a young man who was exposed to a bloom with a value of microcystin-LR of 48.6 µg/L after swimming on the Salto Grande reservoir (Giannuzzi et al. 2011). Regarding monitoring strategies, Argentina has been developing a monitoring program with Uruguay (Argentinean-Uruguayan Binational Commission - CARU) to prevent cyanotoxin exposure and health issues (Aguilera et al., 2018).

Bolivia: Data about cyanobacterial blooms are still incipient, but recent works have shown reports of *Microcystis* blooms in urban lagoons (Morales et al. 2015) and also blooms of the rarely toxic species *Arthrospira fusiformis, Anabaenopsis milleri and Aphanocapsa* sp. in the same waterbody – Alalay Shallow Lake *(*Morales et al. 2017). Even without data about cyanotoxins, these reports relate to the presence of cyanobacteria with eutrophication processes.

Brazil: Records about cyanobacterial blooms come from the 1980s. A review in the literature on phytoplankton ecology in Brazilian environments, considering studies with at least a one-year database, showed that aquatic environments located in areas with a robust anthropogenic influence present a high percentage of cyanobacterial dominance and bloom occurrence. On average, almost 50% of those environments are already presenting cyanobacterial dominance. Part of this occurrence can be attributed to natural causes, but an increase in the number of environments showing cyanobacteria as the dominant group in the phytoplankton community has been observed.

The occurrence of toxic cyanobacterial blooms has already been registered at all Brazilian regions from the North to the South region (Soares et al. 2013; Carvalho et al. 2008; Teixeira-Adloff et al. 2018; Assis et al. 2018; Moura et al. 2018; Barros et al. 2019). These blooms occur mainly in reservoirs, but there are records of occurrence in several coastal lagoons, natural lakes, rivers, and estuaries. It is an especially worrying issue because, in Brazilian regions that usually suffer severe droughts and water scarcity, cyanobacterial blooms have been frequently reported (Barros et al., 2019).

According to a review by Sant'Anna et al. (2000), there were 32 species of cyanobacteria that are potentially cyanotoxins producers already registered in Brazil: 12 Chroococcales, 10 Oscillatoriales and 10 Nostocales. According to Soares et al. (2013), the most common genera are *Microcystis, Raphidiopsis/Cylindrospermopsis* and *Dolichospermum* which have also formed multispecies blooms (co-dominance) representing a problem regarding the availability of more than one type of toxin (e.g. *Microcystis-Raphidiopsis* co-dominance → potential microcystins and saxitoxins availability in water).

Furthermore, the isolation of toxic nanoplanktonic cyanobacteria (*Synechocystis aquatilis)* from coastal areas and toxic picoplanktonic cyanobacterial strains from reservoirs in the Brazilian Northeast region (Domingos *et al*., 1999; Komárek, *et al.,* 2001) define a new challenge for public health and water treatment authorities. Due to the small size of these cells, their identification requires special care, and the removal by traditional methods of water treatment can be more difficult. Therefore, the potential toxicity of these species needs to be considered, and the risk from picoplanktonic cyanobacteria in water supplies needs to be monitored to minimize the hazards of cyanotoxins.

Previous works have shown the strong relation of eutrophication and high temperature on cyanobacterial blooms occurrence, and the presence of cyanotoxins such as microcystins on Brazilian (sub)tropical reservoirs (Cunha et al., 2018). Brazil has been developing polyphasic approaches using molecular strategies for the management of water bodies searching for potentially toxic strains during bloom development (Genuário et al., 2016; Pacheco et al., 2016). Data about cyanotoxins (microcystins, saxitoxins, and anatoxin-a) production by genera such as *Microcystis, Raphidiopsis/Cylindrospermopsis* and *Planktothrix* have been already reported (Sant'Anna et al., 2008).

Chile: The first report about cyanobacterial blooms occurred in 1995. It happened in a natural lake in the Concepción region, where another event was registered in 1998. The main genus was *Microcystis* in both lakes. (Campos et al., 1999; Neumann et al., 2000). There are reports of toxic blooms of *Microcystis* at Lo Galindo lake, an urban lake where microcystins (MC-LR, MC-LA and MC-RR) were detected by Almanza et al. (2016). A recent study has shown the relation between the trophic state of watershed and its utilization and blooms of cyanobacteria at fourteen temperate lakes in south-central Chile (Almanza et al., 2019 and Almanza et al., 2016). Another critical data in Chile is the first report of blooms of *Microcystis* in Chilean North-Patagonian lakes with microcystin (MC-LR) values above 1 $\mu g\ L^{-1}$, and the first report of *Raphidiopsis raciborskii* (formerly *Cylindrospermopsis raciborskii)* at a Chilean lake with no neurotoxins detection (Nimptsch et al., 2016).

Colombia: Some reports about blooms of cyanobacteria are related to aquaculture activities in coastal lagoons, floodplain lakes and estuaries (Mancera and Vidal, 1994). The main genera described are *Microcystis* and *Raphidiopsis/Cylindrospermopsis.* Also, a recent research showed blooms of toxic *Microcystis* in two reservoirs impacted by agricultural and industrial activity producing microcystin (MC-LR) (Herrera et al., 2018). Another recent report showed the presence of nodularin (NOD), cylindrospermopsin (CYN) and microcystins (MC-LR, MC-LW, MC-YR, MC-RR, and MC-LF) in Abreo Malpaso, El Peñol and Playas reservoirs at Antioquia region (León and Peñuela, 2019). The previous report registered blooms of *Okeania, Lyngbya, Symploca, Phormidium, Oscillatoria* and *Spirulina* on the coastal region of Old Providence Island (Puyana et al., 2015). Blooms of *Phormidium* sp., *Planktothrix* sp.*, Oscillatoria* sp. and *Pseudanabaena* sp. were also reported on Cesar River in Salguero, an environment impacted by wastewater disposal (Luna and Issn, 2010).

Ecuador*:* Data about cyanobacterial blooms are scarce. There are reports from the Daule-Peripa reservoir, Daule river (Provincia de Guayas) (Prado and Bucheli, 2012), and Yaguacocha lagoon (Provincia de Imbabura) by Saelens (2015). More recently, blooms of *Raphidiopsis/Cylindrospermopsis* were registered in Lake Yahuarcocha. Blooms of this genus were also detected in Pishira and Playayacu Rivers, both environments impacted by wastewater and eutrophication processes (Van Colen et al., 2017 and Venegas et al. 2018). However, no data about cyanotoxin production was found to date.

Guatemala: There are few data about cyanobacterial bloom occurrence in Guatemala. Recently there was a bloom of *Microcystis* reported on Lake Atitlan (Rejmánková et al., 2011).

Mexico: Most of the information about blooms and their toxicity was developed in the last 10 years. After a screening on freshwater bodies on Mexico, including natural lakes (Zumpango, Laguna Atotonilco, and Cienega Chica), reservoirs (Los Angeles and Valle de Bravo), man-made channels (Cuemanco, Tlameleca) and urban lakes (Chapultepec), Vasconcelos *et al.* (2010) detected microcystins in those environments. Recent work reported *Microcystis* blooms in the Vale Bravo reservoir which is used for water supply and recreation, and also detected microcystins in the raw water (Nandini *et al.*, 2019). A report of toxic blooms of *Raphidiopsis/Cylindrospermopsis* was registered and cylindrospermopsins (CYN) was detected on Lake Catemaco (Berry and Lind, 2010).

Peru: A few data about cyanobacterial blooms have been found. Reports about *Microcystis* and *Limnoraphis robusta* blooms in Lake Titicaca (in the portion called as lake Mayor) were published. Blooms of *Sphaerocavum brasiliense* and *Microcystis wesenbergii* in lagoon Huacachina were also registered by Komárková et al. (2016) and Mendoza-Carbajal (2016). Previous work showed changes in trophic conditions of Lake Titicaca from oligotrophic to mesotrophic and related it to blooms of *Microcystis* and the presence of filamentous cyanobacteria such as *Nodularia inca* at Puyo Bay (Montoya, 2014).

Uruguay: The occurrence of cyanobacterial blooms has been observed in rivers, reservoirs, lakes, coastal lagoons, and estuaries (Perez et al., 1999; Kruk and De Leon, 2002). These events are related to increased eutrophication and changes in river hydrodynamics due to the construction of reservoirs in cascade, which interferes with water retention time and favour bloom formation. Some studies showed the increase of eutrophication and its relationship with cyanobacterial blooms in Uruguayan rivers (Aubriot, 2018; Olano et al. 2019). Data about blooms of N_2-fixing cyanobacteria such as *Raphidiopsis raciborskii* and *Dolichospermum* sp. in Lower Uruguay River were presented by González-Madina et al. (2019) and Kozlíková-Zapomêlová et al. (2016). Blooms of *Microcystis* spp. and *Dolichospermum* spp. were also described by O'Farrell et al. (2012). Studies about microcystin (MC-LR) analyses were performed in the Negro River, and evidenced a constant presence of this cyanotoxin in water (González-Piana et al., 2017). A critical acute intoxication case occurred when a 20-month-old child was intoxicated after recreational activities at Carrasco e Malvin beaches (Monte Video, Uruguay). This child was subjected to liver transplant after acute intoxication by microcystins during an intense *Microcystis* bloom (Vidal et al., 2017).

Venezuela: There are few data on the occurrence of cyanobacterial blooms in Venezuela. Those reports come from 1978. Those data show the critical impact of these events since they have occurred in big lakes and reservoirs used as water supplies for cities, including Caracas and Valencia. The principal genera reported are *Microcystis, Anabaena, Raphidiopsis* and *Synechocystis* (Gonzalez et al., 2004).

A summary of these data is presenting in **(Table 1)**. In general, a gradient on the number of different studies or researches involving toxic cyanobacteria species and their cyanotoxins is observed (**Figure 4).**

Figure 4. Representative flowchart of the estimated amount of studies in different research areas related to cyanobacteria and cyanotoxins in developing countries.

Table 1. Summary of data from Latin American countries

Country	Occurrence of Blooms (*)	Most common genera	Cyanotoxins	Methods for cyanotoxin analysis	Report incidents	Epidemiological studies	Adverse effects	Management actions	Available educational actions and material
Argentina	1,2,3,4,5	*Microcystis Dolichospermum*	Microcystins saxitoxin	HPLC, LC-MS, ELISA	Bad taste and odor; Fish and birds death; Skin irritation; Digestive and respiratory disorders	No data	Bad tastes and odors in drinking water; reduction of tourism; activities; fish death, dog death, skin irritation and respiratory disorders	Phytoplankton monitoring program; Sewage treatment plants; Drinking water guidelines under revision	Raising poster distribution; Workshops; Training courses
Brazil	1,2,3,4,5	*Microcystis, Cylindrospermopsis, Raphidiopsis, Planktothrix Dolichospermum*	Microcystins Saxitoxins Anatoxin-a(s) Cylindrospermopsin	HPLC, LC-MS, ELISA.	Bad taste and odor; Fish and birds death; Human death; Digestive disorders	Epidemiological study with hemodialysis patients	Bad taste and odors in drinking water; Bioaccumulation of microcystins by fish and zooplankton Fish mortality	Phytoplankton monitoring program;	Folders and technical literature distribution; Training courses; Workshops Guidelines
Bolivia	3	*Arthrospira Anabaenopsis Aphanocapsa sp*	No data	No data	No data	No data	No data	No data	No data
Chile	3	Microcystis *Raphidiopsis*	Microcystins	HPLC ELISA MALDI-TOF-MS	No data	No data	No data	Phytoplankton monitoring program	No data
Colombia	2,4,5	*Microcystis Cylindrospermopsis Raphidiopsis*	- Cylindrospermopsin Microcystins Nodularin	UHPLC-MS/MS HPLC, LC-MS,	No data	No data	Massive fish death	Phytoplankton monitoring program	Training course and workshop

Ecuador	1,3	*Cylindrospermopsis*	No data	No data	No data	No data	No data	No data	No data
Guatemala	3	*Microcystis*	No data	No data	No data	No data	No data	No data	No data
Mexico	2, 3	*Microcystis, Dolichospermum Planktothrix, Aphanizomenon Cylindrospermopsis Raphidiopsis*	Cylindrospermopsin Microcystins	HPLC ELISA MALDI-TOF-MS,	No data	No data	No data	No data	No data
Peru	3	*Microcystis Limnoraphis Nodularia Sphaerocavum*	No data	No data	No data	No data	No data	No data	No data
Uruguay	1,2,3,4,5	*Microcystis Dolichospermum Nodularia Cylindrospermopsis Raphidiopsis*	Microcystins	ELISA	No data	No data	Digestive disorders	Phytoplankton monitoring program; Advise against recreational activities near blooms; Drinking water guidelines under revision	Training courses; Workshops
Venezuela	2 , 3	*Microcystis Dolichospermum Cylindrospermopsis*	No data -	No data	No data	No data	Bad taste and odor	No data	Workshops

(*) 1 – Rivers; 2 – Reservoirs; 3 – Lakes; 4 – Costal Lagoons and 5 - Estuaries

The causes of this gradient can be explained by different reasons as follows:

1) Usually, the identification and classification of cyanobacteria, considered here as taxonomic and systematic studies, are the most common data obtained in developing countries. It is relatively easier to find groups with skills on studying the identification of benthic and planktonic cyanobacteria. However, those studies are usually concentrated in some academic institutions and focus on a particular region or ecosystem. Besides the identification, measuring the abundance of these microorganisms in water is an attribution of ecological studies, which focus on studying cyanobacterial population dynamics (as well as community structure and ecosystem functioning), their interactions with other species and the environmental factors.

2) Environmental agencies do most of the monitoring programs, sometimes with the collaboration of an academic group. In general, regulation is made by managers from environmental and health authorities that cannot know enough on the causes and consequences of cyanobacterial blooms. Besides, sometimes, some decision-makers prefer to import experiences and expertise, not considering the variability that can be observed in a particular ecosystem.

3) As observed for taxonomic studies, the researches about ecology, chemistry, and toxicology of toxic cyanobacteria are usually done at universities or research institutes. However, in general, the number of these studies, their continuity and advancements are much more related to the grants available for the research than with the number of experts dedicated to those areas.

4) Studies involving molecular biology techniques started later in developing countries, mainly due to the high cost associated to these approaches. Moreover, usually, these studies are much more established and concentrated on biotechnology programs than on environmental sciences. But they are fundamental (and complementary) to solve some questions related to toxic cyanobacteria issues.

5) Finally, to develop modelling studies is fundamental to have a good and consistent database. Unfortunately, in Latin American countries, few aquatic ecosystems have been monitored adequately for enough time to generate a minimum set of data that allows the development of modelling programs.

Besides, it is hard to find modelling experts (*e.g.* mathematicians, statisticians and physicists) with good understand of environmental or biological sciences. It is also hard to find a biologist who knows enough mathematics or computer science to develop the models. However, this is not necessarily unique to developing countries as it is observed around the world.

3. Critical gaps in Latin America studies and Prospects for Countermeasures

To understand the main gaps observed should be essential to consider the critical points that need to be investigated better.

For **Taxonomy and Systematics, the** main points to be focused are: Identification and classification of cyanobacterial groups regarding their life-history strategies, genetic diversity and phenotypic traits. The main gaps observed on the identification and classification of bloom-forming cyanobacteria species are:

- Identification of different morphotypes. There are some problems related to the identification of some cyanobacteria species because most of the literature available is about species or morphotypes from temperate regions that, of course, usually do not cover the diversity of morphological variability observed in tropical regions.
- Identification of types of resting stages;
- Different strategies among closely related species or different populations of the same species

These two last points can result in severe problems during the proposal of management measures. Nevertheless, the development of new tools for the detection and identification of cyanobacteria (e.g. genetic probes) can reduce the analysis time in monitoring programs while improving specificity.

A good background and a well-established data set are necessary to design a robust and structured **Monitoring Program** on implementing preventive plans and remedial measures. However, to reach these aims it is relevant to improve some points as follows:

- Historical records and local knowledge. If there is no tradition of monitoring, it is not easy to find good historical records when an outbreak occurs. For example, during the investigation of cyanotoxins related to the intoxication of hemodialysis patients in February 1996 in Caruaru city-Brazil (Jochimisen et al., 1998, Azevedo et al., 2002) phytoplankton data from the water supplies were requested. But, as no monitoring was done since July of 1995, it was not possible to know which species of cyanobacteria were present in the water when the intoxication occurred.
- Design of monitoring programs using an early warning system by the improvement of observation systems. Besides that, the optimization of the sampling strategy can guarantee a better assessment at a lower cost.

Therefore, it is necessary to survey, integrate and analyze the available data (historical data) for freshwater and coastal ecosystems and their respective drainage basins, under ecological, geo-morphological, hydraulic and sanitary engineering, and epidemiological point of view. This data would support the elaboration of scenarios that include all aspects of the problem and may, therefore, result in the proposal of feasible mitigating measures.

When economic losses and human poisoning directly related to toxic cyanobacteria occur, another problem that arises is the difficulty of communication among different authorities. This difficulty can be a hard obstacle to the establishment of proper management and mitigation.

The adverse impacts on water supplies due to cyanobacterial blooms are usually underestimated. The reports about these impacts are mainly related to the massive fish mortality that frequently is caused by the reduction of dissolved oxygen concentration in water. The loss of scenic quality and consequent reduction of recreational activities with the economic loss for the tourism business is also described in some regions in Argentina and Brazil. However, the ecological impacts, such as effects on aquatic biodiversity or bioaccumulation of cyanotoxins through the food chain, has been analyzed, estimated and described in only a few scientific studies (Magalhães et al., 2001; Panosso et al., 2003; Ferrão

Filho et al., 2002a,b; Berry and Lind, 2010; Burmester, Nimptsch and Wiegand, 2012; Ferrão-Filho and Kozlowsky-Suzuki, 2011). Moreover, this knowledge is still restricted to academic circles. Consequently, the application of that information is poorly made by workers on aquaculture activities or by authorities involved with water quality or food quality control. The possible distance between the academic information and professional performance must be considered in this case.

A relevant aspect of this situation is that the consequences of toxic cyanobacterial bloom occurrence are underestimated or undiscovered by the different authorities responsible for the environment and water quality control; the management actions or implementation of preventive plans; and remedial measures are only taken into account when an outbreak occurs. It is also common to observe that these actions are restricted to a few weeks surrounding the event, depending on the media attention for the case.

Therefore, an integrated approach to the main problems caused by toxic cyanobacterial blooms and their socio-economic consequences need to be achieved. The cost-effective management of these aquatic ecosystems depends on an understanding of the complex mechanisms that govern those systems. Therefore, the integration of studies on those problems must be encouraged. This integrated work should have an active research component in addition to the training of personnel involved with the multiple water uses.

For the **Ecology** of toxic cyanobacteria, there are two important research questions to point out: 1. How do environmental forces drive toxic cyanobacteria and their biological interactions? 2. What are the effects of eutrophication and climate variability on the occurrence of toxic cyanobacterial blooms? However, to answer these questions becomes difficult if we do not know the following factors previously:

- Critical features and mechanism underlying the population dynamics of cyanobacteria in the context of physical and chemical factors;
- Dynamics of toxin production under different environmental conditions;
- Influence of specific anthropogenic activities on the frequency, intensity, and geographic distribution of particular cyanobacteria species (ecotypes).
- Measuring abundance, cyanotoxins production and risk assessment of cyanobacterial mats as subsides to improve monitoring programs.

But, if we consider the number of studies already done in some countries, it is easy to verify that they have conditions to solve the problems related to those ecological questions.

Any plans for establishing an advisory mechanism would have to be considered very carefully. Moreover, any mitigation strategies can be applied to blooms on a large scale only if it is possible to estimate the effects of the treatment on the local ecosystem.

To implement **Chemical** and **(Eco)Toxicological** studies related to cyanotoxins it is essential to improve the facilities and expertise available for analytical techniques and to promote access for more sensitive and selective methods for chemical analyses. The development of alternative toxicity tests to determine the mode of action of some cyanotoxins as well as their ecological impacts can be a relevant tool. Another point that needs to be considered very carefully is the standardization of analytical techniques because it can be a critical factor to compare results among different laboratories. The implementation of partnerships between public and private sectors, with the active participation of universities and/or research institutes, would produce the necessary conceptual structure to stimulate ideas and creative projects for the solutions to those problems.

4. Final considerations

As discussed above, the improved capabilities for monitoring, mitigation and prediction will be reached if an effective transfer of information between the scientific community and operational organizations is established in Latin America. This problem can be addressed comprehensively and effectively only through international, interdisciplinary, comparative, and collaborative research carried out on several aspects, including targeted studies and technological innovation. Scientific knowledge about cyanobacteria and their toxins can be useful if insights and suggestions are shared with people responsible for protecting water resources and public health.

Good reference models of law and monitoring measures already exist and can be taken as an example, such as Brazilian water potability law (Ministério da Saúde, 2011) and the cyanobacterial blooms monitoring program adopted by Uruguay. Both models and others establish and catenated the duties of each sector of the society (academic, politic and private) during a bloom event. Additionally, a variety of technologies for cyanobacterial blooms management is already well described in the literature and can be easily achieved by professionals who desire to apply those methods (*e.g.* use of macrophytes, barley straw, hypolimnion aeration, hydrogen peroxide, modified clays, barrier methods, etc).

However, it is important to emphasize that the efficiency of countermeasures will depend on the previous scenario structured to face bloom events. In this way, good knowledge about water bodies with records of physical, chemical and biological parameters will allow determining the best method to be applied to deal with such situations, considering the local specific features.

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