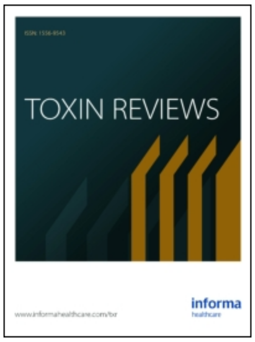

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An overview on cyanobacterial blooms and toxins production: their occurrence and influencing factors

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REVIEW ARTICLE

An overview on cyanobacterial blooms and toxins production: their occurrence and influencing factors

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ABSTRACT

Cyanobacteria are photosynthetic bacteria inhabiting water surface. They can increase to form a mass large enough, termed as cyanobacterial bloom. Cyanobacterial blooms can generate an array of harmful toxins, which may disturb water sources, subsequently posing frightful health threat to living organisms. The occurrence of cyanobacterial blooms and cyanobacterial toxins are globally reported, mainly trigged by eutrophic conditions and climate change. The aim of this review was to provide the current knowledge on cyanobacterial blooms and toxins production; their occurrence and influencing factors. In addition this paper suggests some measures to ensure toxic blooms minimization.

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Cyanobacteria; cyanobacterial blooms; cyanobacterial toxins; influencing factors

1. Introduction

The most important natural resource essential for domestic, agriculture and industrial purposes is water. Consequently water should be save enough to be consumed or utilized with low risk of immediate or long term hazard, thus a vital issue to public health. WHO (2011) demonstrated that cyanobacterial blooms (cyanoblooms) producing cyanobacterial toxins (cyanotoxins) are a fast growing water contamination source (further details are discussed under Cyanobacteria and cyanobacterial blooms, Cyanobacterial toxins, and Occurrence of cyanobacterial blooms and cyanobacterial toxins). In addition various factors including natural and human-influenced may foster bloom occurrences and toxins production (further details are discussed in section 5).

Water pollution resulting from cyanoblooms have globally been reported in oceans, lakes, rivers, lagoons, streams, wells and water reservoirs (Mowe *et al.* 2015, Ndlela *et al.* 2016, Meriluoto *et al.* 2017, Svircev *et al.* 2019, Zhang *et al.* 2019). Figure 1 illustrates examples of cyanoblooms. The massive toxic blooms of *Microcystis* sp. which occurred in Lake Taihu and the western basin of Lake Erie, further producing microcystins affected water usage in Wuxi, China and Ohio, USA respectively for a period (Zhang *et al.* 2010, Carmichael and Boyer 2016). This suggests that cyanoblooms and cyanotoxins may contaminate water source, making it unsafe for ecological and human utilization. Thus the present review summarizes recent knowledge on cyanoblooms and cyanotoxins; their occurrence and influencing factors. This paper further puts forward some pressing measures to ensure toxic cyanoblooms minimization.

2. Cyanobacteria and cyanobacterial blooms

The ancient cyanobacteria organisms, noticeable in rocks dating from the first thousand million years of the earth's history and belong to the kingdom monera (Prokaryota), division eubacteria and class cyanobacteria (Ressom *et al.* 1994, Omidi *et al.* 2018), are a type of photosynthetic bacteria that live in water surface. As cyanobacteria colonies occur in shallow water, they appear in the fossil record in sedimentary rocks deposited in shallow seas and lakes. Cyanobacteria colonies identified as stromatolites emerge in rocks as fossilized mushroom shapes and sheets. Falconer (2005) reported that the Gunflint chert was one of the best stromatolite formations known in Lake Erie. It is of interest cyanobacteria was shown to possess a single circular chromosome completely sequenced in several species, plasmids and small circular strands of DNA (Schwabe 1988, Kaneko *et al.* 1996). Whitton and Potts (2000) found that the chlorophyll-a and pigment

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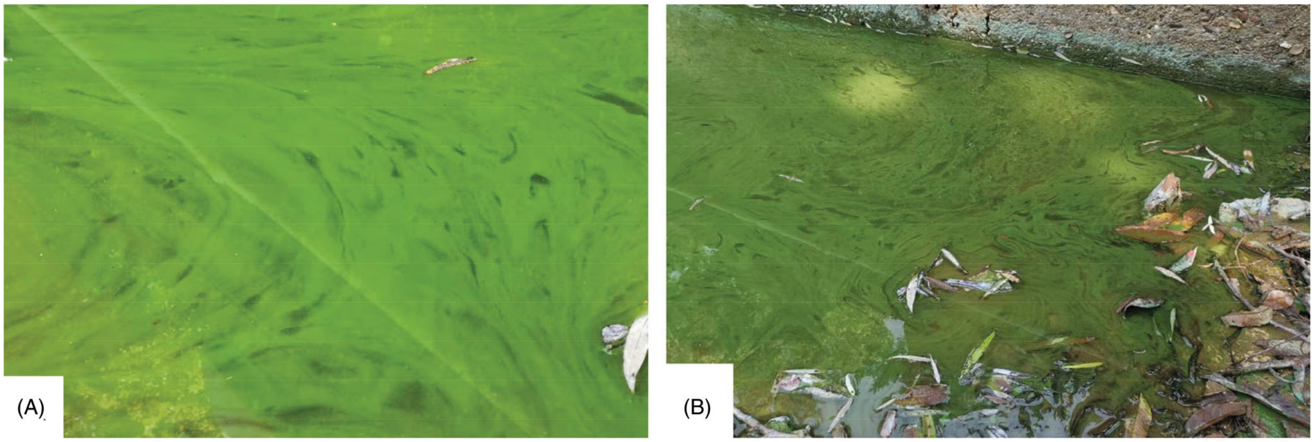

Figure 1. Examples of bloom-forming cyanobacteria in China lakes; (A) Lake Taihu and (B) Dongfang hong pond.

phycocyanin observed in cyanobacteria photosynthetic membranes were responsible for the characteristic blue-green color of the many species. Pigments such as carotenoids and phycoerythrin which give a strong red color to some species may also be present (Bryant 1994).

It is well established that natural conditions together with human-influenced activities enriching water can rapidly increase to form a mass large enough that is visible to the naked eye. This phenomenon is called cyanobloom (Mowe et al., 2015, Ndlela *et al.* 2016, Meriluoto *et al.* 2017, Svircev *et al.* 2019). *Microcystis* sp., *Anabaena* sp., *Nostoc* sp., *Cylindrospermopsis* sp., and *Planktothrix* sp. are some of the common bloom-forming species. Occurrence of toxic cyanoblooms is of great importance regarding the production of drinking water in both developed and developing countries. This is due to the fact that, presence of toxic cyanoblooms in drinking water sources may reduce the water quality and create potential risk of toxin exposure for water consumers which have become a global health concern (Runnegar *et al.* 1994, Sivonen and Jones 1999, Osswald *et al.* 2007, Suleiman *et al.* 2017, Massey *et al.* 2018a, Zhang *et al.* 2019). Further the oxygen depletion induced may result to hypoxia and anoxia in aquatic animals and vegetations (Rabalais *et al.* 2010). Health threats occur when dense accumulation of cyanobacteria cells appears on water surface. This is the period where death and lysis of bacteria cells result to the release of toxins in the watershed consequently destroying the quality of drinking water, by giving it an unpleasant taste and smell (Falconer 1999). Researchers demonstrated that the occurrence of these toxins have caused a number of animal poisoning and deaths, posed great threat to human health and affected plant and crop yields (Runnegar *et al.* 1994, Sivonen and Jones 1999, Osswald *et al.* 2007, Drobac *et al.* 2017, Suleiman *et al.* 2017, Massey *et al.* 2018a, Alosman *et al.* 2020). Animals and humans may be exposed to the harmful effects of these toxins either through direct ingestion of cyanobacteria producing cells, consumption of contaminated water or body contact (Massey *et al.* 2018a, Cao *et al.* 2019a) and irrigation in the case of plants and crops (Drobac *et al.* 2017).

3. Cyanobacterial toxins

The development of cyanoblooms has progressed to promote natural compounds that are toxic to living organisms. The toxins referred to as cyanotoxins exhibit animal, human, plant and crop toxicity. In this section the most commonly reported cyanotoxins including microcystin, nodularin, cylindrospermopsin, anatoxin-a and saxitoxin (Sivonen and Jones 1999, Mowe et al., 2015, Ndlela *et al.* 2016, Meriluoto *et al.* 2017, Svircev *et al.* 2019) were reviewed. Cyanotoxins such as guanitoxin (formerly anatoxin-a(s)), BMAA and lipopolysaccharides were not considered in this section.

3.1. Microcystin

The most frequently reported cyanotoxin globally found in freshwaters, marine habitats and desert environments is cyclic heptapeptide hepatotoxin microcystin. Species of cyanobacteria including *Microcystis, Anabaena, Planktothrix, Nostoc,* and *Cylindrospermopsis* can produce this toxin (Metcalf *et al.* 2012, Ma and Li 2018, Massey *et al.* 2018a, 2018b, Yang *et al.* 2018a, 2020). Microcystin was named after *Microcystis aeruginosa*, the cyanobacterium in which the toxin was initially isolated and described (Carmichael *et al.* 1988).

Bishop *et al.* (1959) originally identified microcystin as Fast-Death Factor which was subsequently renamed by Konst *et al.* (1965). Currently over 270 microcystin variants have been isolated from cyanoblooms (Bouaicha *et al.* 2019, Massey *et al.* 2020a), with the most widespread and acutely toxic being MC-LR, MC-RR and MC-YR (Liu *et al.* 2018, Yang *et al.* 2018b, 2020, Massey *et al.* 2020b). Microcystins share a common genetic structure cyclo-(-D-Ala1-L-X2-D-MeAsp3-L-Z4-Adda5-D-Glu6-Mdha7). Adda is (2S, 3S, 8S, 9S) 3-amino-9 methoxy-2,6,8-trimethyl-10-phenyldeca-4, 6-dienoic acid, D-MeAsp is D-erythro-b-methylaspartic acid, Mdha is N-methyldehydroalanine, and X and Z are variable L-amino acids (Sivonen and Jones 1999, Massey *et al.* 2018b, Alosman *et al.* 2020, Wei *et al.* 2020). Adda the unusual amino acid is an important element for biological activity expression. Combining X and Z (or Y), the two variable L-amino acids are responsible for the several microcystin variants and are also used in their name selection. Generally, microcystins have a size of approximately 3 nm in diameter and a molecular weight ranging between 900 and 1,100 Da (Donati *et al.* 1994, Ma and Li 2017). Microcystins are capable to inhibit serine/threonine protein phosphatases 1 (PP1) and PP2A, change the expression levels of miRNA, and cause cytoskeleton disorder, DNA impairment, autophagy and apoptosis (MacKintosh *et al.* 1990, Dawson 1998, Yang *et al.* 2018). Exposure to microcystins primarily via ingestion and body contact may negatively affect various mammalian organs including liver, kidney, nervous system, gastrointestinal tract, reproductive system and cardiovascular (Li and Ma 2017, Massey *et al.* 2018a, Yi *et al.* 2019, Cao *et al.* 2019a, 2019b). In February 1996, hemodialysis patients at a hemodialysis center in Caruaru, Brazil, were affected by microcystin pollution that resulted from microcystin contamination in the hospital's water supply. Out of 131 patients treated, 116 experienced visual disturbances, nausea and vomiting, about 100 of them developed acute liver failure and more than 50 patients lost their lives (Jochimsen *et al.* 1998, Azevedo *et al.* 2002, Massey *et al.* 2018a). It is worthwhile noting the toxic effects of microcystins, led the International Agency for Research on Cancer (IARC) to classify these toxins as a possible carcinogen (IARC 2010). Further to minimize and prevent hazards of microcystins, the World Health Organization (WHO) has set a provisional 1 μg/L microcystins, and maximum 20 000 cyanobacterial cells mL^{-1} or 10 μg/L of chlorophyll-a (where about 2–4 μg/L microcystins is anticipated) guidelines for drinking and recreational water respectively (WHO 1998, 2003).

3.2. Nodularin

Nodularin is a group of cyclic pentapeptide hepatotoxin that consists of five variable amino acids. Nodularin mostly produced by *Nodularia spumigena*, *Nostoc* and *Iningainema* (*Scytonemataceae*) are widely disseminated around the subtropical and temperate regions, and are primarily found in coastal sea and freshwater (McGregor and Sendall 2017). The chemical structure of nodularin molecule is cyclo-(D-MeAsp^1-L-Arg^2-Adda^3-DGlu^4-Mdhb^5), where Mdhb is 2-(methylamino)-2-dehydrobutyric acid (Buratti *et al.* 2017). At present, approximately 10 variants of nodularin have been discovered, among which NOD-R is the most abundant (Spoof and Catherine 2017). The toxic consequences including liver functional disturbance and structural disruption induced by nodularin are due to its ability to inhibit PP1, PP2A and PP3 (Dawson 1998). Nodularins have globally been found (Chorus and Bartram 1999), and reported to be responsible for the deaths of animals and potent cyanotoxin in humans, however, the hazard of these toxins to humans has not been fully elucidated (Chen *et al.* 2013). Although this cyanotoxin is considered as a liver tumor initiator and promoter, the IARC has not classified it as part of human carcinogenicity due to inadequate exposure data (IARC 2010). It is of interest that no guidelines have been set for nodularins. Therefore evaluating the toxicity of nodularins is estimated from microcystins, which have been demonstrated to have similar toxic mechanism (Pearson *et al.* 2010).

3.3. Cylindrospermopsin

Cylindrospermopsin originally isolated from the cyanobacterium *Cylindrospermopsis raciborskii*, is an alkaloid cytotoxin consisting of a tricyclic guanidine moiety, hydroxymethyluracil and sulfate (Ohtani *et al.* 1992). It has a molecular weight of 415 Da (Falconer 1999). Cylindrospermopsin was first discovered in tropical Australian waters (Hawkins *et al.* 1985) and has subsequently been found in a number of water bodies across the globe (Chiswell *et al.* 1999, Carmichael *et al.* 2001, Mowe *et al.* 2015, Svircev *et al.* 2019). It is of interest cyanobacteria species including *Umezakia natans*, *Anabaena bergii*, *Aphanizomenon ovalisporum*, *Aphanizomenon flosaquae* and *Raphidiopsis curvata* (Falconer 2005) can also produce this toxin. Cylindrospermopsin is capable of inhibiting protein synthesis, glutathione and cytochrome P450 to cause pathological symptoms in the liver, intestine, kidneys, heart, spleen, thymus and eye (Runnegar *et al.* 1994, Terao *et al.* 1994, Sivonen and Jones 1999). Kiss *et al.*

(2002) and Humpage *et al.* (2000) also demonstrated that the alkaloid toxin can induce genotoxic and neurotoxic effects. Human health issues attributed to this toxin occurred in Palm Island, Queensland, Australia in 1979. About 148 people were reported poisoned after *Cylindrospermopsis raciborskii* blooms in a drinking water reservoir was treated with copper sulfate, which resulted in cyanobacterial cells lyse, releasing large amount of cylindrospermopsin into the water. The affected individuals exhibited signs of headache, fever, vomiting and bloody diarrhea (Hawkins *et al.* 1985). In view of cylindrospermopsin toxic manifestations, a necessary drinking water guideline is being considered by WHO (Sivonen and Jones 1999) and USA (EPA 2006). It is worth knowing that Falconer (2005) recommended a tentative guideline value of 1 μg/L concentration for this cyanotoxin.

3.4. Anatoxin-a

Anatoxin-a is a small alkaloid and potent neurotoxin promoter. It is a bicylic secondary amine, smallest cyanotoxin, and has a molecular weight of 165 Da. Osswald *et al.* (2007) indicated that *Anabaena* sp., *Aphanizomenon* sp., *Microcystis* sp., *Oscillatoria* sp., *Arthrospira* sp., *Raphidiopsis* sp., *Planktothrix* sp., *Phormidium* sp., *Nostoc* sp. and *Cylindrospermum* sp. are capable to produce this toxin. The amine pKa value of 9.4 renders the cationic form of anatoxin-a the most prevalent form in natural waters and its oxidation may be pH-dependent. Homoanatoxin-a with an additional methylene unit on its side chain has been identified as a variant of anatoxin-a (Skulberg *et al.* 1992). Anatoxin-a is a potent nicotinic agonist capable of producing neuromuscular blockade leading to paralysis and eventually death owing to respiratory arrest (Fawell *et al.* 1999, Osswald *et al.* 2007). Although anatoxin-a is not considered widespread as the cyclic peptide hepatotoxins, it is documented to have caused animal poisonings in some parts of the world identified (Fawell *et al.* 1993, Sivonen and Jones 1999, Svircev *et al.* 2019). Due to the toxic consequences, Fawell *et al.* (1999) recommended 1 μg/L anatoxin-a concentration to provide significant water safety since no official drinking water guideline is established.

3.5. Saxitoxins

Saxitoxins commonly associated with red tides are a group of carbamate alkaloid neurotoxins with a varying molecular weight of about 388 Da, and are commonly referred to as paralytic shellfish poisons (Sivonen and Jones 1999, Carmichael 2001, Murray *et al.* 2011). Saxitoxins were originally isolated and characterized from marine dinoflagellates and acted as paralytic shellfish poisons, hence the name (Anderson 1994). Cyanobacteria species such as *Anabaena, Cylindrospermopsis*, *Lyngbya*, *Raphidiopsis*, *Planktothrix* and *Aphanizomenon* are found to generate these toxins (Sivonen and Jones 1999, Murray *et al.* 2011). Over 20 variants of saxitoxin have been identified with the most common and toxic being saxitoxins (unsulfonated), gonyautoxins (monosulfonated) and C-toxins (disulfonated), and their variable positions can be hydroxylated, sulfated, or carbamoylated (Nicholson and Burch 2001). Rogers and Rapoport (1980) indicated that the tricylic molecule had two guanidine groups with pKa values of 8.2 and 11.3. The cationic molecule easily dissolves into water and concentrates in shell fish. When ingested, the toxin functions as sodium channel blocking agents to induce paralysis. It is well established that animal deaths and human poisonings have been caused due to the ability of this toxin to bio-accumulate in shellfish (Anderson 1994, Suleiman *et al.* 2017, Edwards *et al.* 2018). Symptoms such as burning of the lips, tongue and throat, excessive sweating, vomiting and diarrhea, dizziness, numbness, difficulty in breathing, muscle weakness and paralysis may occur within 30 min of exposure (Carmichael 2001, Llewellyn 2006, Suleiman *et al.* 2017). Although no official guideline value exists, the hazard this cyanotoxin generates led to the establishment of the Australia drinking water guideline of 3 μg/L of saxitoxin equivalence (Nicholson and Burch 2001).

4. Occurrence of cyanobacterial blooms and cyanobacterial toxins

Numerous investigators have reported the existence of cyanoblooms and cyanotoxins in water bodies worldwide under an extensive variety of environmental conditions (Lei *et al.* 2014, Antunes *et al.* 2015, Mowe *et al.* 2015, Srivastava *et al.* 2015, Svircev *et al.* 2019). The common cyanotoxins described in section 3 have been identified in the entire continent with the exception of Antarctica where anatoxin-a has not been detected. It is worth knowing that the cyanotoxins reported in Europe and North America are widespread compared to Asia and South America (Antunes *et al.* 2015, Mowe *et al.* 2015, Meriluoto *et al.* 2017, Svircev *et al.* 2019). Interestingly Africa is reported to lag behind in terms of exploration and information dispensation on cyanotoxins since only a few records exists especially in recent times (Ndlela *et al.* 2016). Figure 2 depicts world map showing the occurrence of cyanoblooms. Table 1 illustrates the occurrence of dominant cyanobacterial species and cyanotoxins on continental base. Studies included in Table 1 were based on previous reviews on cyanoblooms and cyanotoxins. Table 2 shows the occurrence of dominant cyanotoxins identified in water bodies of some countries. Studies included in Table 2 were also selected according to countries in a continent with much records of cyanotoxins occurrence, focusing on the more recent publications.

Practically most coastal countries experience cyanoblooms and cyanotoxins, leading to illness and death in humans, fish, seabirds, marine mammals, and other oceanic life ecosystems, and destruction of recreational facilities (Mowe *et al.* 2015, Ndlela *et al.* 2016, Meriluoto *et al.* 2017, Massey *et al.* 2018a, Svircev *et al.* 2019). Among the cyanobacteria species, Microcystis has been given extensive consideration due to its extremely abundant biomass, frequent occurrence and ability to produce microcystins (Mowe *et al.* 2015, Ndlela *et al.* 2016, Meriluoto *et al.* 2017, Svircev *et al.* 2019). It is of interest that the Figure and Tables indicating areas with records of cyanoblooms and cyanotoxins may be over or under represented. Therefore, further research is required to identify and characterize these across the globe.

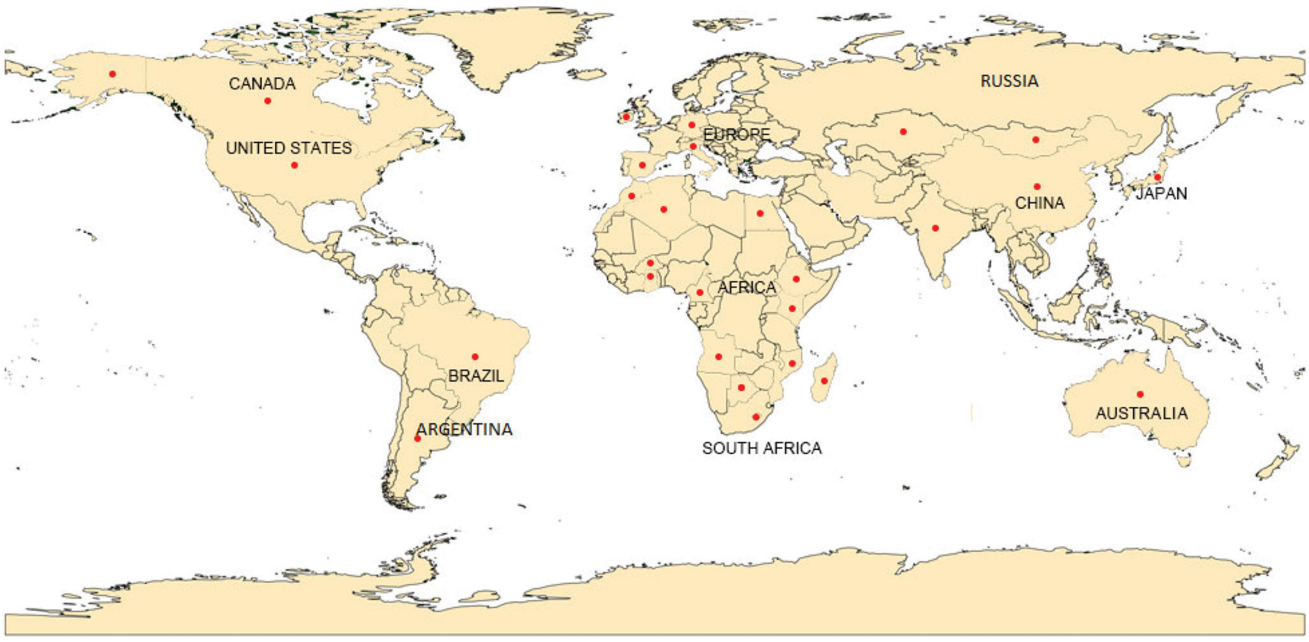

Figure 2. World map showing the occurrence of cyanobacterial blooms. The red dots indicate the existence of cyanobacterial blooms.

Table 1. The occurrence of dominant cyanobacterial species and cyanobacterial toxins on continental base.

Continent	Dominant cyanobacterial species	Dominant cyanobacterial toxins	Reference
Africa	*Microcystis* sp., *Anabaena* sp., *Oscillatoria* sp., *Cylindrospermopsis* sp. and *Planktothrix* sp.	Microcystins and anatoxin-a	(Antunes *et al.* 2015, Mowe *et al.* 2015, Ndlela *et al.* 2016, Svircev *et al.* 2019)
Antarctica	*Nostoc* sp., *Phormidum* sp., *Oscillatoria* sp. and *Anabaena* sp	Microcystins	(Hitzfeld *et al.* 2000, Jungblut *et al.* 2006, Kleinteich *et al.* 2014, 2012)
Asia	*Microcystis* sp., *Anabaena* sp., *Oscillatoria* sp. and *Cylindrospermopsis* sp.	Microcystins and cylindrospermopsin	(Lei *et al.* 2014, Antunes *et al.* 2015, Mowe *et al.* 2015, Srivastava *et al.* 2015, Svircev *et al.* 2019)
Europe	*Microcystis* sp., *Cylindrospermopsis* sp., *Anabaena* sp., *Oscillatoria* sp., *Aphanizomenon* sp. and *Planktothrix* sp.	Microcystins, anatoxin-a, cylindrospermopsin and saxitoxins	(Antunes *et al.* 2015, Mowe *et al.* 2015, Meriluoto *et al.* 2017, Svircev *et al.* 2019)
North America	*Microcystis* sp., *Anabaena* sp., *Oscillatoria* sp., *Aphanizomenon* sp. and *Cylindrospermopsis* sp.	Microcystins, anatoxin-a and cylindrospermopsin	(Antunes *et al.* 2015, Mowe *et al.* 2015, Pick 2016, Meriluoto *et al.* 2017, Svircev *et al.* 2019)
South America	*Microcystis* sp., *Anabaena* sp., *Cylindrospermopsis* sp. and *Aphanizomenon* sp.	Microcystins and cylindrospermopsin	(Antunes *et al.* 2015, Mowe *et al.* 2015, Svircev *et al.* 2019)
Oceania	*Microcystis* sp., *Anabaena* sp. and *Cylindrospermopsis* sp.	Microcystins, saxitoxins and cylindrospermopsin	(Antunes *et al.* 2015, Mowe *et al.* 2015, Svircev *et al.* 2019)

Table 2. The occurrence of dominant cyanobacterial toxins in water bodies of some countries.

Continent	Country	Water source	Dominant cyanobacterial toxins	Reference
Africa	Egypt	Bardawil Lagoo	Microcystin	(El-Kassas *et al.* 2016)
		Lake Maryout	Microcystin	(Ghobrial *et al.* 2015)
		Fish Ponds	Microcystin	(Dawah *et al.* 2015)
		Nile River	Microcystin	(Gomaa *et al.* 2014, Mohamed *et al.* 2015, 2006)
		Irrigation canal	Microcystin	(Mohamed 2001, 2002, Mohamed and Hussein 2006)
		El-Dowyrat fish farm	Microcystin	(Mohamed and Hussein 2006, Mohamed 2007)
	Nigeria	Lamingo reservoir	Microcystin	(Ajuzie 2012)
		Lekki lagoon	Microcystin	(Adesalu and Ikegwu 2010)
		Engineering pond	Microcystin	(Chia *et al.* 2009)
		Biological Sciences pond A	Microcystin	(Chia *et al.* 2009)
		Biological Sciences pond B	Microcystin	(Chia *et al.* 2009)
		Biological Sciences pond C	Microcystin	(Chia *et al.* 2009)
		Prof Nok pond A	Microcystin	(Chia *et al.* 2009)
		Prof Nok pond B	Microcystin	(Chia *et al.* 2009)
		Aliyu Fish pond	Microcystin	(Chia *et al.* 2009)
		Limi Hospital pond A	Microcystin	(Chia *et al.* 2009)
		Limi Hospital pond B	Microcystin	(Chia *et al.* 2009)
		Limi Hospital pond C	Microcystin	(Chia *et al.* 2009)
		Rock Road, Government Reserved Area	Microcystin	(Chia *et al.* 2009)
		Mid-Cross River	Microcystin	(Okogwu and Ugwumba 2009)
		Samaru stream	Microcystin	(Tiseer *et al.* 2007)
	South Africa	Theewaterskloof dam	Microcystin	(Oberholster *et al.* 2015)
		Hartebeespoort dam	Microcystin	(Ballot *et al.* 2014)
		Loskop dam	Microcystin	(Nchabeleng *et al.* 2014)
		Sunset dams	Microcystin	(Masango *et al.* 2010)
		Nhlanganzwani dam	Microcystin	(Masango *et al.* 2010)
		Lake Krugersdrift	Microcystin	(Oberholster *et al.* 2009)
		Orange River	Cylindrospermopsin	(van Vuuren and Kriel 2008)
		Lake Midmar	Microcystin	(Oberholster and Botha 2007)
	Uganda	Lake Victoria	Microcystin	(Haande *et al.* 2011)
		Lake Mburo	Microcystin	(Havens 2008)
		Lake Kachera	Microcystin	(Havens 2008)
Antarctica		Adelaide Island	Cylindrospermopsin	(Kleinteich *et al.* 2014)
		Adelaide Island	Microcystins	(Kleinteich *et al.* 2014)
		King George Island	Microcystin and saxitoxin	(Genuario *et al.* 2013)
		Livingston Island	Microcystins	(Kleinteich *et al.* 2012)
		Mc Murdo Dry Valleys	Microcystins	(Puddick *et al.* 2015)
		Mc Murdo Ice Shelf	Microcystins	(Wood *et al.* 2008)
		Mc Murdo Ice Shelf	Microcystins	(Jungblut *et al.* 2006)
		Mc Murdo Ice Shelf	Nodularins and microcystin	(Hitzfeld *et al.* 2000)
Asia	Bangladesh	Ishakha Lake	Microcystins	(Affan *et al.* 2016)
		Brahmmaputra	Microcystins	(Affan *et al.* 2015)
		Sutiakhali pond	Microcystins	(Affan *et al.* 2015)
		Bailor pond	Microcystins	(Affan *et al.* 2015)
		Mymensingh Municipal Pond	Microcystins	(Jahan *et al.* 2010)
		Aquaculture pond in Gazipur, Dhaka	Microcystins	(Ahmed *et al.* 2008)
	China	Tong Ting Lake	Microcystins	(Feng *et al.* 2019)
		Lake Dianchi	Microcystin and anatoxin-a	(Zhu *et al.* 2014, Wang *et al.* 2015; 2019)
		Dongfang hong pond	Microcystins	(Liu *et al.* 2018)
		Three Gorges Reservoir	Microcystins	(Lu *et al.* 2018)
		Lake Erhai	Microcystin	(Yu *et al.* 2014)
		Lake Hongze	Microcystin	(Ren *et al.* 2014)
		YangheReservoir	Microcystin	(Wang *et al.* 2013)
		Qinhuai River basin	Microcystin	(Xu *et al.* 2011)
		Lake Taihu	Microcystin	(Zhang *et al.* 2010)
		Lake Xuanwu	Microcystin	(Xu *et al.* 2010)
	Singapore	Freshwater Reservoir	Microcystin	(Te *et al.* 2017)
		Kranji Reservoir	Microcystin	(Te and Gin 2011, Penn *et al.* 2014)
	South Korea	Han River	Microcystin	(Suh *et al.* 2005)
		Daechung Reservoir	Microcystin and anatoxin-a	(Oh *et al.* 2001, Joung *et al.* 2002)
		Paldang Reservoir	Microcystin	(Park *et al.* 2000)
		Naktong River	Microcystin	(Srivastava *et al.* 1999)
		Lake Kasumigaura	Microcystin and anatoxin-a	(Park *et al.* 1993)
		Lake Sagami	Microcystin	(Park *et al.* 1993)
		Lake Suwa	Microcystin and anatoxin-a	(Park *et al.* 1993)
		Pond Metoba	Microcystin	(Park *et al.* 1993)
		Lake Abashiri	anatoxin-a	(Park *et al.* 1993)
		Pond Makinoga	Anatoxin-a	(Park *et al.* 1993)

(*continued*)

Table 2. Continued.

Continent	Country	Water source	Dominant cyanobacterial toxins	Reference
Europe	Bulgaria	Golyamo Skalensko Lake	Microcystins and saxitoxins	(Teneva *et al.* 2014)
		Malko Skalensko Lake	Microcystins	(Teneva *et al.* 2014)
		Reservoir Pchelina	Microcystins	(Pavlova *et al.* 2006)
		Lake Shabla	Microcystin	(Pavlova *et al.* 2006)
		Lake Durankulak	Microcystins	(Pavlova *et al.* 2006)
		Reservoir Mandra	Microcystins	(Pavlova *et al.* 2006)
		Reservoir Bistritsa	Microcystins	(Pavlova *et al.* 2006)
	France	Tarn River	Anatoxin-a	(Echenique-Subiabre *et al.* 2018)
		Lake Aydat	Microcystin and anatoxin-a	(Sabart *et al.* 2015)
		Recreational water body	Microcystins and saxitoxins	(Ledreux *et al.* 2010)
		Lake Ribou	Microcystin and cylindrospermopsin	(Brient *et al.* 2009)
		Lake La Dathe ́e	Microcystin and cylindrospermopsin	(Brient *et al.* 2009)
		Vern/Seiche	Cylindrospermopsin	(Brient *et al.* 2009)
		Lake Boulet	Cylindrospermopsin	(Brient *et al.* 2009)
		Marcille Robert	Microcystin, and cylindrospermopsin	(Brient *et al.* 2009)
		Pond Le Pertre	Microcystin, and cylindrospermopsin	(Brient *et al.* 2009)
		La Loue River	Anatoxin-a	(Gugger *et al.* 2005)
		Freshwater	Nodularin	(Beattie *et al.* 2000)
	Germany	Lake Tegel	Anatoxin-a	(Fastner *et al.* 2018)
		Lake Bützsee	Cylindrospermopsin	(Rucker *et al.* 2007)
		Lake Zermützelsee	Cylindrospermopsin	(Rucker *et al.* 2007)
		Lake Stolpsee	Cylindrospermopsin	(Rucker *et al.* 2007)
		Lake Großer Plessower See	Cylindrospermopsin	(Rucker *et al.* 2007)
		Lake Ruppiner See	Cylindrospermopsin	(Rucker *et al.* 2007)
		Arendsee	Microcystin	(Fastner *et al.* 1999)
		Oestertalsperre	Microcystin	(Fastner *et al.* 1999)
		Schlachtensee	Microcystin	(Fastner *et al.* 1999)
		Schwielowsee	Microcystin	(Fastner *et al.* 1999)
		Speicher II Radeburg	Microcystin	(Fastner *et al.* 1999)
		Tegeler See	Microcystin	(Fastner *et al.* 1999)
		TS Bautzen	Microcystin	(Fastner *et al.* 1999)
		TS Pohl	Microcystin	(Fastner *et al.* 1999)
		TS Weida	Microcystin	(Fastner *et al.* 1999)
		Wannsee	Microcystin	(Fastner *et al.* 1999)
		Zeuthener See	Microcystin	(Fastner *et al.* 1999)
	Turkey	Porsuk Dam Lake	Microcystin and cylindrospermopsin	(Koker *et al.* 2017)
		Omerli Dam Lake	Microcystin and cylindrospermopsin	(Koker *et al.* 2017)
		Manyas Lake	Microcystin and cylindrospermopsin	(Koker *et al.* 2017)
		Devegecidi Dam Lake	Microcystin and cylindrospermopsin	(Koker *et al.* 2017)
		Lake Sapanca	Microcystins, nodularin, anatoxin-a and cylindrospermopsin	(Albay *et al.* 2003, Greer *et al.* 2016, Koker *et al.* 2017)
		Lake Iznik	Cylindrospermopsin	(Albay *et al.* 2003, Akcaalan *et al.* 2014)
		Kucukcekmece Lagoon	Microcystins	(Albay *et al.* 2005)
		Lake Taskisi (Calticak)	Microcystins	(Albay *et al.* 2003)
North America	Canada	Lake Roxton	Microcystin	(Levesque *et al.* 2014)
		Lake William	Microcystin	(Levesque *et al.* 2014)
		Lake Champlain's Missisquoi Bay	Microcystin	(Levesque *et al.* 2014)
		Wascana Lake	Microcystin	(Donald *et al.* 2011)
		Pakowki Lake	Microcystin	(Park *et al.* 2001)
		Echo Lake	Microcystin	(Dillenberg and Dehnel 1960)
		Long Lake	Microcystin	(Dillenberg and Dehnel 1960)
		Katepwa Lake	Microcystin	(Dillenberg and Dehnel 1960)
	Guatemala	Lake Atitlan	Cylindrospermopsin and saxitoxin	(Rejmánková *et al.* 2011)
	Mexico	Natural lake Cienega Chica	Microcystin	(Vasconcelos *et al.* 2010)
		Natural lake Laguna Atotonilco	Microcystin	(Vasconcelos *et al.* 2010)
		Natural lake Zumpango	Microcystin	(Vasconcelos *et al.* 2010)
		Reservoir Los Angeles	Microcystin	(Vasconcelos *et al.* 2010)
		Reservoir Valle de Bravo	Microcystin	(Vasconcelos *et al.* 2010)
		Man-made channel Cuemanco	Microcystin	(Vasconcelos *et al.* 2010)
		Man-made channel Tlameleca	Microcystin	(Vasconcelos *et al.* 2010)
		Urban lake Chapultepec	Microcystin	(Vasconcelos *et al.* 2010)
		Lake Lago Catemaco	Cylindrospermopsin	(Berry and Lind 2010)
		Valle de Bravo Reservoir	Microcystin	(Merino-Ibarra *et al.* 2008)
		Quemado lake	Microcystin	(Caldwell and Caldwell 1978)

(*continued*)

Table 2. Continued.

Continent	Country	Water source	Dominant cyanobacterial toxins	Reference
	USA	Maumee River	Microcystin	(Jankowiak *et al.* 2019)
		Sandusky River	Microcystin	(Jankowiak *et al.* 2019)
		Utah Lake	Microcystin	(Li *et al.* 2019)
		Harsha Lake	Microcystin and saxitoxin	(Chen *et al.* 2017, Lu *et al.* 2019)
		Eel River	Anatoxin-a and Microcystin	(Bouma-Gregson *et al.* 2018)
		Lake Michigan.	Microcystin	(Bartlett *et al.* 2018)
		Lake Erie	Microcystin	(Lee *et al.* 2015, Carmichael and Boyer 2016, Hu *et al.* 2016, Chaffin *et al.* 2018)
		Grand Lake St. Marys	Microcystin	(Gorham *et al.* 2017)
		St. Lucie Estuary	Microcystin	(Lapointe *et al.* 2017)
		Ottawa National Wildlife Refuge wetland	Microcystin	(Hu *et al.* 2016)
		California DWTP	Microcystin	(Szlag *et al.* 2015)
		Texas DWTP	Microcystin	(Szlag *et al.* 2015)
		Florida DWTP	Microcystin	(Szlag *et al.* 2015)
		Oklahoma DWTP	Cylindrospermopsin and Microcystin	(Szlag *et al.* 2015)
		Lake Huron	Microcystin	(Fahnenstiel et al. 2008)
		Salton Sea	Microcystin	(Carmichael and Li 2006)
South America	Argentina	Parana River	Microcystins	(Elizabet *et al.* 2016)
		Drainage canal of a sewage treatment facility in Pila town	Microcystins	(Qi *et al.* 2015)
		Rio de la Plata estuary	Microcystin	(Giannuzzi *et al.* 2011)
		Salto Grande Dam	Microcystin	(Giannuzzi *et al.* 2011)
		Piedras Moras reservoir	Microcystin	(Mancini *et al.* 2010)
		Río de la Plata river	Microcystin	(Andrinolo *et al.* 2007)
		Lake Planetario	Microcystins	(Ehrenhaus and Susana 2006)
		San Roque reservoir	Microcystins	(Cazenave *et al.* 2005)
	Brazil	Araçagi pond	Microcystins, nodularins and cylindrospermopsins	(Walter *et al.* 2018)
		Boqueirão	Microcystins, nodularins, and cylindrospermopsins	(Walter *et al.* 2018)
		Saulo Maia	Microcystins, nodularins, and cylindrospermopsins	(Walter *et al.* 2018)
		Armando Ribeiro Gonçalves reservoir	Saxitoxins and microcystins	(Fonseca *et al.* 2015)
		Passagem das Traíras reservoir	Saxitoxins and microcystins	(Fonseca *et al.* 2015)
		Itans reservoir	Saxitoxins and microcystins	(Fonseca *et al.* 2015)
		Garagalheiras reservoir	Saxitoxins and microcystins	(Fonseca *et al.* 2015)
		Alagoinha Reservoir	Microcystin	(Bittencourt-Oliveira *et al.* 2014)
		Arcoverde Reservoir	Microcystin and Cylindrospermopsin	(Bittencourt-Oliveira *et al.* 2014)
		Carpina Reservoir	Microcystin	(Bittencourt-Oliveira *et al.* 2014)
		Duas Unas Reservoir	Microcystin and Cylindrospermopsin	(Bittencourt-Oliveira *et al.* 2014)
		Ingazeira Reservoir	Microcystin	(Bittencourt-Oliveira *et al.* 2014)
		Ipojuca Reservoir	Microcystin and Cylindrospermopsin	(Bittencourt-Oliveira *et al.* 2014)
		Jucazinho Reservoir	Microcystin and Cylindrospermopsin	(Bittencourt-Oliveira *et al.* 2014)
		Mundaú Reservoir	Microcystin	(Bittencourt-Oliveira *et al.* 2014)
		Tapacurá Reservoir	Microcystin	(Bittencourt-Oliveira *et al.* 2014)
		Venturosa Reservoir	Microcystin	(Bittencourt-Oliveira *et al.* 2014)
		Water reservoir of Vargem das Flores	Microcystin	(Gomes *et al.* 2012)
		Salto Grande Reservoir	Microcystin	(Carneiro *et al.* 2012)
		Armando Ribeiro Gonçalves reservoir	Microcystins and saxitoxins	(Costa *et al.* 2006)
	Chile	Inshore waters of western Patagonia	Microcystin	(Leon-Munoz *et al.* 2018)
		Lo Galindo Lake	Microcystins	(Almanza *et al.* 2016)
		Lake Rocuant	Microcystin	(Campos *et al.* 1999)
	Uruguay	Carrasco Beach	Microcystins	(Vidal *et al.* 2017)
		Salto Grande Reservoir	Microcystin	(de la Escalera *et al.* 2017)
		Fray Bentos freshwater systems	Microcystin	(de la Escalera *et al.* 2017)
		Estuarine Montevideo	Microcystin	(de la Escalera *et al.* 2017)
		Estuarine Punta del Este	Microcystin	(de la Escalera *et al.* 2017)
		Carmelo freshwater systems	Microcystin	(de la Escalera *et al.* 2017)
		Colonia freshwater systems	Microcystin	(de la Escalera *et al.* 2017)

(*continued*)

Table 2. Continued.

Continent	Country	Water source	Dominant cyanobacterial toxins	Reference
		Lago Javier Lake	Microcystin	(Vidal and Kruk 2008)
		Laguna Blanca Lake	Microcystin	(Vidal and Kruk 2008)
		Laguna Chica Lake	Microcystin	(Vidal and Kruk 2008)
		Laguna del Sauce Lake	Microcystin	(Vidal and Kruk 2008)
Oceania	Australia	Lake Yangebup	Microcystin	(Reichwaldt *et al.* 2013)
		Carbrook Cable Ski Lake	Nodularin	(McGregor *et al.* 2012)
		Fitzroy River	Microcystin	(Bormans *et al.* 2004)
		Water treatment plant located in Queensland	Microcystin	(Hoeger *et al.* 2004)
		Water treatment plant near Brisbane	Cylindrospermopsin and microcystin	(Hoeger *et al.* 2004)
		Lake Elphinstone	Microcystin	(White *et al.* 2003)
		Gippsland Lakes area of Southern Victoria	Nodularin	(Van Buynder *et al.* 2001)
		Teemburra	Cylindrospermopsin	(McGregor and Fabbro 2000)
		Cania	Cylindrospermopsin	(McGregor and Fabbro 2000)
		Borumba	Cylindrospermopsin	(McGregor and Fabbro 2000)
		Eungella	Cylindrospermopsin	(McGregor and Fabbro 2000)
		Wuruma	Cylindrospermopsin	(McGregor and Fabbro 2000)
		Coolmunda	Cylindrospermopsin	(McGregor and Fabbro 2000)
	New Zealand	Lake Forsyth	Nodularin	(Wood and Dietrich 2011)
		Lake Rotorua	Microcystin	(Wood and Dietrich 2011)
		Waitaki River,	Microcystin	(Wood *et al.* 2010)
		Hutt River	anatoxin-a	(Wood *et al.* 2007)
		Lakes Rotoiti	Microcystin	(Wood *et al.* 2006)
		Lake Rotoehu	Microcystin	(Wood *et al.* 2006)
		Waikanae River	Anatoxin-a	(Hamill 2001)
		Mataura River	Anatoxin-a	(Hamill 2001)

Antarctica is an extreme and vast continent, relatively isolated from the rest of the world. Antarctica characterized by cold climate and is currently not suitable for mammalian survival has also been reported to have experienced cyanoblooms and subsequent production of four cyanotoxins (as indicated in Table 2). Kleinteich *et al.* (2014) found that *Oscillatoria* sp. and *Nostoc* sp. could produce cylindrospermopsins and microcysins respectively in Adelaide Island. In King George Island, *Hydrocoryne* spp. were shown to produce microcystin and saxitoxin (Genuario *et al.* 2013). Further Jungblut *et al.* (2006) also noted that *Phormidium* sp., *Oscillatoria* sp., *Nostoc* sp. and *Anabaena* sp. could produce different variants of microcystins in Mc Murdo Ice Shelf. The evidences suggest that Antarctica continent also has strong cyanotoxins adaptability. However, further studies to determine the adaptability of other cyanotoxins such as anatoxin-a in Antarctica is required. It is of interest that *Microcystis* sp. known for its extremely abundant biomass, frequent occurrence and ability to produce microcystins has not been discovered in this continent.

5. Factors influencing the occurrence of cyanobacterial blooms

Cyanobacterial blooms although were recognized since ancient era, various researchers have noted that they are gradually becoming greater in size, amount and degree worldwide (Taranu *et al.* 2017, 2015, Liu *et al.* 2018, Feng *et al.* 2019). The formation of cyanoblooms though has been reported as a natural occurrence across freshwater-to-marine continuum, a number of environmental factors including nutrient, carbon dioxide (CO_2), weather conditions, water body, salinity, heavy metals, sunlight, pH, brief periods of drought and heavy rain may result to the acceleration, promotion and expansion of the blooms (Sivonen and Jones 1999, Bouvy *et al.* 2000, Baldia *et al.* 2003, Johnk *et al.* 2008, Davis *et al.* 2009, Molot *et al.* 2014, Paerl *et al.* 2016, Jia *et al.* 2018, Omidi *et al.* 2018, Wang *et al.* 2019). Understanding the involvement of these factors influencing cyanoblooms are based on experimental and inferential data.

5.1. Nutrients

It is reported that nutrients enrichment by nitrogen and phosphorus are the most important factors affecting the development of cyanobacteria species in water sources (Huszar *et al.* 2000, Oh *et al.* 2000, Paerl and Otten 2013, Jankowiak *et al.* 2019). Sivonen and Jones (1999) demonstrated that the decay of excessive blooms may result to decreased dissolved oxygen and the subsequent release of cyanotoxins.

Observation indicates that cyanobacteria often dominate phytoplankton communities under high concentrations of nitrogen, phosphorus and organic compounds due to anthropogenic input. In addition, human nutrient over enrichment in water, particularly nitrogen and phosphorus, associated with urban, agricultural and industrial development, has promoted eutrophication which favors cyanoblooms emergence (Paerl *et al.* 2001, 1988, Zhang *et al.* 2010, Carmichael and Boyer 2016). It is of interest that the worldwide utilization of nitrogen fertilizer is progressively surpassing that of phosphorus. This has resulted to the increase in nitrogen to phosphorus ratio in several water bodies (Dolman *et al.* 2012, Grizzetti *et al.* 2012, Jankowiak *et al.* 2019, Lu *et al.* 2019). Phosphorus though is considered a key factor in freshwater ecosystems limiting the growth of phytoplankton and toxin evolution (Schindler *et al.* 2008), Oh *et al.* (2000) showed a decrease amount of microcystin under the lowest phosphorus concentrations and under phosphorus limiting conditions, an increased level of microcystin from *Microcystis aeruginosa* was found.

It is well established that nitrogen fixation is an important feature of some cyanobacteria species and in terms of nutrition nitrogen-fixing, cyanobacteria are considered the most self-sufficient among other organisms. They are photoautotrophs that require only light energy, CO_2, dinitrogen (N_2), water and some minerals (Paerl and Huisman 2009, Paerl and Otten 2013, Paerl *et al.* 2016, 2001). Heterocysts are specialized nitrogen-fixing cells. Heterocysts have thick cell wall, do not pose photosynthetic membrane and are larger, clearer and highly refractive under light microscope appearance. They may occur within the filament of photosynthetic cells or terminally on a filament (Paerl and Huisman 2009, Paerl and Otten 2013, Paerl *et al.* 2016, 2001). Due to the differences in size, shape and location of heterocysts, they form a significant component in species identification. Within the heterocysts, the enzyme nitrogenase reduces molecular nitrogen to ammonia, which is incorporated into the amido group of glutamine. The thickened cell wall enables molecular oxygen to enter the cell, to be reduced (Bryant 1994, Paerl *et al.* 2016, 2001), thus helping to maintain a highly reducing environment within the cell, necessary for nitrogen reduction.

It is worth noting that some cyanobacteria species appear to be able to fix atmospheric nitrogen without visible heterocysts. This may be related to the anaerobic conditions in which the organisms can survive (Paerl and Huisman 2009, Paerl and Otten 2013, Paerl *et al.* 2016, 2001). A high density of suspended cells may lead to the formation of surface scums and high toxin concentrations. Nitrogen concentration may not be important for *Cylindrospermopsis* sp., due to the fact that *Cylindrospermopsis* sp. are nitrogen-fixing cyanobacteria species (Gondwe *et al.* 2008, Abreu *et al.* 2018). Rapala *et al.* (1997) showed that the nitrogen fixing *Anabaena* sp. had higher level of microcystin in nitrogen deficient medium. In contrast, Sivonen (1990) indicated that the non-nitrogen fixing *Microcystis* sp. and *Oscillatoria* sp. synthesized more toxins when nitrogen was enriched. *Planktothrix agardhii* and *Microcystis* spp. were also found to produce microcystins under the induction of nitrogen in Wascana Lake, Saskatchewan, Canada (Donald *et al.* 2011). Further, Gobler *et al.* (2016) demonstrated that the rise in nitrogen favored proliferation of *Microcystis* sp. which induced microcystin in Lake Erie. These reveal that the presence of nitrogen concentration do not appear to be a factor for *Cylindrospermopsis* and *Anabaena* blooms but it is an important element for *Microcystis*, *Oscillatoria* and *Planktothrix* blooms.

5.2. Concentration level of carbon dioxide

Carbon dioxide is a prerequisite for toxic cyanoblooms in terms of photosynthesis and growth. In the process of blooms generation, the concentration of dissolved CO_2 in water can be depleted to create a concentration gradient across the air to water interface (Verspagen *et al.* 2014). Low-Décarie *et al.* (2011) reported that at low dissolved CO_2 concentration, cyanobacteria became predominant competitors compared to eukaryotic phytoplankton (green algae) that benefited from high dissolved CO_2 concentration. On the contrary Ji *et al.* (2017) found that green algae can be strong competitors under CO_2 depleted conditions, and bloom-forming cyanobacteria having high-flux bicarbonate uptake systems may gain from increased CO_2 concentrations. In a recent publication regarding laboratory and field studies, Sandrini *et al.* (2016) investigated the ability of *Microcystis* sp. to generate toxic cyanoblooms and both laboratory and field evidence showed that the increasing carbon concentrations caused rapid adaptive alterations in the genotype composition of cyanoblooms. Also Verspagen *et al.* (2014) through laboratory experiments and mathematical models speculated that cyanoblooms will intensify when CO_2 level increases. These findings signify that rising CO_2 concentrations are capable to facilitate the intensification of bloom-forming cyanobacteria in eutrophic and hypertrophic waters.

5.3. Weather conditions

Weather conditions such as temperature and wind have demonstrated involvement in the growth of cyanoblooms. While warm and calm weather enhance the production of cyanoblooms (Paerl and Huisman 2008), cold and windy conditions favor other species development (Kanoshina *et al.* 2003). In temperate regions, cyanoblooms usually occur in summer and last for the entire period (Johnk *et al.* 2008, Davis *et al.* 2009) or less. Conversely, at any time of the year, cyanoblooms are capable to occur in tropical regions and generally last for a few weeks at a time (Huszar *et al.* 2000, Figueredo and Giani 2009, Prakash *et al.* 2009). El-Shehawy *et al.* (2012) reported that global warming and temperature gradients also contribute to cyanoblooms formation and the subsequent production of different cyanotoxins. In addition, possible consequences of global warming on physiological and molecular changes in cyanobacteria and resulting effects on microcystin generation were demonstrated (El-Shehawy *et al.* 2012). *Anabaena* sp. and *Microcystis* sp. were also shown to produce microcystins between temperatures 18 °C and 25 °C (Sivonen and Jones 1999). At higher temperatures, *Anabaena* sp. produced MC-RR while MC-LR was generated at temperatures below 25 °C (Rapala *et al.* 1997). Studies indicated that higher temperatures favored *Cylindrospermopsis* sp. (Bouvy *et al.* 2000, Huszar *et al.* 2000, Briand *et al.* 2002, Figueredo and Giani 2009). For instance a *Cylindrospermopsis* blooms in a shallow pond in France was found to be affected by high temperature indentified as key factor in germination of akinetes (Briand *et al.* 2002).

Using long-term historical statistics and short-term field measurement study, Wu *et al.* (2015) assessed the consequences of changes in wind patterns on cyanoblooms in Lake Taihu and noted that the changes favored the increased progression of the blooms, mainly composed of *Microcystis* sp. Wu *et al.* (2013) also investigated the cyanoblooms fading and reemergence in Lake Taihu in response to short-term hydrodynamic alterations, through field sampling, long-term ecological data, high-frequency sensors and MODIS satellite images and showed that the dominant easterly wind was primarily accountable for cyanobacterial biomass acquisition, following bloom proliferation. Further Moreno-Ostos *et al.* (2009) observed that the changes in wind speed affected cyanobacteria development in a Mediterranean reservoir. During winter, the surface time series of fluorescence was positively correlated with the short-term variations in wind speed while negative correlation existed during the summer (Moreno-Ostos *et al.* 2009). These findings indicate that high temperatures and changes in wind patterns or speed appear to be a factor causing the rise and fall of cyanoblooms formation.

5.4. Type of water body

This is considered a vital factor for cyanobacteria species dominance, and is gradually receiving much attention owing to frequent blooms evolution. The behavior of cyanobacteria species may differ entirely in different water columns (Dokulil and Teubner 2000). Interestingly the factors causing species dominance are many a time difficult to identify since numerous interacting factors are usually involved which vary in diverse environments (Dokulil and Teubner 2000, Bakker and Hilt 2016). Research indicated that the large shallow lake Taihu was conducive to *Microcystis* sp. growth and shallow river-run lake in Germany also encouraged *Aphanizomenon* sp. growth (Dokulil and Teubner 2000). In Austria the shallow urban lake Alte Donau was conducive to *Cylindrospermopsis* sp. growth while deep alpine lake Mondsee favored *Planktothrix* sp. growth (Dokulil and Teubner 2000). In a recent study, Bakker and Hilt (2016) demonstrated that water-level fluctuation had the potential to mitigate cyanoblooms. Water-level drawdown or temporal drying out may not support cyanoblooms formation while water-level rise may promote cyanoblooms development (Bakker and Hilt 2016). The results suggest that water depth, morphometry, water retention time and quality of inlet water may account for the cyanobacteria species dominance leading to blooms emergence.

5.5. Salinity

Salinity has been demonstrated to influence species growth and the subsequent bloom formations. Observations however indicate that species salinity tolerance varies among cyanobacteria species. Moisander *et al.* (2002) studied the effect of salinity on cyanobacteria proliferation and found that the growth of *Anabaenopsis* sp. and *Nodularia* sp. occurred between salinities 2 to 20 gL^{1} and 0 to 20 gL^{1} respectively. While *Cylindrospermopsis* sp. growth occurred at 4 gL^{1}, *Anabaena* sp. growth occurred at 15 gL^{1}. Tonk *et al.* (2007) also showed that at salinity level 10 gL^{1}, *Microcystis* sp. growth was attained. Between salinities 0.28 to 0.31 gL^{1} and 0.14 to 0.16 gL^{1}, growth of *Aphanizomenon* sp. and *Nodularia* sp. were respectively observed (Rakko and Seppala 2014). Further at salinity 7 ppm, Silveira and Odebrecht (2019) demonstrated the formation of *Nodularia spumigena* blooms and production of nodularin. These outcomes suggest that at salinity levels 0 to 20 gL[1], varying cyanobacteria species are capable of growing leading to bloom formations.

5.6. Heavy metal

Heavy metals are one of the most common pollutants worldwide, inducing serious hazards to the environment and public health. Concentrations of heavy metals in water bodies have been shown to promote cyanobacteria species magnification, following bloom formations. Lukac and Aegerter (1993) investigated the effect of trace heavy metals on the exponential growth of *Microcystis* sp. and found a distinct effect on the growth rate by iron. Zeng *et al.* (2012) also compared the bioaccumulation characteristics of cadmium and zinc in *Microcystis* sp. and reported that the species had a bioaccumulation capacity for the metals. In a recent investigation, Jia *et al.* (2018) demonstrated an enhanced extracellular bound of copper, zinc, lead, chromium and cadmium during cyanoblooms period. Further, cadmium, lead and chromium were detected in several local vegetables including radish, soybean, and cowpea which were irrigated with cyanoblooms broth collected from the lake (Jia *et al.* 2018). Interestingly, Surosz and Palinska (2004) indicated the inhibition of toxic metals on *Anabaena* sp. growth when the influence of copper and cadmium was assessed on the development of *Anabaena* sp. Although copper and cadmium inhibited the growth of *Anabaena* sp., trace metals at favorable

Table 3. Studies demonstrating the combination of various factors leading to the augmentation of cyanobacterial blooms.

Water source	Location	Description of influencing factors	Bloom	Toxins	Reference
Lake Dianchi	China	The hypereutrophic water conditions, low wind velocities and mild temperatures	Cyanobacterial bloom		(Wang *et al.* 2019)
Miyun reservoir	China	Surface water temperature, irradiance and low nutrient conditions	*Microcystis* bloom		(Su *et al.* 2019)
Shrimp ponds	Southern Brazil	Under conducive temperature and salinity	*Nodularia spumigena* bloom	Nodularin	(Silveira and Odebrecht 2019)
Maumee river	USA	Nutrients and elevated temperatures	*Microcystis* bloom		(Jankowiak *et al.* 2019)
Sandusky rivers	USA	Nutrients and elevated temperatures	*Planktothrix* bloom		(Jankowiak *et al.* 2019)
Baekje reservoir	Korea	Water temperature, nitrogen and phosphorus concentrations	Cyanobacterial bloom		(Park *et al.* 2017)
Lake Taihu	China	Effects of extreme weather conditions including heavy rainfall and strong winds had an influence on phosphorus and nitrogen	Cyanobacterial bloom		(Yang *et al.* 2016)
Ishakha Lake	Bangladesh	Temperatures and nutrients	Cyanobacterial bloom	Microcystin	(Abu *et al.* 2016)
Lake Lo Galindo	Chile	Temperature, nutrients and wind speed	*Microcystis* bloom		(Almanza *et al.* 2016)
Natural and drinking water bodies	Bangladesh	The combination of increased nitrate-nitrogen from fish feed, organic manure, poultry and dairy farm waste and fertilizer from agricultural land favorable water temperature	Cyanobacterial bloom	Microcystin	(Affan *et al.* 2015)
Hongze Lake	China	Water temperature, chemical oxygen demand (COD)Mn, nitrate (NO(3)-N), total nitrogen and/or total phosphorus	Cyanobacterial bloom		(Ren *et al.* 2014)
Lake Atitlan	Guatemala	Nitrogen, phosphorus, temperature and wind	Cyanobacterial bloom	Cylindrospermopsin and saxitoxin	(Rejmánková *et al.* 2011)
Daechung reservoir	Korea	Phosphorus concentration together with water temperature	*Microcystis* bloom		(Joung *et al.* 2011)
Baltic Sea	Gulf of Finland	The influence of weather conditions (temperature and wind)	Cyanobacterial bloom		(Kanoshina *et al.* 2003)
Steilacoom Lake	USA	Higher total phosphorus, decreased water transparency, high water column stability, high surface water temperature and pH, and decreased lake flushing.	*Microcystis* bloom	Microcystin	(Jacoby *et al.* 2000)

concentrations are likely to influence the growth of *Microcystis* sp., which may subsequently induce cyanoblooms development.

5.7. Sunlight

To illustrate the association between sunlight and cyanobacterial proliferations, Zhou *et al.* (2014) regulated the natural light intensities in Meiliang Bay, Lake Taihu with varying shading ratio (0% (full sunlight), 10%, 25%, 50% and 75% of original natural sunlight intensities) and reported that the higher shading ratios (75%) were very effective to control the average and total cyanoblooms biomass, while 50% shading ratio showed efficient control in peak value of phytoplankton biomass or postpone in cyanobloom occurrences. The data suggest that different sunlight densities may have the potential to influence the occurrence of cyanoblooms.

It is worth knowing that the combination of these factors and not a single factor alone contribute to the increased cyanoblooms formation and severity (Jacoby *et al.* 2000, Paerl *et al.* 2001, Jankowiak *et al.* 2019, Wang *et al.* 2019). Table 3 illustrates studies demonstrating the combination of various factors leading to the augmentation of cyanoblooms. Beside these studies, conceptual model has also been used to assess the relations between cyanoblooms and environmental factors. In a novel conceptual model, Molot *et al.* (2014) linked the role of anoxia, nitrogen, phosphorus, iron and sulfate to the evolution of cyanoblooms under favorable light, temperature, pH and salinity. Therefore, understanding the combination of the various factors leading to cyanoblooms formation is of great importance. It will be interesting to investigate the combine effect of nutrient, CO_2, weather conditions, water body, salinity, heavy metals and sunlight on these processes; acceleration, promotion and expansion of cyanoblooms. Future research will also be needed to gain more explanation on the combine mechanism of the various factors inducing cyanoblooms.

6. Conclusion and future directions

Cyanobacteria found in water surface can form dense called cyanoblooms. Cyanoblooms and the subsequent production of several cyanotoxins including microcystin, cylindrospermopsin, anatoxin-a and saxitoxin disturb water bodies, and further pose health hazards on the ecology and human. Evidences have proven the occurrence of cyanoblooms and cyanotoxins in Europe, North America, Asia, South America, Africa and even the cold Antarctica which currently do not support life. Although cyanoblooms and cyanotoxins occur naturally in both marine and freshwater habitats, the combination of factors including nutrient, CO_2, weather conditions, water body, salinity, heavy metals and sunlight accelerate, promote and expand

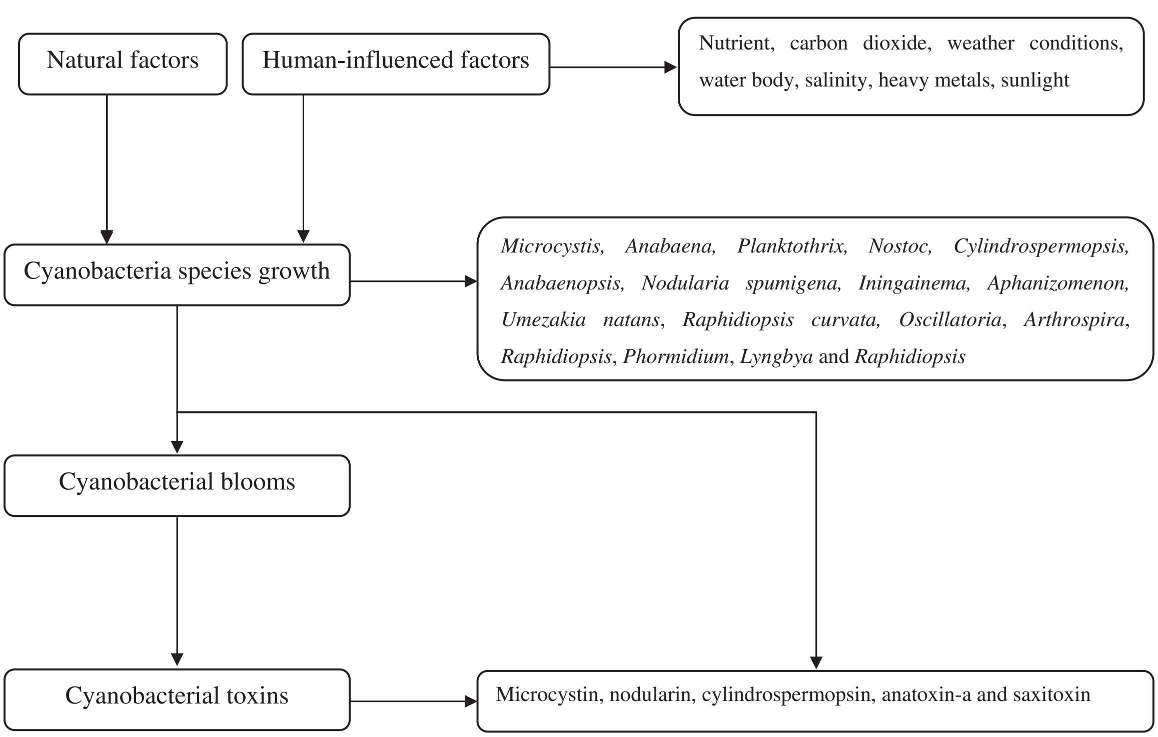

Figure 3. Flow chat illustrating cyanobacterial blooms and cyanobacterial toxins generation.

bloom occurrences. Figure 3 is a flow chat illustrating cyanoblooms and cyanotoxins generation.

Even though the understanding of toxic cyanoblooms is on the rise, some major areas await additional investigation. Since water quality is a critical consideration in determining water resource availability for human consumption, aquatic life, recreation, as well as plant and crop yield, immediate measures are required to ensure cyanoblooms and cyanotoxins minimization if scientists are to offer sound guidance for water resource management. The following are some of the areas that should be addressed with future studies.

1. Extensive mechanism research is needed on the natural occurrence of cyanoblooms.
2. Standard guidelines and measures should be taken and ensured to control anthropogenic activities including social economy, industrialization and agriculture.
3. Water safety policies on cyanoblooms and cyanotoxins, and their implementations should be considered.
4. Public education, sensitization programs and awareness on the toxic manifestations of cyanoblooms and cyanotoxins, and related illness is of great importance particularly in remote settings where lagoons, rivers and streams are the main water sources.
5. Various countries should develop guideline values for cyanotoxins in water for drinking, bathing, recreational and irrigational purposes.

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