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REVIEW

Cyanobacterial blooms in freshwater bodies from a semiarid region, Northeast Brazil: A review

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ABSTRACT

Harmful cyanobacterial blooms have caused several problems in freshwater environments due to their prolific growth and the harmful cyanotoxins produced by some species. The occurrence of these organisms has increased in recent decades due to climate change and eutrophication, although most studies are from temperate regions in the Northern hemisphere. This review presents data about cyanobacteria occurrence, dominance, and toxicity events in freshwater bodies in a semiarid region of Northeast Brazil, in the tropical Southern hemisphere. We performed a literature survey of cyanobacteria publications from 1930 to 2016. We made a list of all the dominant species registered in each state, noted their distribution and occurrence of dominance events involving one or more species, and the registered records of toxic blooms, including information about the toxins involved and the range of values. We selected 102 publications that described cyanobacteria occurrence from states in Northeast Brazil; these publications included relevant contributions regarding cyanobacteria distribution, richness, density, and biomass. Forty-nine dominant species were recorded, with the most representation found in the state of Pernambuco (30 spp.). The genera with the highest occurrences were *Microcystis*, *Cylindrospermopsis*, *Planktothrix*, *Dolichospermum* (=*Anabaena*), and *Geitlerinema*, especially the species *Cylindrospermopsis raciborskii*, *Microcystis aeruginosa*, and *Planktothrix agardhii*. Episodes of toxic blooms were observed in four states. Microcystins, cylindrospermopsin, saxitoxins, and anatoxin-a(S) were found to be associated with these blooms. In Northeast Brazil, harmful cyanobacterial blooms are common in urban and public reservoirs. However, in recent years, cyanobacterial blooms in this region have been more intense and perennial, with high biomass occurring throughout the year.

Key words: Continental waters; cyanotoxins; *Cylindrospermopsis raciborskii*; harmful algal blooms; tropical blooms.

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INTRODUCTION

The accelerated growth of toxic cyanobacteria has generated serious problems in the management of inland waters that are used for irrigation, fishing, and human supply. Anthropic interferences through the input of nutrients in aquatic environments (in addition to climatic changes) can increase cyanobacterial harmful algal blooms (cyanoHABs) (Paerl and Huisman, 2009; Paerl and Otten, 2013; Paerl *et al.*, 2016). The conditions that cause these blooms have become increasingly more frequent in inland waters worldwide, especially during dry seasons (Carmichael and Boyer, 2016). Global warming favours cyanobacterial dominance because the changes in precipitation patterns promote an elevated water residence time in reservoirs during the dry season or more time for loading nutrients in the rainy season (Paerl and Huisman, 2008).

In Northeast Brazil, which is characterized by a semiarid climate, the cyanoHABs are more pronounced (*e.g.*, Bittencourt-Oliveira *et al.*, 2014; Lopes *et al.*, 2015; Brasil *et al.*, 2016; Lins *et al.*, 2016), which are favored by water scarcity, high temperatures, elevated water residence time, and artificial eutrophication. The recurrence of cyanoHABs became a public health problem due to toxins produced by these organisms. These secondary metabolites can cause serious damage to humans and animals, including irritation and acute, chronic, or even lethal poisoning (Carmichael and Boyer, 2016). Several studies focusing on the presence and detection of cyanotoxins in public water supply reservoirs were carried out in some states in Northeast Brazil. These studies have described the presence of microcystins (Chellappa *et al.*, 2008; Bittencourt-Oliveira *et al.*, 2010; Piccin-Santos and Bittencourt-Oliveira, 2012; Vasconcelos *et al.*, 2013; Mendes *et al.*, 2016), cylindrospermopsin (Bittencourt-Oliveira *et al.*, 2011, 2014), saxitoxins (Molica *et al.*, 2002; Fonseca *et al.*, 2015; Lopes *et al.*, 2015), and anatoxin-a(S) (Molica *et al.*, 2005).

The first studies focused mainly on certain taxonomical aspects (Drouet, 1937, 1938; Carvalho-de-La-Mora, 1989). Studies focusing on the dominance and toxicity of these organisms emerged only after the

"Caruaru tragedy" in 1996, when dozens of renal patients in a haemodialysis clinic died after intravenous exposure to microcystins (Carmichael *et al.*, 2001; Azevedo *et al.*, 2002). After this incident, research efforts were directed to monitor various supply reservoirs, including the important report by Bouvy *et al.* (2000), which monitored water quality and the occurrence of bloom-forming cyanobacteria *Cylindrospermopsis* Seenayya & Subba Raju in 39 reservoirs in Pernambuco state. Afterwards, many other studies have taken place, and the number of cyanoHABs associated with frequent episodes of toxicity has increased over time. However, more knowledge about the dynamics of these blooms and the species responsible for these phenomena is needed to further understand these processes in aquatic environments.

After the deaths of the "Caruaru tragedy", as well as a higher incidence of cyanoHABs, Brazil became the first country to adopt specific legislation that includes the analysis of cyanobacteria and cyanotoxins as parameters when monitoring water supply. For example, the regulation of the Brazilian Ministry of Health, Number 2.914/2011, which makes analysis of microcystins and saxitoxins in reservoirs destined for human supply mandatory. Additionally, this regulation establishes maximum limits of 1.0 μg L^{-1} of microcystins and cylindrospermopsin, and 3.0 μg L^{-1} of saxitoxins in these water sources (Brazil, 2011). However, further efforts are still needed to monitor these toxins, as well as public policies focused on populations with risk of contamination, since reports of toxin-producing species and the registration of newly affected regions have increased in recent years (Grattan *et al.*, 2016).

To analyse the various problems that are associated with cyanoHABs in waterbodies used for human supply, we reviewed studies to describe and characterize these organisms. Based on published material between 1930 and 2016, we show the distribution, dominance, and toxic events associated with the presence of cyanobacteria in lentic water bodies in Northeast Brazil.

METHODS

Data was obtained from articles published in indexed journals accessed through the Scielo (for articles in Brazilian journals), Scopus, and the Web of Science (for articles in international journals) databases. To obtain further information on the occurrence of cyanobacteria in freshwater bodies in Northeast Brazil, we also used Google Scholar to search for articles published between 1930 and 2016.

This bibliographical search was carried out from April to July 2016. We used different combinations of keywords to find appropriate articles, including cyanobacteria, cyanotoxins, toxic blooms, reservoirs, and Northeast Brazil (in English and Portuguese). We used journals that specialize in various disciplines, such as taxonomy, ecology, toxicology, molecular biology, and floristic. Only papers reporting the occurrence of planktonic cyanobacteria in lentic freshwater bodies in Northeast Brazil were selected. These papers also needed to include information about dominance events or present an elevated contribution in richness during at least one sample period. We established the following criteria to include articles: i) if more than one study presented data from the same environment and sample period, only one paper was used; ii) the studies about a phytoplankton community where cyanobacteria had no contributions in richness, density, biomass, or relative abundance were excluded; and iii) in studies that evaluated different depths in the same environment (with or without the formation of scums), only surface data of water bodies was considered. Furthermore, we selected studies that used quantitative density or biomass data to report the presence of cyanoHABs or establish dominance. Then, all species classified as dominant were listed to analyse the distribution and frequency of cyanobacteria representatives. Additionally, we investigated whether these events consisted of a single dominant species or involved two or more alternating or codominant species. The frequency of the dominant species in all dominance events was assessed in all states (n=149).

A multivariate analysis of variance (PERMANOVA) was carried out in order to verify if the species composition of cyanoHABs differed among the states in Northeast Brazil. Afterwards, using the R package IndicSpecies, we performed an indicator species analysis to identify what bloom-forming species were most representative of the states of Northeast Brazil. These analyses were performed in software R 3.4.0 with a significance level of $P<0.05$ (R Core Team, 2017).

We analysed the occurrence of cyanotoxins in different states in the Northeast region. We identified the various types of cyanotoxins and their detected values. Finally, we described the main species present in every cyanoHAB.

RESULTS

We surveyed 102 papers that recorded cyanobacteria through different approaches. These papers contained information about cyanobacteria found in six states as follows: Pernambuco was the most recorded state (55), followed by Rio Grande do Norte (25), Ceará (8), Paraíba (8), Bahia (3), and Maranhão (3) (Fig. 1). We found no records of cyanobacteria in the states of Alagoas, Sergipe, and Piauí. Among the different disciplines, ecological studies (72) presented the most published studies (in all states analysed, more than 60% of the articles were ecological studies), followed by toxicology (22), floristic surveys (4), taxonomy (2), and molecular techniques (2) (Fig. 1).

The history of cyanobacteria research in Northeast Brazil

We found an increasing trend in the number of papers published over the years. Pioneering studies about cyanobacteria were published in the 1930s in Ceará state. However, over the next 60 years, only three studies were published, all focusing on floristic and/or taxonomic surveys. For instance, there was only one paper published in the 1980s that included descriptions of cyanobacteria in Pernambuco state (Drouet, 1937, 1938; Carvalho-de-La-Mora, 1989). These studies represented only the initial step towards recording cyanobacterial species in this region (Fig. 2).

After the Caruaru tragedy in 1996, there was an increase in the number of publications involving the Northeast region of Brazil, primarily in Pernambuco state. Between 2007 and 2011 most articles involved ecological descriptions in the states of Pernambuco and Rio Grande do Norte (19 and 11 papers, respectively) (Fig. 2). In the past 10 years, the interest in these types of studies has increased in this region, and the number of studies in other states, such as Paraíba, Ceará, and Bahia, has also increased during this period (Fig. 2).

Among the 102 papers that we selected, 67 studies presented dominance of one or more cyanobacteria species in at least one sample period (Supplementary Tab. 1), which amounted to 79 environments (33 in Pernambuco, 25 in Paraíba, 14 in Rio Grande do Norte, 5 in Ceará and 2 in Bahia). Most of these studies were carried out in reservoirs used for public supply (97.5%), with only a small percentage carried out in lakes (2.5%).

Occurrence and distribution of dominant cyanobacteria in Northeast Brazil

We recorded 49 dominant cyanobacterial species in lentic ecosystems in Northeast Brazil. These species belong to 19 genera and are distributed in the Chroococcales (20 spp.), Nostocales (16 spp.) and Oscillatoriales (13 spp.) orders. Of all the registered species, 30 were from Pernambuco state, 27 from Rio Grande do Norte, 7 from Paraíba, 4 from Ceará and 3 from Bahia. No dominant species were found in Maranhão state (Tab. 1).

Regarding the dominant genera recorded in most studies, we found that *Microcystis* Lemmermann and *Planktothrix* Anagnostidis & Komárek were present in all states, *Cylindrospermopsis* Seenayya & Subba Raju was present in all states except Bahia, *Dolichospermum* (Bornet & Flahault) P. Wacklin *et al.* (=*Anabaena* Bornet & Flahault) was distributed in the states of Rio Grande do Norte, Pernambuco, and Bahia, and *Geitlerinema* (Anagnostidis & Komárek) Anagnostidis was only present in Rio Grande do Norte and Pernambuco (Fig. 3). Among the dominant species, *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya & Subba Raju was the species most frequently found in aquatic environments in Northeast Brazil (55%), followed by *Microcystis aeruginosa* (Kützing) Kützing (26%) and *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek (25%) (Tab. 1).

The species composition of bloom-forming cyanobacteria presented significant differences among the states, with a greater number of species in the states of Pernambuco and Rio Grande do Norte (PERMANOVA: $F=3.5196$, $P<0.001$). Among the indicator species, *M. protocystis* was considered an indicator of blooms in the state of Rio Grande do Norte, *M. aeruginosa* of blooms in Paraíba and Rio Grande do Norte, and *P. agardhii* an indicator of blooms in the states of Bahia and Ceará. A greater number of dominance events (blooms) occurred in Pernambuco state, and usually involved a single

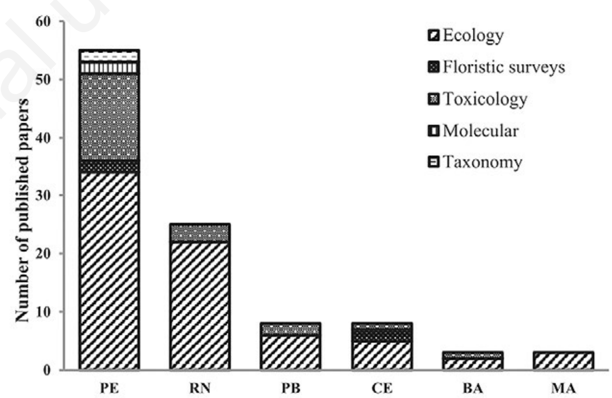

Fig. 1. Distribution of the number of papers about cyanobacteria using varied approaches in different states in Northeast Brazil. PE, Pernambuco; RN, Rio Grande do Norte; PB, Paraíba; CE, Ceará; BA, Bahia; MA, Maranhão.

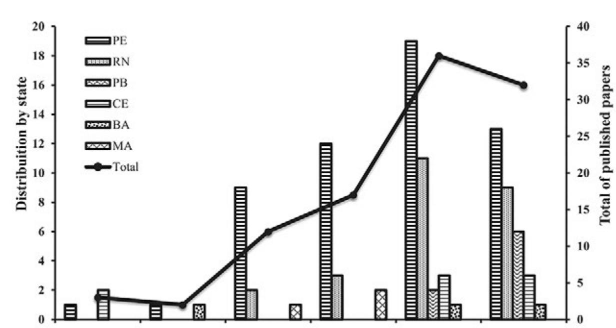

Fig. 2. Distribution and chronological evolution of the number of published works about cyanobacteria by state in Northeast Brazil.

Tab. 1. Number of cyanobacterial dominance events, occurrence frequency (OF%) (n=149), and species distribution in different states of Northeast Brazil.

Species	PE	RN	PB	CE	BA	OF(%)
Chroococcales						
Aphanocapsa cumulus Komárek & Cronberg	2					1
Aphanocapsa delicatissima West & G.S.West		1				1
Aphanocapsa incerta (Lemmermann) Cronberg & Komárek		1				1
Aphanocapsa nubila Komárek & Kling			1			1
Aphanocapsa spp.		1				1
Coelosphaerium naegelianum Unger		1				1
Merismopedia glauca (Ehrenberg) Kützing		1				1
Merismopedia punctata Meyen	1					1
Merismopedia tenuissima Lemmermann	1					1
Microcystis aeruginosa (Kützing) Kützing	10	14	15			26
Microcystis botrys Teiling	1					1
Microcystis flosaquae (Wittrock) Kirchner	1					1
Microcystis novacekii (Komárek) Compère	3	1				3
Microcystis panniformis Komárek *et al.*	11	12				15
Microcystis protocystis W.B.Crow	2	11	3			11
Microcystis spp.	5	6		1	1	9
Sphaerocavum brasiliense Azevedo & Sant' Anna		2				1
Sphaerocavum spp.		1				1
Synechocystis aquatilis Sauvageau	1					1
Woronichinia botrys (Skuja) Komárek & Hindák	1					1
Nostocales						
Anabaena circinalis Bornet & Flahault (=*Dolichospermum circinale* (Bornet & Flahault) Wacklin *et al.*)		6				4
Anabaena constricta (Szafer) Geitler (=*Johanseninema constrictum* (Szafer) Hasler *et al.*)	1					1
Anabaena planctonica Brunnthaler (=*Dolichospermum planctonicum* (Brunnthaler) Wacklin *et al.*)		2				1
Anabaena spiroides Klebahn (=*Dolichospermum spiroides* (Klebhan) Wacklin *et al.*)	1					1
Anabaena spp.	2	2			1	3
Aphanizomenon gracile Lemmermann		5				3
Aphanizomenon cf. *issatschenkoi* (Usacev) Proshkina-Lavrenko		1				1
Aphanizomenon cf. *manguinii* Bourrelly		1				1
Cylindrospermopsis acuminatocrispa Couté & Bouvy	1					1
Cylindrospermopsis catemaco Komárková-Legnerová & Tavera	3					2
Cylindrospermopsis philippinensis (W.R.Taylor) Komárek	3					2
Cylindrospermopsis raciborskii (Woloszynska) Seenayya & Subba Raju	48	16	14	4		55
Cylindrospermopsis spp.	2	1				2
Dolichospermum circinale (Bornet & Flahault) Wacklin *et al.*			1			1
Raphidiopsis curvata Fritsch & M.F.Rich	1	1				1
Sphaerospermopsis aphanizomenoides (Forti) Zapomelová *et al.*	1					1
Oscillatoriales						
Geitlerinema amphibium (Gomont) Anagnostidis	10					7
Geitlerinema splendidum (Gomont) Anagnostidis		1				1
Geitlerinema unigranulatum (R.N.Singh) Komárek & M.T.P.Azevedo	1					1
Oscillatoria splendida Gomont (=*G. splendidum*)	1					1
Oscillatoria tenuissima Gomont			1			1
Oscillatoria spp.	1	1				1
Phormidium fragile Gomont (=*Leptolyngbya fragilis* (Gomont) Anagnostidis & Komárek)		1				1
Planktolyngbya limnetica (Lemmermann) Komárková-Legnerová & Cronberg		3				2
Planktothrix agardhii (Gomont) Anagnostidis & Komárek	15	8	10	3	2	26
Planktothrix isothrix (Skuja) Komárek & Komárková	1	1				1
Planktothrix spp.				1		1
Pseudanabaena catenata Lauterborn	2					1
Pseudanabaena spp.	1					1
Total of species	30	27	7	4	3	

cyanobacterium species (monospecific dominance) per environment. The same pattern was observed for Paraíba state (Fig. 4). However, we observed a distinct pattern in Rio Grande do Norte state, with a high number of dominance events involving the coexistence or alternation of four or more cyanobacterial species (Fig. 4). Although we had very few records of dominance events for the states of Ceará and Bahia, they were constituted by one, two, or three species (Fig. 4).

Toxicity events associated with cyanobacterial dominance

Several cyanoHABs with proven toxicity were registered in Northeast Brazil. Toxin analysis was usually performed using biochemical/immunochemical methods or bioassays in mice or fish. Harmful algal blooms were identified in the states of Pernambuco, Rio Grande do Norte, Ceará, and Paraíba. The highest number of toxic bloom events was registered in Pernambuco state, and included toxins, such as microcystins (among them microcystin-LR), cylindrospermopsin, five variants of saxitoxins and anatoxin-a(S). In Rio Grande do Norte state, microcystins and three variants of saxitoxins were recorded, while for Ceará only three types of saxitoxins were registered, and in Paraíba only microcystins (including microcystin-LR) were recorded (Tab. 2).

DISCUSSION

The increasing occurrence of cyanobacteria has been recorded in freshwater ecosystems all over the world. However, this scenario is becoming more pronounced in Northeast Brazil due to water scarcity in reservoirs (associated with cultural eutrophication), which has been shown to promote recurring cyanoHABs events. According to Saad and Atia (2014), these events have harmful consequences on aquatic environments around the world, mainly due to the increase of nutrient inputs, such as nitrogen and phosphorus.

Reservoirs have been the focus of these studies not only because they are often located in semi-arid regions that are favourable for the development of cyanobacteria, but also because most of these organisms are potential producers of toxins that affect aquatic biota and, consequently, have harmful effects on human health. In this review, we assessed the contribution of over half a century (1930s to 2016) of cyanobacteria studies and found that in recent decades, more attention has been focused on these studies. The number of papers has increased particularly since the 1990s in the Northeast region, especially after the occurrence of the tragedy involving cyanobacteria poisonings in Pernambuco state (Carmichael *et al.*, 2001; Azevedo *et al.*, 2002).

The occurrence of cyanoHABs is usually associated with an interaction of various factors, such as eutrophication, low turbulence, and high temperatures (Dokulil and Teubner, 2000; Bittencourt-Oliveira *et al.*, 2014; Soares *et al.*, 2013; Paerl and Otten, 2013). These factors enable the dominance of colonial and filamentous species that can cause numerous negative effects on domestic, industrial, and recreational uses, especially in lakes and reservoirs (Dokulil and Teubner, 2000). The incidence and intensity of these blooms in recent years support that an increase in water temperature and changes in rainfall patterns (both consequences of climate change) are playing an important role in cyanobacterial

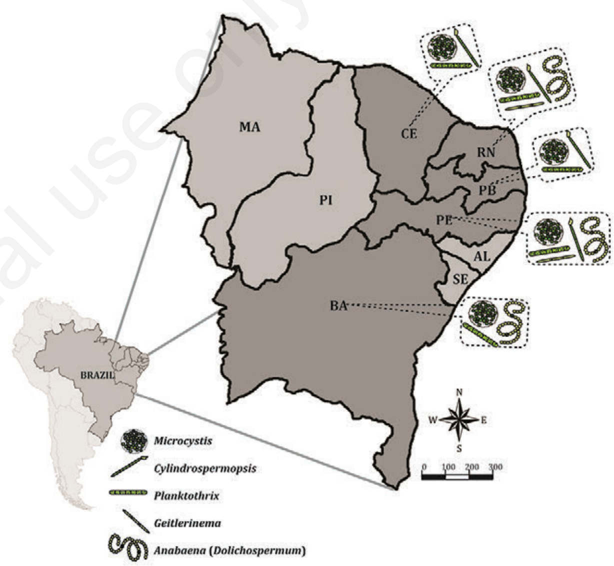

Fig. 3. Distribution of the main dominant cyanobacteria genera in different states in Northeast Brazil.

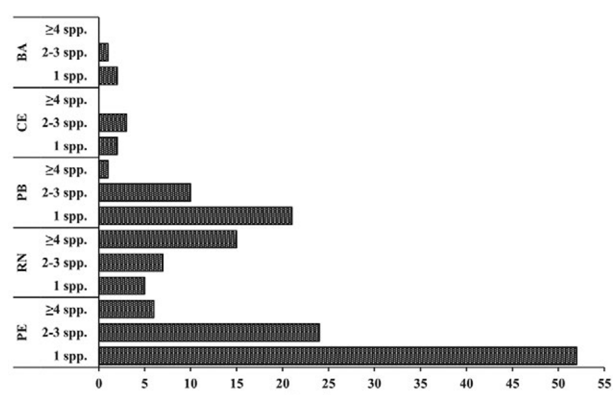

Fig. 4. Number of dominance events and cyanobacteria species per event (n=79) in different states in Northeast Brazil.

proliferation (Elliott, 2012; Paerl and Paul, 2012; Paerl and Otten, 2013). Given that global temperatures are expected to increase in the 21st century (Corlett, 2012) and that rainfall reductions and drought increases are predicted for the next 30 years (Dai, 2013), cyanoHABs issues become even more problematic as these environmental variables may increase the occurrence and biomass of these organisms.

Extreme climatic events are already being observed in Northeast Brazil, causing changes in the phytoplankton community, especially in the dominance of cyanobacteria (Lira *et al.*, 2014; Câmara *et al.*, 2015; Brasil *et al.*, 2016; Costa *et al.*, 2016). Bouvy *et al.* (2000) made one of the most important reports on cyanoHABs (in almost 40 reservoirs in the Northeast) associated with climate change, when the severe drought of 1998 (a consequence of the El Niño in 1997) made the environment favourable for cyanobacteria proliferation, specially *Cylindrospermopsis*

Tab. 2. Occurrence and distribution of dominant cyanobacteria species present in toxic blooms, detected toxins, amount of toxins, and papers that cited the occurrence of these cyanotoxins.

Species	Detected cyanotoxins	Amount	Reference
Pernambuco			
*Anabaena spiroides**	MCs	10.3 to 836,280 ng g^{-1}	
*Aphanocapsa cumulus**	MC-LR	0.08 to 3.7 ng mg^{-1}	
Cylindrospermopsis raciborskii	CYL	33.3 to 2.718 ng g^{-1}	Bouvy *et al.* (1999)[a],
Geitlerinema amphibium	STX	52 ng L^{-1}	Domingos *et al.* (1999),
Merismopedia tenuissima	neoSTX	51 ng L^{-1}	Molica *et al.* (2002; 2005),
Microcystis aeruginosa	GTX	+	Bittencourt-Oliveira *et al.* (2010; 2011; 2014),
M. botrys	dcSTX	+	Piccin-Santos and Bittencourt-Oliveira (2012),
M. novacekii	Analogue of STX	+	and Lorenzi *et al.* (2015)
M. panniformis	ATX-a(s)	+	
Planktothrix agardhii			
P. isothrix			
Sphaerospermopsis aphanizomenoides			
Rio Grande do Norte			
Aphanizomenon gracile			
Ap. cf. *issastschenkoi*	MCs	0.0023 to 24.195 µg L^{-1}	
Ap. cf. *manguinii*			
Anabaena circinalis			
An. planctonica			
Anabaena spp.	STXs	0.003 to 3.14 µg L^{-1}	
C. raciborskii			Costa *et al.* (2006)[a],
M. aeruginosa	STX	+	Chellappa *et al.* (2008),
M. novacekii			and Fonseca *et al.* (2015)
M. panniformis	C-toxins	+	
M. protocystis			
Microcystis spp.	GTX	+	
P. agardhii			
Ceará			
*C. raciborskii**	STX	+	Lopes *et al.* (2015)
P. agardhii *	dcSTX	+	
	dcGTX	+	
Paraíba			
C. raciborskii	MCs	0.1 to 41.16 µg L^{-1}	Vasconcelos *et al.* (2013),
Dolichospermum circinale			Lins *et al.* (2016), and
M. aeruginosa	MC-LR	27.3 µg L^{-1}	Mendes *et al.* (2016)
P. agardhii			

**Species isolated for cyanotoxin detection; [a]toxicity confirmed through bioassays with mice and/or fish; MC, microcystin; CYL, cylindrospermopsin; STX, saxitoxin; neoSTX, neosaxitoxin; GTX, gonyautoxin; dcSTX, decarbamoylsaxitoxin; ATX-a(s), anatoxin-a(s); dcGTX, decarbamoylgonyautoxin; +, cyanotoxin detected but not quantified.*

raciborskii. Thus, global warming is expected to promote an increasing number of cyanoHABs episodes (Paerl, 2009; Whitehead *et al.*, 2009; Wilk-Woźniak *et al.*, 2016).

In temperate and subtropical regions an increase in water temperature and total phosphorus are expected to promote highly hazardous cyanoHABs (Davis *et al.*, 2009; Rigosi *et al.*, 2015). However, the response to global warming and eutrophication depends on the trophic state of the water bodies and the bloom-forming species, with nutrients being the main factor influencing blooms in oligotrophic lakes, and water temperature becoming more influential in mesotrophic lakes. In eutrophic and hypereutrophic lakes, published evidence suggests nutrients and temperature interact synergistically to promote cyanobacteria (Rigosi *et al.*, 2014). Extreme climate events, like changes in precipitation patterns, can also favour cyanoHABs in subtropical lakes (Haakonsson *et al.*, 2017). In tropical regions, blooms are more frequent and persistent throughout the year, with higher biomass and toxic records (Bouvy *et al.*, 2000; Bittencourt-Oliveira *et al.*, 2014), in contrast with temperate regions where cyanoHABs are restricted to shorter periods of the year, mainly in the summer (Ger *et al.*, 2016).

In our analysis, we observed that *Cylindrospermopsis raciborskii*, *Microcystis aeruginosa*, and *Planktothrix agardhii* were the most frequent species occurring in aquatic environments in Northeast Brazil. These species are often responsible for the formation of blooms in tropical ecosystems (Mowe *et al.*, 2015). They share important adaptive traits, such as the presence of aerotopes and the ability to produce toxins (Komárek and Johansen, 2015a, 2015b), that favour the dominance of this group in reservoirs (Soares *et al.*, 2013; Moura *et al.*, 2015). Previously, the emergence of these species in freshwater ecosystems, under various hydrologic, physical, and chemical conditions, has been found to be related to a set of adaptive strategies developed to reflect the changes caused by global warming, such as wide phenotypic plasticity and a greater ecological tolerance (Kling, 2009), resulting in the successful proliferation of these organisms (Paerl and Huisman, 2009). The species *C. raciborskii*, *M. aeruginosa*, and *P. agardhii*, which were present in most bloom events, were found to be involved in perennial events of cyanobacterial dominance in the Northeast eutrophic reservoirs (Bouvy *et al.*, 1999; Huszar *et al.*, 2000). As noted in most studies on cyanobacteria in Pernambuco and Paraiba states, most dominance events consisted of only one species (monospecific dominance), with rare cases of codominance between two or more species. In addition, in Rio Grande do Norte, most cases of dominance involved codominance of several species. In a recent review about Brazilian water bodies, Soares *et al.* (2013) showed that the most cases of cyanobacterial dominance were constituted by several representatives of the *Microcystis* genus. Currently, the species *C. raciborskii* has a wide distribution on all continents, especially in temperate regions, where it is considered an invasive taxon, due to its buoyancy and nitrogen fixation capacity, tolerance to low light, and resistance to predation by zooplankton (Padisák, 1997; Briand *et al.*, 2004). On the other hand, blooms of *Microcystis* species are becoming more prolific around the world, with records on all continents, especially in temperate European, North American and Australasian countries. In these cases, many blooms are accompanied by microcystin records (Harke *et al.*, 2016). In the tropics, the most prevalent bloom-forming cyanobacteria are *Microcystis* spp. in Africa and Asia, and *C. raciborskii* in South America and Australia (Mowe *et al.*, 2015).

Compared to other semiarid regions around the world, the waters of Northeast Brazil have similar bloom-forming species as those found in semiarid Mediterranean reservoirs, represented by the genera *Microcystis* and *Planktothrix* (Naselli-Flores *et al.*, 2007). In semiarid regions, reservoirs are the main water source for people, and a reduction in water volume during the summer can promote cyanoHABs (Naselli-Flores and Barone, 2005). Therefore, besides confronting water scarcity, the Brazilian population in the semiarid also has problems due to increasing frequency and amplitude of blooms.

With the high occurrence of cyanoHABs, some studies about biomanipulation were developed to minimize the biomass of this group in reservoirs. For example, the introduction of omnivorous fish reduced the biomass of large cladocerans in a study by Okun *et al.* (2008). However, this response was independent of the density of fish, and therefore, only a large-scale removal of these fish could lead to a significant reduction in the biomass of the phytoplankton community. On the other hand, research involving the biomanipulation of the zooplankton community showed that in the absence of nutrient limitation, limited by nitrogen or phosphorus, zooplankton could reduce the total biomass of phytoplankton, however, there was an increase in the biomass of *C. raciborskii* (Severiano *et al.*, 2017).

Toxic dominance events have been observed in the states of Pernambuco, Rio Grande do Norte, Paraíba, and Ceará, implying that there might be certain conditions at these places that favour the proliferation of toxic cyanobacteria. These blooms (and the consequent cases of human poisoning) have been registered on all continents since the 19^{th} century (Carmichael, 1992). This excessive cyanobacterial growth has caused numerous problems to the environment, mainly due to the synthesis and release of toxins, such as hepatotoxins, neurotoxins, and dermatoxins (Chorus and Bartram, 1999). Therefore, monitoring these metabolites is essential for identifying their risks in continental waters, and ensuring the safety of the water supply for the human population (Brittain *et al.*, 2000).

Regarding the reservoirs evaluated in this literature review, we recorded the presence of microcystins, saxitoxins, cylindrospermopsin, and anatoxin-a(S). The most frequent cyanotoxin was the microcystins. The amounts of these toxins are expected to increase in eutrophic conditions, being related to high concentrations of nitrogen, turbity, and cyanobacterial biomass (Taranu *et al.*, 2017). However, we cannot specify which species produced these toxins, since the identification and quantification of these compounds were performed using bloom samples composed of more than one cyanobacterium species, making it impossible to associate the toxin with its producing species. Furthermore, studies have shown that toxin concentrations are not always related to the density or biomass of species that produce these compounds, as verified by Bittencourt-Oliveira *et al.* (2014) in Pernambuco reservoirs.

Among the toxins produced by cyanobacteria, microcystins were the most frequent in aquatic environments in Northeast Brazil. Microcystins are considered the most potent hepatotoxins (Romero-Oliva *et al.*, 2014), and more than 240 microcystin variants have been identified (Svirčev *et al.*, 2017; Spoof and Catherine, 2017) in several genera of cyanobacteria, such as *Microcystis*, *Planktothrix*, and *Anabaena*, among others (Paerl and Otten, 2013). Among these toxins, microcystin-LR (identified in various bloom events in the states of Pernambuco and Paraíba) stands out as the most toxic, frequently found in aquatic ecosystems (Brittain *et al.*, 2000) and associated with several cases of intoxication in both humans (Carmichael *et al.*, 2001; Azevedo *et al.*, 2002), and fish (Chellappa *et al.*, 2008). Microcystins can also be toxic to aquatic macrophytes (Amorim *et al.*, 2017), and crop plants (Bittencourt-Oliveira *et al.*, 2016), posing risks for the people and animals that feed on these plants. The main mode of action of microcystins is the inhibition of the proteins phosphatase 1 and 2A, resulting in the disruption of the enzymatic activities of hepatocytes, which are highly sensitive to these toxins (Falconer, 2008). Saxitoxins, or paralytic shellfish poison (PSP) (Wiegand and Pflugmacher, 2005), were present in blooms registered in the states of Pernambuco, Rio Grande do Norte, and Ceará. These neurotoxins are produced by cyanobacteria of the genera *Anabaena*, *Aphanizomenon* Bornet & Flahault, *Cylindrospermopsis* and *Planktothrix* (Paerl and Otten, 2013) and are potent antagonists of neuronal voltage-dependent sodium channels. These toxins have been shown to cause paralysis or even death by respiratory arrest (Humpage, 2008). Cylindrospermopsin and anatoxin-a(S) were only identified in blooms registered in the state of Pernambuco. Cylindrospermopsin is a hepatotoxin that is synthesized by species belonging to the *Aphanizomenon*, *Cylindrospermopsis*, and *Raphidiopsis* Fritsch & Rich genera (Paerl and Otten, 2013); this toxin has been shown to inhibit protein synthesis in aquatic animals and plants (Kinnear, 2010). The neurotoxin anatoxin-a(S), which is produced by *Anabaena* species, interrupts acetylcholine esterase activity (Chorus and Bartram, 1999), causing respiratory arrest and death (Falconer, 2008).

CONCLUSIONS

Northeast Brazil is experiencing a high occurrence of cyanobacterial blooms that are composed of several species, many of which are potentially toxic. The high frequency and intensity of blooms can be explained by increased eutrophication and climate change (warming and drought) which affect many freshwater bodies in the tropics. Further studies are particularly needed in the tropical Southern hemisphere, including the North-eastern region of Brazil, where there are still few records of these metabolites in the states of Ceará and Paraíba, and no reports in the states of Maranhão, Piauí, Bahia, Alagoas, and Sergipe. The records of cyanotoxins in drinking water supply reservoirs in Northeast Brazil poses serious risks to human health, highlighting the continued importance to monitor their presence and develop effective mitigation measures.

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