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An Overview of Cyanobacteria Harmful Algal Bloom (CyanoHAB) Issues in Freshwater Ecosystems

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Abstract

This chapter will present an overview of cyanobacterial harmful algal blooms (cyanoHABs) and biotic and abiotic factors, as well as various aspects associated with these worldwide ecological bursts. The exact causes of the cyanoHABs are still not well defined, but eutrophication and climate change (temperature increase, light intensity variation, etc.) are the two assumed main factors that may promote the proliferation and expansion of cyanobacterial blooms. However, these premises need to be profoundly investigated as the optimal combination of all factors such as increased nutrient loading, physiological characteristics of cyanobacterial species, and climate effects which could lead to the blooming pattern will require robust modeling approaches to predict the phenomena. Negative issues associated with cyanoHABs are diverse including the toxic products (cyanotoxins) released by certain taxa which can damage the health of humans and animal habitats around the related watershed as well as generate a huge water quality problem for aquatic industries.

Keywords: cyanobacteria, cyanotoxins, freshwater ecosystems, mathematical modeling, ecotoxicity

1. Introduction

Freshwater ecosystems (lakes, rivers, and reservoirs) play an important role in regulating Earth's climate and they are of high ecological and socioeconomic value, as well as a crucial

life-giving resource for humanity. However, these water bodies are fragile and anthropic pressures such as discharge of sewage, industrial pollutants, eroding soil, and deposition of effluents rich in nitrates and phosphorus cumulating by the tourist industry and urbanization have accelerated the rate and extent of their continuous eutrophication which has led to a loss of water quality and biodiversity. Worldwide, the massive proliferation of cyanobacterial harmful algal blooms (cyanoHABs) is among the major undesirable effects resulting of eutrophication [1–4]. To date, environmental factors identified as contributing toward their global expansion included increased nutrient inputs via anthropogenic activities and temperatures and CO₂ concentrations due to changing global climate [5–10]. Nevertheless, these aspects need to be investigated in the future and the combination of increased nutrient loadings, physiological characteristics of cyanobacterial species, and climate change such as increase of temperature and variation of light intensity and quality will require robust modeling approaches to predict the blooming phenomena.

Since freshwater bodies around the world can be used as drinking water reservoirs or recreational areas, the blooming phenomena have gained attention as possible health hazards. The problems associated with toxic cyanobacterial blooms in these different areas are diverse, from environmental asphyxiation due to excessive consumption of oxygen, to purely esthetic problems in recreational areas when the blooms are a colorful and often smelly scum on the surface of the water [5, 11, 12]. To these common problems are added productions by certain species of cyanobacteria of various secondary metabolites with a specific toxic potential (hepatotoxins, neurotoxins, and dermatotoxins) causing water quality problems for fisheries, aquaculture, farming, and sanitary hazards to human and animal health [13–17]. This chapter focuses on the cyanoHAB occurrence as well as on environmental factors favoring their proliferation, possible human and animal health outcomes associated with their toxins and a review of robust modeling approaches to predict the bloom pattern.

2. Involving factors in cyanoHAB pattern

2.1. Abiotic factors

Among the abiotic factors, nutrients, including inorganic nitrogen (N) and phosphorus (P), temperature, and light intensity, and hydrodynamic parameters of the water body (turbidity and residue time) have been reported as the most important factors in the proliferation of cyanobacteria [2, 4, 6]. The availability of nutrients such as N and P is essential for the growth of cyanobacteria. For example, field experiments by monitoring surveys of phytoplankton for 3 years (2012–2014) in Lake Erie (U.S.A.) showed that inter-annual differences in the duration, intensity, and toxicity of cyanobacterial blooms in this area were considered related to in-lake and tributary nutrient (N and P) concentrations [2]. This ecosystem observation is consistent with other earlier field and laboratory studies which have shown that cyanobacterial bloom occurrence and cyanobacterial species growth in cultures, respectively, have been controlled by the availability of both inorganic nitrogen and phosphorus [18–21]. However, cyanobacteria taxa such as N₂-fixing (diazotrophic) and non-N₂ fixing (nondiazotrophic) species have a

variety of mechanisms to compete for nitrogen. A strong relationship between the growth and toxin synthesis of diazotrophic and nondiazotrophic cyanobacteria and inorganic dissolved N in the medium has commonly been reported in the literature [22–25]. Efforts often focus on total nitrogen (TN) and there exist important gaps in the understanding of how N speciation (NO_3^- and NH_4^+) influences cyanobacterial blooms and cyanotoxin synthesis. For example, in lakes showing symptoms of N limitation during late summer, numerous studies reported that cyanobacteria such as *Microcystis*, a non- N_2 fixing genus, have been shown to become dominant by rapidly assimilating recycled ammonium [26–29]. Indeed, laboratory and *in situ* studies have shown that cyanobacteria appear to out-compete other algal species for reduced N forms such as ammonium and urea [26, 27, 30]. For example, Donald et al. [31] reported that fertilization of the lake Wascana (Canada) with ammonium increased total algal abundance about 350% and cyanobacterial biomass over 500%. In a recent study examining the effects of different forms of N (nitrate, ammonium, and urea) in Lake Erie (U.S.A.), Chaffin et al. [32] have shown that the ammonium enrichment resulted in greater cyanobacterial biovolume than in the nitrate and urea enrichments. While nitrate is generally the most abundant form of nitrogen in freshwater ecosystems, it is the least preferred form of nitrogen, since its uptake by cyanobacteria requires multiple steps of intracellular reduction to ammonia [32–34]. Hence, while nitrogen (N) plays a primary role in shaping the relative abundance of cyanoHABs in a freshwater ecosystem, phosphorus (P) likely acts and interacts to influence these populations as well. The ability of cells to store phosphorus as polyphosphates [35] allows them to double several times even in phosphorus-limiting conditions [36]. Phosphorus affinities are higher in cyanobacteria compared to eukaryotic algae [37]. The concentration of phosphorus around 0.03 mg L^{-1} is enough for the sufficient growth of the cyanobacteria [38]. Therefore, phosphorus is commonly considered to be the limiting nutrient in freshwater ecosystems, and high concentrations of this nutrient often correlate to the occurrence of cyanobacterial blooms worldwide [2, 6, 39–42]. In contrast, instead of considering the effects of N and P separately, numerous studies highlight the importance of the ratio of TN to TP (TN:TP) in determining cyanobacterial growth [42, 43]. For example, several studies in many freshwater bodies showed that when the ratio TN:TP decreased, a shift has been reported in phytoplankton assemblages toward cyanobacteria dominance [2, 12, 44].

Light intensity and quality are other important factors in phytoplankton growth. Phytoplankton can photosynthesize, using the pigments chlorophyll-a (Chl-a) and -b, therefore at a certain light intensity, depending on the species, the algae will be at maximum productivity. The pigments are also sensitive to specific wavelengths: blue and red light. Using two species as an example, *Aphanizomenon flos-aquae* is less light dependent than *Dolichospermum flos-aquae*, so in situations where there is less light, *Aphanizomenon flos-aquae* would be at maximum production. The cyanobacterial light harvesting mechanism is different from that of the eukaryotic algae and contains phycobiliproteins, which allows cyanobacteria to absorb light from a wide light spectrum [36]. In the fast-changing light environment, cyanobacteria have a photoadaptation mechanism, which reduces the number of harvesting mechanisms and turns the energy into the heat [36]. There is also a photoprotective mechanism that cyanobacteria use: energy dissipation mechanism [36]. They have a UV photoprotection mechanism as well: mycosporine-like amino acids (MAAs) and scytonemin that absorbs UV light and helps them to survive with high level of irradiance [45].

Water temperature leads to cyanobacterial bloom development and plays a critical role in buoyancy and assimilation of essential nutrients and synthesis of toxins [46–48]. For example, Kosten et al. [19] by examining 143 lakes along a latitudinal transect ranging from subarctic Europe to southern South America found that temperature and TN concentrations were the strongest explanatory variables for cyanobacterial biomass. This finding is also consistent with that reported by Beaulieu et al. [20] who examined the proliferation of cyanobacteria in 1147 lakes and reservoirs of different trophic status in the United States and showed that the best linear multiple regression model for predicting these events was based on TN and temperature of the lake water. Therefore, in terms of global climate change, it is obvious that the increase of water temperature will be observed, and cyanobacteria will have the prevalence in the growth rate compared to the other phytoplankton.

Turbidity is another factor that influences algal growth. The particulate matter in the water column affects light penetration and temperature of the water. An excess of sediments in the water would decrease the light penetration, which in turn may prevent large algal blooms. The sediments also aid in lowering the amount of temperature fluctuations in the water. A more consistent and possibly lower temperature would help prevent large algal blooms [49]. The higher the pH, the higher diversity of cyanobacteria can be found with a prevalence of nonfixers (*Microcystis* spp.), while N-fixers are more dominant at low pH [50]. The structure of the lake plays the accessory role in bloom formations. The depth of a water body, speed of flow, and presence of small coves make every water body unique and need additional attention.

Abiotic factors described above are not the only ecological factors influencing the occurrence and frequent dominance of cyanobacteria in the phytoplankton. Their widespread representation in freshwaters depends also on biotic factors such as buoyancy, allelopathic effects, and zooplankton grazing among others that will be examined in the next section.

2.2. Biotic factors

Cyanobacterial species have numerous physiological adaptations that permit them to exploit nutrients and light differentially. Some species belonging to the genera *Microcystis*, *Anabaena* (renamed *Dolichospermum*), *Planktothrix*, *Aphanizomenon*, and *Cylindrospermopsis* among others possess gas vesicles that provide them buoyancy and vertical movement through the water column and can therefore effectively dominate other pelagic planktonic algae for available sunlight and nutrients [51]. This physiological capacity confers a substantial ecological advantage to these species, as they can congregate at a dense mass in the water column of stratified lakes and move up and down in the water column to maximize photosynthesis in the surface layers where there is more photosynthetically active radiation and to take up nutrients in dark deeper layers where the concentration of nutrients is higher. In addition, the ability of these genera to fix and assimilate dissolved nitrogen gas when the external concentrations of dissolved nitrate and ammonia fall to low levels is a supplementary biotic factor that offers them an ecological advantage over other phytoplanktonic species [52, 53]. Moreover, the resistance of the larger, gas-vesicle colony-forming cyanobacteria such as *Microcystis* to sinking loss or consumption by grazers can provide a significant advantage when this factor operates against

small, nonmotile unicellular phytoplankton [54–56]. In addition, some species of cyanobacteria produce allelopathic substances that prevent the growth of submerged vegetation and other algae [57, 58], as well as increased resistance to predation by zooplankton, reducing the diversity of grazing species, and therefore the formation of blooms [59]. Besides zooplankton grazing, fish activities, benthic fauna, bacteria relationship, and viral lyses are considered as supplementary biotic factors that control algal blooms [7].

3. Mathematical modeling: a necessary approach for studying cyanoHAB proliferation

3.1. General context

As we notice from previous parts, relationships between the bloom patterns and involved factors are highly complex, therefore appropriate prognostic techniques to forecast blooms and evaluate their spatio-temporal evolution are indispensable. However, due to the complicity and nonlinearity of the phenomenon, none of the research on predictive approaches seems accurate and none has performed well to date. Moreover, no existing research could help to identify the very important factor: thresholds of blooms under the environmental conditions. This part of the chapter will review some mainstreams of mathematical models used in the bloom prediction.

3.2. Deterministic versus probabilistic

With the development of super-powerful computers and computational techniques, many mathematical models for predicting the algal growth have been developed in recent years. There are two main families of mathematical models which are commonly used: deterministic and probabilistic (or stochastic). The deterministic approach can be chosen when the nature of problem and dataset have well determined, repeatable, and fixed outputs for the same inputs. This means they have a precise *cause-effect* relationship. Conversely, a stochastic approach is preferable when a system has some inherent *randomness* and we must estimate possible outcomes with their *occurrence probability* to define its behavior. Stochastic models are fundamentally built based on the randomness and uncertainty of the nature of bloom pattern, reflected through a large amount of field data. These data are indispensable for the modeler to validate and test the precision and accuracy of their models. Among the category of stochastic models, machine learning techniques provide many powerful tools to solve some relevant difficulties in predicting HAB. Machine learning techniques were developed for quantitative finance, enabling researchers to tap huge datasets. There are many publications in recent years in which diverse Supervised Machine Learning (SML) models have been applied to solve a wide range of problems, including the Artificial Neural Network (ANN) and Support Vector Machine (SVM). ANN is a SML approach widely used to predict the algal abundance [60–64] while SVM is used much less in algal research [65–67]. Some studies used genetic algorithms (GA) to create prediction model [68, 69]. The basic concept of these models lies in the combined effects of a set of explanatory variables (X_i) on one or some target variables (Y_i),

and then classification or regression decision depending on the nature of Y_i . The variables Y_i (outputs of the study) in most of the models target the pigment Chl-a, which stands for the growth of algal communities, biomass (algal abundance) quantity, and the number of algal cell counts.

Wei et al. [61] suggested a model to predict the timing and magnitude of four different types of algae: *Microcystis*, *Oscillatoria*, *Synedra*, and *Phormidium*. Algal blooms responded to the orthogonal combinations of water temperature, light penetration, dissolved oxygen, chemical oxygen demand, total nitrogen (TN), total phosphorus (TP), zooplankton, and pH value. This study used backpropagation ANN; data in this study were collected monthly during 15 years from 1982 to 1996 and these data were divided randomly into two sets: training dataset and testing dataset. This study also analyzed the sensitivity of the model in which pH played a key role in the blooming of algae and all four types of algae are more sensitive to TP than TN.

Another study conducted by Wilson and Recknagel [60] used feedforward ANN to predict the bloom of algae in Australia. They suggested a regression model between four inputs (phosphorus, nitrogen, underwater light, and water temperature) and one main output (biomass) was designed. In 30-day-ahead model, beside algae biomass, they added the second output chlorophyll-a and used time delay neuron network structure where inputs are one-time step (e.g., 30 days) in the past relative to output variables. Fernández et al. [70] suggested a model to predict the presence of cyanotoxins in fresh water in Spain. A group of six inputs consisting of both biological and chemical factors is used and the output is the presence of cyanotoxins ($\mu\text{g L}^{-1}$). The most significant aspect of this model is the product of the concentration of *M. aeruginosa* and *W. naegeliana*, followed by turbidity, total phosphorus, alkalinity, and water temperature. This model used generic algorithm (GA) and multivariate adaptive regression spline (MARS) techniques in which 10-fold cross validation was used to train and validate the model. Park et al. [62] developed an early-warning model for freshwater algal bloom based on Chl-a concentration using ANN and SVM. These authors used the weekly data in 7-year period (from 2006 to 2012) to design a 7-day interval prediction model for two lakes in Korea. Five water quality parameters including Chl-a, orthophosphate as phosphorus ($\text{PO}_4\text{-P}$), ammonium nitrogen ($\text{NH}_3\text{-N}$), nitrate nitrogen ($\text{NO}_3\text{-N}$), water temperature, and two meteorological data (solar radiation and wind speed) are inserted as inputs and output for ANN and SVM models.

Recently, Nelson et al. [71] used the Random Forest algorithm to characterize and quantify relationships between 10 different conditions and five dominant cyanobacteria genera. All explanatory variables were lagged by 1-month step to reflect the division rates of cyanobacteria in natural environments. Outputs are the biomass values of five different types of cyanobacteria genera.

As approaches using the probabilistic models are limited due to their complex concepts and high randomness levels, especially due to the needs of a large amount of data to validate them, which use various factors that influence cyanobacterial growth, the deterministic strategies will allow the evaluation of the risks associated with cyanobacteria in the context of “less data needed” and moreover, many physical parameters could be incorporated in coupling with biochemical factors. Various deterministic approaches [72–78] have been used in the

understanding of the distribution of cyanobacteria. The Lagrangian deterministic model follows the cyanobacterial colony in the water column so that a mathematical model can be created to describe bloom density. The Kromkamp and Walsby [72] model is only used to estimate settling velocities and the Visser et al. [76] model is an improved model, which incorporates the irradiance-response curve of density change and proposed an equation that describes the rate of density change in the dark. The Lagrangian approach is used for studying movement of cells in a laboratory setting, but an Eulerian approach enables exploration of full-scale spatial distribution of cells at specific times. Bruggeman and Bolding [79] built a framework called the Fortran-based framework for aquatic biogeochemical models where the biochemical model was connected to a physical model. Then a self-contained complex biological model was combined with a hydrodynamic model by the Fortran-based framework for aquatic biogeochemical model. This model was used to calibrate physiological parameters for the phytoplankton. Recently, the work of Ndong et al. [80] has shown a sophisticated 2D Eulerian frame model to evaluate the phototactic behavior effect of cyanobacteria, as well as the effects of light and wind on the distribution of cyanobacteria and estimate coupled effects of biological and physical factors on cyanobacteria.

The new tendency of research based on the deterministic approach is using remote sensing data or satellite imagery in the detection of the spatiotemporal patterns of blooms and explains how they change under the environmental conditions. The issue with this imagery is that the movement patterns of cells in the water column may be missed. The response to light intensity, nutrient levels, and temperature also needs to be considered, which means that numerical data along with imagery are required to complete the data. Agent-based models have been used to observe the 2D and 3D transport trajectories of cyanobacteria. These models are coupled with an Eulerian model, which allows the cyanobacteria to drift in the model [81–83].

3.3. Future perspectives

The overall and common goal of all models was to attempt to explain the risks of algal/cyanobacterial blooms and to study their evolution under environmental conditions leading to the improvement or decision process used to monitor cyanobacteria. However, as previously mentioned, almost all existing models have focused on the target variables such as Chl-a concentration development, cell count numbers of taxa or genera, biomass, etc.; from them, authors could conclude about the bloom situation. There are therefore two main directions of modeling among many others that should be developed: (1) determination of biophysical threshold for blooms and (2) quantifying and modeling the toxin concentration released by toxic species.

Remote sensing data combined with machine learning algorithm are also an encouraging perspective. But one of the potential pitfalls for machine learning strategies is the extremely low signal-to-noise ratio. Machine learning algorithms will always identify a pattern, even if there is none. In other words, the algorithms can view flukes as patterns and hence are likely to identify false strategies. Every model regardless of what category it belongs to can have its weak and strong points and need a serious validation step to be universally applicable, useful, and accurate.

4. Dominant taxa found in cyanoHABs in freshwater

Although cyanobacterial blooms are a worldwide phenomenon, there are differences in typical genera found in temperate and tropical regions (Table 1). *Microcystis* was the most frequently occurring bloom genus throughout the world, while *Cylindrospermopsis* and *Dolichospermum* (Syn. *Anabaena*) blooms occurred in various tropical areas such as Australia, America, and Africa.

Region	Dominant species	References
Africa	<i>Microcystis flos-aquae</i> , <i>M. wesenbergii</i> , <i>Oscillatoria</i> sp., <i>Dolichospermum</i> sp., <i>Lingbya</i> sp., <i>Anabaenopsis</i> sp.	[3, 48, 84, 85]
Western Asia	<i>Planktothrix rubescens</i> , <i>M. aeruginosa</i> , <i>Nodularia spumigena</i> , <i>Aphanizomenon ovalisporum</i> , <i>P. agardhii</i> , <i>Synechocystis</i> sp., <i>Dolichospermum</i> sp.	[84, 86]
Southern Asia	<i>Dolichospermum</i> sp., <i>Aphanizomenon</i> sp., <i>Microcystis</i> sp., <i>Cylindrospermopsis</i> sp., <i>Planktothrix</i> sp.	[84, 86]
Eastern Asia	<i>Dolichospermum</i> sp., <i>Microcystis</i> sp., <i>Aphanizomenon</i> sp., <i>Merismopedia</i> sp., <i>Cylindrospermopsis</i> sp., <i>Nostoc</i> sp., <i>Planktothrix</i> sp.	[7, 84, 85]
Oceania	<i>D. planctonicum</i> , <i>D. circinale</i> , <i>Aphanizomenon tenuicaulis</i> , <i>C. raciborskii</i> , <i>A. ovalisporum</i> , <i>A. issatschenkoi</i> , <i>P. rubescens</i> , <i>Kamptonema formosum</i> , <i>M. aeruginosa</i> , <i>M. panniformis</i>	[48, 84–86]
South and Central America	<i>M. aeruginosa</i> , <i>Cylindrospermopsis</i> sp., <i>Dolichospermum</i> sp., <i>Nodularia</i> sp., <i>Lingbya</i> sp.	[7, 48, 84, 85]
North America	<i>M. aeruginosa</i> , <i>M. viridis</i> , <i>M. wesenbergii</i> , <i>Aphanizomenon schindleri</i> , <i>D. flos-aquae</i> , <i>D. planctonicum</i> , <i>D. circinale</i> , <i>D. lemmermani</i> , <i>D. smithii</i> , <i>D. viquiera</i> , <i>C. raciborskii</i> , <i>P. rubescens</i> , <i>Lyngbya majuscula</i> , <i>L. wollei</i> , <i>Phormidium</i> sp., <i>Woronichinia naegeliana</i>	[7, 87–89]
Europe	<i>Microcystis</i> sp., <i>Dolichospermum</i> sp., <i>Aphanizomenon</i> sp., <i>Planktothrix</i> sp., <i>Nodularia</i> sp., <i>Cylindrospermopsis</i> sp., <i>Phormidium</i> sp., <i>Anabaenopsis</i> sp., <i>Gloeotrichia</i> sp.	[7, 84, 86, 90]

Table 1. Dominant cyanobacterial taxa recorded worldwide.

5. Negative outcomes from cyanoHABs

5.1. Cyanobacterial toxins and their environmental concentrations

Cyanotoxins are classified according to their mode of action into three families: neurotoxins (nervous system), hepatotoxins (liver), and dermatotoxins (skin) [4, 17, 91]. Blooms formed by cyanobacteria producing hepatotoxins (microcystins and cylindrospermopsin) are more widespread than neurotoxic blooms [4, 92–95] and therefore, they are considered priority for biomonitoring, especially in drinking and recreational waters.

Cyanotoxins are intracellular toxins that are released into water only during cellular senescence or death and lysis or through water treatment processes such as application of algaecide [96, 97]. Therefore, total concentrations (intracellular plus extracellular) of microcystins, the

most common cyanotoxins, vary from trace to several milligrams per liter [91, 98]. For example, very high concentrations have been reported up to 8428 $\mu\text{g L}^{-1}$ in Southwest wetlands, Australia [99], 19,500 $\mu\text{g L}^{-1}$ in Lake Suwa, Japan [41], 23,718 $\mu\text{g L}^{-1}$ in Dam Nhanganzwane, South Africa [100], 29,200 $\mu\text{g L}^{-1}$ in Lake Oubeira, Algeria [101], or 36,500 $\mu\text{g L}^{-1}$ in Lake Horowhenua, New Zealand [102]. Messineo et al. [103] reported that in several Italian lakes, concentrations of total cylindrospermopsin varied from nondetectable values up to 126 $\mu\text{g L}^{-1}$. However, neurotoxins are less common in the freshwater ecosystems. For example, Rapala et al. [104] reported up to 1070 $\mu\text{g L}^{-1}$ of saxitoxin in Finnish lakes. Anatoxin-a was detected in two shallow reservoirs (Konstantynów and Kraśnik) in Poland at concentrations ranging from 0.03 to 43.6 $\mu\text{g L}^{-1}$ during a bloom of *D. flos-aquae* [105]. Recently, Roy-Lachapelle et al. [106] reported that the concentrations of the BMAA in 12 different lake waters in Canada ranged between 0.009 and 0.3 $\mu\text{g L}^{-1}$.

5.2. Ecotoxicological effects of cyanotoxins

Cyanotoxins such as hepatotoxins and neurotoxins target in humans and animals the liver and nervous system, respectively, but they often have important side effects too. When present in freshwater ecosystems, they may also affect organisms at different trophic levels, especially those having identical or similar target organs, tissues, or cells.

5.2.1. Acute effects

The occurrence of cyanoHABs in aquatic ecosystems is often associated with fish mortality (**Figure 1**). In addition, terrestrial organisms such as livestock, dogs, and birds that are associated with these freshwater ecosystems in which cyanoHABs occur may also be at risk of cyanotoxins exposure from preying on toxic aquatic prey and/or drinking contaminated water. For example, Georges Francis was the first in 1878 to implicate cyanobacteria in the poisoning of farm animals, in Alexandrina Lake, Milang, Southern Australia [107]. Since then, a significant number of cases of animal poisonings attributable to cyanotoxins have been documented worldwide [108–111]. Fish and invertebrates which are exposed over their entire life cycle to cyanotoxins are the most aquatic organisms affected, followed by birds, livestock and poultry, and dogs [111]. Acute ecotoxicity data of cyanotoxins were compiled by several studies [112–114]. The most documented cyanotoxin effects are those on microcystins due to their occurrence at high concentrations up to 28 mg L^{-1} and the dominance of cyanobacterial species producing them [91]. In addition, depending on their mechanism of action as potent and specific inhibitors of protein phosphatases and inducer of oxidative stress, microcystins can affect a range of invertebrate and vertebrate organisms [109, 114, 115]. Therefore, they cause changes in the trophic levels and adverse impacts on the functioning of freshwater ecosystems. This begins with the zooplankton community, which has its composition changed, especially by the mortality of certain species resulting therefore in the reduction of their diversity [59, 109, 116, 117]. For example, the copepod *Diaptomus birgei* was the most sensitive to microcystins with a lethal concentration (LC_{50}) at 48 h of 0.45 to 1.0 $\mu\text{g mL}^{-1}$ followed by the cladoceran *Daphnia pulex*, *D. hyaline*, and *D. pulicaria* with LC_{50} at 48 h of 9.6, 11.6, and 21.4 $\mu\text{g L}^{-1}$, respectively [109].

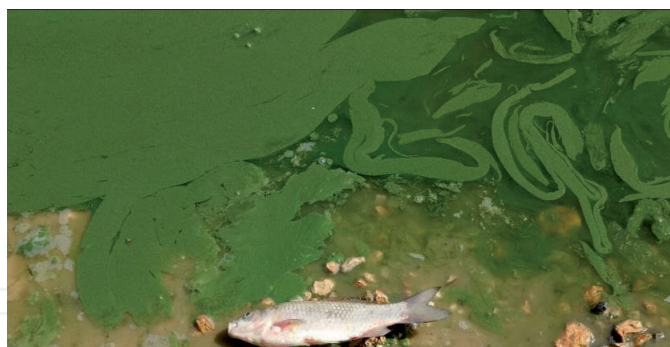


Figure 1. *Microcystis* sp. bloom associated with fish mortality (photo: N.Y. Benayache).

However, mollusks and decapods appeared to be relatively tolerant to microcystins [109, 111]. For example, the LC_{50} at 96 h for microcystin-LR equivalent in the decapod *Kalliapseudes schubartii* [118] and the crayfish *Procambarus clarkia* [119] is 1.58 and 0.567 mg L⁻¹, respectively. Similarly, bivalves bioaccumulate high concentrations of microcystins without symptoms of acute toxicity [120].

Mass mortalities of fish have also been attributed to microcystins [14, 111, 121]. However, some studies suggested that most of fish mortalities can also be attributed to hypoxic conditions resulting from bloom respiration and senescence and not only to cyanotoxins [122, 123]. Like bivalves, fish appear to be less sensitive to toxin's short-term exposure than zooplankton. For example, experimental investigations on the rainbow trout have been shown that this fish species appeared to be relatively tolerant to high concentrations of microcystin-LR and death was recorded only at 1000 µg kg⁻¹ bw [124]. Several studies reported that the dose inducing the mortality of the half of the test population (LD_{50}) of microcystin-LR in fish ranges from 20 to 1500 µg kg⁻¹ body weight [125].

For the other classes of alkaloid cyanotoxins such as cylindrospermopsin and neurotoxins (anatoxins and saxitoxins), there are few or no studies that have examined their acute toxicity on aquatic organisms. For example, Ferrão-Filho et al. [126] reported that the exposure of three cladoceran species (*Daphnia gessneri*, *D. pulex*, and *Moina micrura*) to a saxitoxin-producer strain (T3) of *Cylindrospermopsis raciborskii* at cell densities of 10³ and 10⁴ cells/mL for 24 h resulted in a complete paralysis of *D. pulex*; however, *D. gessneri* was not sensitive and *M. micrura* was intermediate in sensitivity. Osswald et al. [127] demonstrated that when common carp *Cyprinus carpio* larvae were exposed to a lyophilized suspension (10⁷ cells/mL) of a strain of *Anabaena* sp. producing anatoxin-a, all fish died between 24 and 29 h.

5.2.2. Subchronic and chronic effects

Aquatic organisms are continuously exposed over long periods of time or even their entire life cycle to cyanotoxins; therefore, evaluation of chronic effects of these toxins is important for an accurate environmental risk assessment. Several studies have shown that aquatic organisms that are exposed in the long term to cyanotoxins through the diet may die or display impaired feeding, immunosuppression, increased susceptibility to disease, avoidance behavior, physiological dysfunction, abnormal development, and reduced growth and reproduction

[109, 125]. For example, chronic exposure of parent *Daphnia magna* to either microcystin-LR at 5 or 50 $\mu\text{g L}^{-1}$, or to cyanobacterial crude extract containing the same amount of total microcystins, resulted in the decrease of the survival of offspring or cessation of eggs and reduced number of neonates and deformations of neonates such as incomplete development of the antennae [128]. Moreover, several studies have shown that when embryos and larvae of different species of fish including chub (*Leuciscus cephalus*), common carp (*Cyprinus carpio*), loach (*Misgurnus smizolepis*), rainbow trout (*Oncorhynchus mykiss*) and zebrafish (*Danio rerio*) were immersed in solutions of 0.5–50 μg microcystins/L for up to 30 days, it resulted in interferences with hatching, developmental defects, liver damage, and/or increased mortality [129–132]. In another chronic study, Ernst et al. [133] by investigating the effect of a high microcystin concentration on eggs and larvae of whitefish (*Coregonus lavaretus*) exposed to blooms of *Planktothrix* sp. during winter 1998 and 2000 in a Lake Ammersee (Germany) hatchery reported malformations of eggs and disturbances of reproduction success, suggesting that the disappearance of some coregonid age groups observed in this lake may be a result of these development effects of microcystins. In a laboratory study, oral subchronic exposure of the common carp (mean body weight of 322 g) to *Microcystis* by feeding with bloom scum at a dose of 50 μg microcystins/kg body weight for 28 days resulted in inhibition of growth, severe damage in hepatocytes, and significant increase of some plasmatic enzyme activities such as alanine aminotransferase and aspartate aminotransferase [134].

5.2.3. Ecotoxicity of cyanotoxin mixtures

Aquatic organisms are most likely subject to acute, subchronic, and chronic impacts resulting from exposure to a mixture class of cyanotoxins and not to individual toxins. Cyanobacterial species producing different toxins such as hepatotoxins, neurotoxins, and dermatotoxins have been shown to coexist in blooms [91], therefore making the exposure to toxin mixtures a plausible scenario. To investigate this scenario with considering the possible synergistic toxicity of complex matrices, Esterhuizen-Londt et al. [135] tested the effects of two artificial toxin mixtures containing cyanobacterial hepatotoxins (microcystin-LR, -YR, and -RR), cyanobacterial hepatotoxins (microcystin-LR and cylindrospermopsin), and the neurotoxin β -N-methylamino-L-alanine hydrochloride, respectively, versus a crude cyanobacterial bloom extract (dominated by *Microcystis aeruginosa* with minor proportions of *Anabaena* sp. and *Oscillatoria* sp.) on the oxidative status of *Daphnia pulex*. The results showed that the cyanobacterial extract elicited higher oxidative stress response on *D. pulex* compared to exposure with the two artificial toxin mixtures. According to these studies, authors suggested that other unidentified compounds present in the cyanobacterial extract with synergistic effects may enhance the toxic effects. In fact, previous studies found stronger developmental effects of cyanobacterial extracts containing microcystins [136, 137] on the African clawed frog *Xenopus laevis* embryos and anatoxin-a [138] on common carp *Cyprinus carpio* larvae than their respective purified toxins.

In addition, in natural environments, cyanotoxins could interact with other anthropogenic micropollutants present in aquatic ecosystems and therefore, could attenuate or potentiate their adverse effects on aquatic organisms. For example, combined influence of microcystin-LR and a pesticide, carbaryl, was investigated on *Daphnia pulex* [139]. The results showed

that the interaction between carbaryl and microcystins was highly significant and the two chemicals in a combinatorial exposure induced synergistic effects with frequent premature offspring delivery with body deformations including dented carapax or undeveloped heart. Furthermore, Cazenave et al. [140] observed less pronounced teratological effects within 24 h as well as nonsignificant increase in the activity of glutathione S-transferase (GST) in embryos of zebrafish (*Danio rerio*) exposed to either microcystin-LF or microcystin-RR in combination with natural organic matters compared to embryos exposed to pure toxins.

5.3. Bioaccumulation of cyanotoxins in food web and impacts on animal and human health

Zooplankton have been clearly identified as the best bioaccumulator of cyanotoxins and may transfer them to higher trophic levels in the aquatic food web [141–144]. Mollusks have also been shown to accumulate high concentrations of cyanotoxins with hepatopancreas being the organ presenting the highest concentrations followed by the intestines [115, 145]. As with invertebrates, fish can also accumulate high concentrations of microcystins but on average 3.5 times lower in planktivorous fish than in zooplankton [115]. For example, the highest concentrations of microcystins were found in the liver of the planktivorous fish *Osmerus eperlanus* reaching up to 874 μg microcystins/g dry weight [146]. However, in another planktivorous fish such as the silver carp *Hypophthalmichthys molitrix*, the highest concentrations of microcystins were found in the intestines reaching up to 137 $\mu\text{g g}^{-1}$ DW [147]. Carnivorous fish, meanwhile, accumulate less microcystins with the maximum concentration up to 51 $\mu\text{g g}^{-1}$ DW measured, for example, in the liver of perch *Perca fluviatilis* [146]. Overall, carnivorous fish, as superior predators, had lower mean microcystin content than planktivorous and omnivorous fish, suggesting transfer and bioaccumulation of microcystins, however without biomagnification in the food chain. In contrast, fish may act as an efficient vector of cyanotoxins to upper trophic levels such as birds and humans. In fact, numerous bird deaths have been reported in which most deaths are associated with the consumption of toxic prey, for example, fish or mollusks that have consumed or otherwise bioaccumulated cyanobacterial toxins [109, 110, 148, 149]. For humans, Chen et al. [150] confirmed for the first time the presence of microcystins in serum samples (average 0.39 ng/ml) of fishermen at Lake Chaohu, China. According this study, daily intake by the fishermen was estimated to be in the range of 2.2–3.9 μg MC-LR equivalent, whereas the provisional World Health Organization tolerable daily intake (TDI) for daily lifetime exposure is 0.04 $\mu\text{g kg}^{-1}$ or 2–3 μg per person. However, as has been described previously, the different species of fish accumulate microcystins mainly in the intestine and liver/hepatopancreas; this poses no risk to human health if these organs are taken from animals before consumption.

6. Conclusions

The chapter has sketched a general overview on cyanoHABs which recently become a real worrisome issue at the global scale due to their effects on water resources and animal and human health. They will cause ongoing issues as they will certainly reoccur over and over the coming years, especially under the promoting factors of climate changes and global warming effects, as much as the abuse of all watersheds due to anthropogenic actions.

Different research studies around the world have highlighted the complex relationships between cyanobacterial growth and environmental factors. The cyanoHAB dominance can result from a variety of interactions among biotic and abiotic components. The presence of toxic cyanobacteria can influence the human society at all scales, such as direct effects on drinking and recreational water resources, as well as the transfer of their toxins to higher trophic levels, resulting in fish kills and threats to all animal and human health.

Keeping our water resources clean, healthy, and safe for current and next generations becomes, therefore, a big challenge for our planet. The task of monitoring and managing cyanobacterial blooms and their negative outcomes including toxins released is a pressing concern for all. The chapter hence will serve to increase awareness of common challenges and existing capacities as well as lay the foundation for ongoing discussion and research on various subjects related to CyanoHABs that will be needed for effective management for the years to come.

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Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this chapter and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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