ANNUAL REVIEWS

Annual Review of Environment and Resources

Harmful Cyanobacterial Blooms: Biological Traits, Mechanisms, Risks, and Control Strategies

Lirong Song,[1,2,*] Yunlu Jia,[1,*] Boqiang Qin,[3]
Renhui Li,[4] Wayne W. Carmichael,[5] Nanqin Gan,[1]
Hai Xu,[3] Kun Shan,[6] and Assaf Sukenik[7,8]

[1] State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China; email: lrsong@ihb.ac.cn

[2] Freshwater Algae Culture Collection, National Aquatic Biological Resource Center, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, China

[3] State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

[4] Zhejiang Provincial Key Laboratory for Subtropical Water Environment and Marine Biological Resources Protection, Wenzhou University, Wenzhou, China

[5] Department of Biological Sciences, Wright State University, Dayton, Ohio, USA

[6] Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences, Chongqing, China

[7] Kinneret Limnological Laboratory, Israel Oceanographic and Limnological Research, Migdal, Israel

[8] Morris Kahn Marine Research Station, Leon H. Charney School of Marine Sciences, University of Haifa, Haifa, Israel

Annu. Rev. Environ. Resour. 2023. 48:123–47

First published as a Review in Advance on September 8, 2023

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-112320-081653

*These authors contributed equally to this article.

Keywords

harmful cyanobacterial blooms, climate change, eutrophication, cyanotoxins, freshwaters

Abstract

Harmful cyanobacterial blooms (CyanoHABs) impact lakes, estuaries, and freshwater reservoirs worldwide. The duration, severity, and spread of CyanoHABs have markedly increased over the past decades and will likely continue to increase. This article addresses the universal phenomena of cyanobacterial blooms occurring in many freshwater ecosystems worldwide. Based on analysis of ecophysiological traits of bloom-forming cyanobacteria and their interactions with environmental processes, we summarize and decipher the driving forces leading to the initiation, outbreak, and persistence of the blooms. Due to the coupling effects of eutrophication, rising CO_2 levels and global warming, a multidisciplinary joint research approach is critical for better understanding the CyanoHAB phenomenon and its prediction, remediation, and prevention. There is an urgent need to evaluate and guide proper use of bloom control techniques at large scales, using science-based and environmentally friendly approaches.

Contents

1. INTRODUCTION

Cyanobacteria bloom in freshwater ecosystems is characterized by a rapid proliferation of biomass often to nuisance or harmful levels frequently identified as harmful cyanobacterial blooms (CyanoHABs). Blooms impact lakes, estuaries, and freshwater reservoirs worldwide, posing severe threats to aquatic and public health. The duration, severity, and distribution of CyanoHABs have markedly increased over the past decades (1, 2) and will continue to increase due to the combined effects of eutrophication, rising CO_2 levels, and global warming (3). Ho et al. (4) investigated the summertime bloom intensity for 71 large lakes globally over three decades and revealed that most lakes (68%) suffered increasingly frequent bloom events. On a continental scale, the intensification of cyanobacterial blooms—both spatial and temporal—was observed in Asia, followed by South America, Africa, and Europe (5) but mostly in the developing countries of Asia and Africa (1). Over the past two decades, more than 60% of the lakes in China have been infected with CyanoHABs, in which the toxin producer, *Microcystis aeruginosa*, is one of the dominant species (6). For instance, in the early summer of 2007, a massive accumulation of *Microcystis* biomass in Lake Taihu overwhelmed the drinking water plants and caused a water crisis in the city of Wuxi, which affected more than 4 million people (7). In the United States, a toxic bloom event occurred in Lake Erie that elevated levels of the peptide liver toxins called microcystins (MCs), resulting in a shutdown of water supply to more than 500,000 inhabitants of Toledo, Ohio (8). The recent

Harmful cyanobacterial bloom (CyanoHAB): a natural phenomenon in which massive proliferation of cyanobacteria in water forms surface scum and may lead to abnormal water color

Eutrophication: a process of nutrient enrichment leading to massive proliferation of algae or macrophyta in aquatic ecosystems mass mortality event of approximately 400 African elephants in Botswana has been attributed to biotoxins produced by cyanobacteria, an alarming early warning signal of future environmental catastrophes in Southern Africa intensified by hot and dry climatic extremes (9). A recent study by Wilkinson et al. (10), however, reported that bloom intensification has not been widespread for hundreds of lakes in the United States.

It is generally recognized that an outbreak of cyanobacterial bloom depends on both the external environmental factors and the biological traits of the bloom-forming species. The intensity and persistence of the bloom is intricately governed by the interaction between nonbiological factors and biological traits. Over the past decades, CyanoHABs have been intensively studied to yield advanced understanding of the ecophysiology of blooms and their environmental impact (11). Consequently, various approaches to control and mitigate CyanoHABs were proposed and implemented to fulfill the urgent needs of water authorities for early detection and mitigation of blooms (12).

However, the pace of translation from scientific discovery to the rational application of prediction, remediation, and prevention seems to be lagging behind the demands of both the public and policymakers. Several techniques or measures that are being widely used for bloom control have been emerging without reasonable consideration of the trade-off between cost, ecosystem safety, and health risks. It is therefore necessary and urgent for the scientific community and decision-makers to understand the processes and dynamic mechanisms from different perspectives to help establish environmentally friendly and ecosystem safety strategies for combating CyanoHABs.

2. BLOOM-FORMING CYANOBACTERIA: DIVERSITY OF SPECIES AND BIOLOGICAL TRAITS

Currently, the phylum cyanobacteria (Cyanoprokaryota or blue-green algae) presents 5,323 species, 427 genera, 65 families, and 13 orders (13, 14). They are important primary producers contributing to the plankton, benthos, epiphyton, and epilithon in various aquatic and terrestrial ecosystems (12). Bloom-forming taxa belong to all major morphological groups of cyanobacteria and include planktonic colonial forms (e.g., *Microcystis*, *Woronochinia*), picoplankton (e.g., *Synechococcus*), and N_2-fixing and nonfixing planktonic filaments (e.g., *Dolichospermum*, *Aphanizomenon*, *Raphidiopsis*, *Nodularia*, *Planktothrix*, and *Pseudanabaena*) (6, 15) (**Table 1**). The bloom-forming genera *Microcystis*, *Dolichospermum*, *Aphanizomenon*, and *Raphidiopsis* often dominate, spanning from spring to fall (12). Traditional taxonomy based on morphology does not reflect the true evolutionary relations among cyanobacteria taxa. Molecular studies have been responsible for the significant increase in the number of taxa described since 2010 (16). Genome-based classification would upend the previous assumption of niche specialization and range restriction. For example, the *Microcystis* pangenome revealed that *Microcystis* contains 15 putative genospecies and thereby may help in resolving some of the complexities and controversies that have long characterized eco-evolutionary research and management of this important CyanoHABs taxon (17). Nevertheless, morphological identification of taxa is still performed first in routine monitoring in many places worldwide (18), and morphology supports many studies regarding cyanobacteria distribution, ecology, and physiology (16).

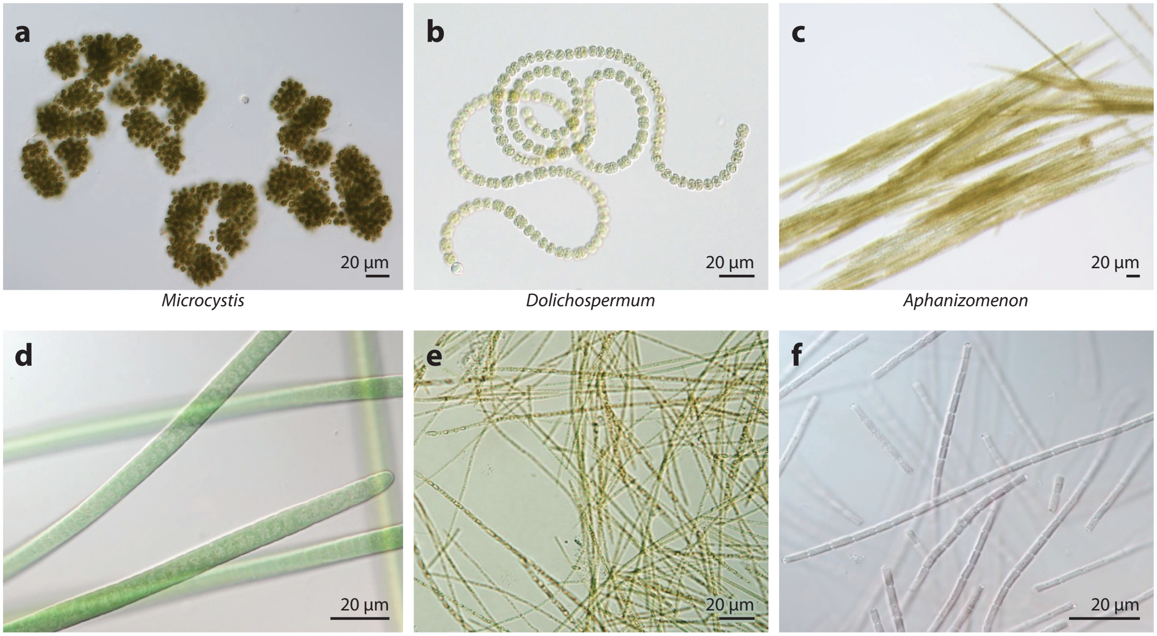
The major bloom-forming cyanobacteria genera are shown in **Figure 1** and **Table 1**. Several studies have illustrated the biological features of bloom-forming cyanobacteria ranging from molecular to community levels, rendering them capable of maximizing resource use to adapt to ever-changing environments while outcompeting other algae to achieve dominance, proliferation, and persistence.

At the molecular level, *Microcystis* genomes are extensively open and plastic (19–23), a strategy shared by multiple bacteria genera including ecologically important marine *Prochlorococcus* (24) and

Table 1 Major bloom-forming cyanobacteria genera listed by taxa and secondary metabolites

Taxon	Revised nomenclature	Secondary metabolites	Major bloom-forming species
Microcystis	Not applicable (NA)	Microcystin, β-cyclocitral, dimethyl disulfide, dimethyl trisulfide, isopropylthiol, β-methylamino-L-alanine (BMAA)	*M. aeruginosa*, *M. flos-aquae*, *M. ichthyoblabe*, *M. novacekii*, *M. panniformis*, *M. smithii*, *M. viridis*, *M. wesenbergii*
Anabaena	*Dolichospermum*	Geosmin, saxitoxin, anatoxin-a	*D. affine*, *D. circinale*, *D. compactum*, *D. flos-aquae*, *D. planctonicum*, *D. spiroides*
Aphanizomenon	*Aphanizomenon*	Geosmin	*A. flos-aquae*, *A. gracile*
	Cuspidothrix		*C. issatschenkoi*
Planktothrix	*Planktothrix*	Geosmin, saxitoxin	*P. agardhii*, *P. mougeotii*
	Planktothricoides	2-Methylisoborneol	*P. raciborskii*
Cylindrospermopsis	*Raphidiopsis*	Cylindrospermopsin, saxitoxin	*R. raciborskii*
Pseudanabaena	NA	2-Methylisoborneol	*P. limnetica*, *P. galeata*, *P. cinerea*
Nodularia	NA	Nodularin	*N. spumigena*
Anabaenopsis	NA	Microcystin	*A. arnoldi*, *A. millerii*
Radiocystis	NA	NA	*R. fernandoi*

bloom-forming *Raphidiopsis raciborskii* (25). A recent comparative genomic study reveals that the nonredundant pan gene families of 23 *Microcystis* strains reached 22,009, which has exceeded the human genome size (23). All 23 genomes shared only 1,660 core gene families, less than half the gene number in individual isolates (23). Functional characterization of the tremulous pan gene pool indicates that those pan genes (the so-called genomic backbone) are abundant in energy



Microcystis *Dolichospermum* *Aphanizomenon*

Planktothricoides *Raphidiopsis* *Pseudanabaena*

Figure 1

Major genera of bloom-forming cyanobacteria, including *Microcystis* (*a*), *Dolichospermum* (*b*), *Aphanizomenon* (*c*), *Planktothricoides* (*d*), *Raphidiopsis* (*e*), and *Pseudanabaena* (*f*). Scale bar: 20 µm.

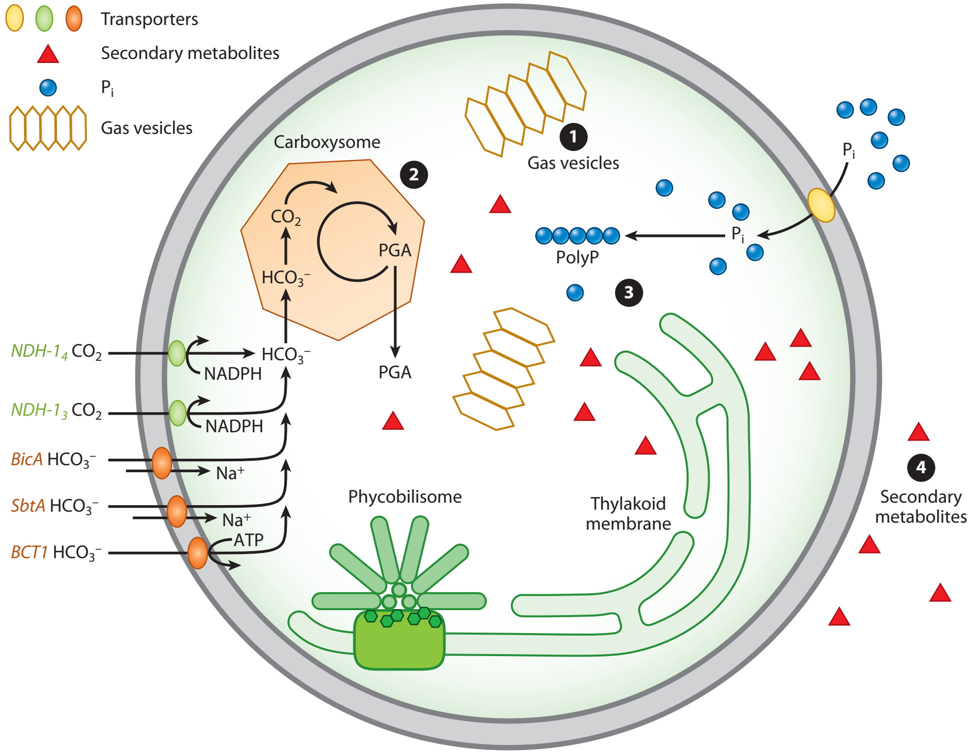


Figure 2

Schematic overview of the main biological traits of a typical bloom-forming cyanobacterial cell. ❶ Large amounts of gas vesicles are responsible for buoyancy regulation in the water column. ❷ The apparatus carboxysome and C_i uptake systems are responsible for enriching sufficient CO_2 and adapting to CO_2 changes in the environment. ❸ Surpluses of P will be stored as polyphosphate (polyP) to provide intracellular P sources in case of P deficiency. ❹ Secondary metabolites (e.g., microcystins) may play a role in prey defense and stress resistance. Abbreviations: ATP, adenosine triphosphate; C_i, inorganic carbon; CO_2, carbon dioxide; NADP, nicotinamide adenine dinucleotide phosphate; P, phosphorus; PGA, 3-phosphoglycerate; P_i, inorganic phosphorus; PolyP, polyphosphate.

conversion, metabolism, translation, and biogenesis (23), and flexible genes (so-called accessory and unique genes) are involved in mainly the defense system (20, 26), secondary metabolism, replication, recombination, repair, signal transduction, and transcription (23).

At the morphology level, bloom-forming cyanobacteria are unicellular, colonial, or filamentous. They have several traits that enable them to thrive in a wide range of physicochemical conditions. These biological traits are depicted in **Figure 2** and summarized below.

2.1. Gas Vesicles and Buoyancy Regulation

Gas vesicles are proteinaceous structures that facilitate buoyancy for cyanobacteria, allowing them to float or sink to take advantage of the surrounding light and nutrient conditions (27, 28). The cells of most bloom-forming species contain up to several thousand gas vesicles, which are hollow and water impermeable cylinders made up of protein subunits. They are filled with gases that diffuse from the surrounding medium (29). Some species may migrate up and down the water column on a diurnal cycle by varying the amount of dense carbohydrate inclusions that act as ballast in their cells; therefore, buoyancy regulation is an interplay of vesicle synthesis, protein and carbohydrate production, colony size, and light intensity (30). Gao et al. (31) noted an increase in pH upregulated gas vesicle protein genes at both mRNA and protein levels and, consequently, enhanced buoyancy of the cells. According to the buoyancy response to light, *Microcystis* strains may roughly be classified into two eco-types: strains that may not float at typical low light but become buoyant and float at high light intensities and strains that sink at high light intensity (30).

CO_2-concentrating mechanism (CCM): the efficient active transportation and concentration of CO_2 by some algae when CO_2 availability is limited

2.2. Carbon Utility

The CO_2-concentrating mechanism (CCM) is an important feature in cyanobacteria (32–34). The CCM of cyanobacteria comprises two components: (*a*) RubisCO enclosure in carboxysomes and CO_2 enrichment via carbonic anhydrase and (*b*) bicarbonate enrichment via bicarbonate uptake transporters such as BicA, SbtA, and CmpABCD. CCM enables the efficient active transportation and concentration of C_i around RubisCO within the carboxysome of cyanobacteria when C_i availability is limited or deprived (normally due to the alkaline environment imposed by active photosynthesis and growth of the cyanobacteria). Five distinct transport systems for active C_i uptake are known, including two types of Na^+-dependent HCO_3^- transporters (BicA and SbtA), one traffic ATPase (BCT1) for HCO_3^- uptake, and two CO_2 uptake systems based on modified nicotinamide adenine dinucleotide phosphate hydrogen (NADPH) dehydrogenase complexes (NDH-I-3 and NDH-I-4) (35).

Huisman's lab (36) has provided evidence that differences in the C_i adaptation of individual *Microcystis* genotypes primarily relate to the genotypic and phenotypic plasticity of components of the CCM. Although this mechanism and the genetic repertoire are highly conserved among other cyanobacteria, variations in the use and effectiveness of CCM in *Microcystis* have been identified at the species and strain level (37). Therefore, the difference in the C_i uptake system may be responsible for the variation of strains' success during carbon replete and deplete conditions. Specifically, *bicA* and *sbtA*, located on the same operon, provide insight into a *Microcystis* strain's ability to uptake C_i (36, 38). The C_i generalist, which has both *bicA* and *sbtA*, can take advantage of C_i across a wide range of concentrations. Other genotypes individually lack either low- or high-affinity bicarbonate uptake transporters BicA and SbtA and show corresponding differences in their adaptation to low or high CO_2 levels (36).

2.3. Phosphorus Acclimation

Phosphorus (P) is essential to the synthesis of DNA, RNA, adenosine triphosphate (ATP), and phospholipid and plays a vital role in cellular signal transduction. However, P is the main limiting factor in most aquatic ecosystems and has often been the key factor driving the succession of phytoplankton communities (39, 40). P limitation affects growth rate, but bloom-forming cyanobacteria could survive P limitation for quite a long time. *Microcystis* maintained growth and photosynthetic activity even after 10 days of P limitation (41). Multiple mechanisms were proposed to interpret the long-time survival of *Microcystis* under P limitation. Upon P replete conditions, *Microcystis* cells have a high uptake velocity for orthophosphate (42, 43). Surpluses of P will be stored as polyphosphate (polyP) packed in granules or bodies when P-limited cells are transferred to P-repleted condition. PolyP composed of a few to many hundreds of phosphate residues are reservoirs for inorganic orthophosphate and an energy source under P limitation. *Microcystis* cells showed much higher capacity to synthesize polyP than *Dolichospermum* and other phytoplankton (44). In addition, the extracellular polymeric substances (EPS) of colonial *Microcystis* cells were suggested as another P pool, as colonial *Microcystis* cells with much higher EPS showed stronger resistance to P limitation than unicellular cells (43). Under P-limiting conditions, metabolic activities including transcription and translation were downregulated to reduce the requirement of P, concomitant with upregulation of high affinity phosphate-specific transporter complex (PstSABC) transporters to acquire low levels of P (45, 46). Expressions of *pstS* and *sphX* genes were strongly upregulated (50- to 400-fold) under low inorganic P conditions, as tested with more than ten strains of *Microcystis* from different countries (47). The increased expression of PstSABC transporters has also been reported in other freshwater bloom-forming species such as *Raphidiopsis* and *Dolichospermum* (48, 49). Still, there were other diversified mechanisms coping with P limitation among different bloom-forming cyanobacteria. Dissolved organic phosphates (DOP) were alternative P resources for cyanobacteria. However, field *Microcystis* cells and laboratory P-limited cells seldom secret alkaline phosphatases (ALP), which are supposed to degrade DOP and catalyze the release of orthophosphate. On the contrary, large amounts of ALP surrounded filamentous cyanobacteria *Dolichospermum* in field studies (44). *Aphanizomenon ovalisporum* induced the secretion of ALP in other phytoplankton by secreting the hepatotoxin cylindrospermopsin (50). The presence of phosphonates (phosphonic acids) in aquatic ecosystems could support the growth of filamentous cyanobacteria, including bloom-forming *Raphidiopsis*, *Oscillatoria*, and *Pseudanabaena*, but not *Dolichospermum* nor *Microcystis* (51). Marine cyanobacteria have been reported to use nonphosphorus membrane lipids, such as sulfoquinovosyl diacylglycerols, to substitute for the phosphatidylglycerol under conditions of P limitation (52). However, sulfolipid synthesis is not considered a P acclimation mechanism for freshwater cyanobacteria (45).

Alkaline phosphatase (ALP): an induced enzyme that plays an important role in absorption and utilization of organophosphorus by cyanobacteria via converting organophosphorus into orthophosphate

Secondary metabolites: the intermediate substances produced by biological metabolism responsible for synthesizing nonessential substances required for life

Cyanotoxins: toxic secondary metabolites produced by cyanobacteria

2.4. Secondary Metabolites

At the community level, the prey defense function might be a biological trait contributing to the formation of cyanobacterial blooms. One of the defense mechanisms in prokaryotic cyanobacteria is associated with the production of a suite of secondary metabolites including cyanotoxins (**Table 1**). Even though the biosynthesis genes of cyanotoxins date back to the reported existence of metazoans (53), these substances may have evolved a defensive function over time (54). Among these cyanotoxins, MCs were intensively studied. Although the ecological and adaptive role of MCs is still elusive, studies have observed the effect of MCs in defense against herbivorous zooplankton (55, 56), supporting the cell proliferation of MC-producing cyanobacteria. To confirm the antigrazing function of MCs, further study should be performed to evaluate other bioactive secondary metabolites besides their impact on zooplankton. Up to now, information has been largely limited on the signaling mechanism within cyanobacterial populations and on the cascade of events triggered by cyanobacterial cells' recognition of predators.

A diverse group of bioactive secondary metabolites released by cyanobacteria have allelopathic activity, affecting the biological processes of other phytoplankton or macrophytes (57). This biological trait can also aid cyanobacterial dominance, succession, and bloom formation (58). The described allelochemicals or potential allelochemicals have been identified and included chlorinated aromatic compounds, cyclic and noncyclic peptides, polyketides, alkaloids, and fatty acids (59). A few cyanobacterial genera have been examined as allelopathic or potentially allelopathic (*Anabaena*, *Calothrix*, *Gomphosphaeria*, *Aphanizomenon*, *Hapalosiphon*, *Fischerella*, *Microcystis*, *Nodularia*, *Nostoc*, *Oscillatoria*, *Phormidium*, *Scytonema*, and *Trichormus*) (60).

The biological trait of secondary metabolism can also benefit certain cyanobacterial dominance in the environment under abiotic stress, e.g., nutrient limitation. Bar-Yosef et al. (50) found that the cyanotoxin cylindrospermopsin (CYN) produced by *A. ovalisporum* and *R. raciborskii* can influence other phytoplankton species to help ameliorate the P limitation. They observed that CYN mediates the interaction between its producers and other phytoplankton and induces nearby algal cells to secrete ALP, leading to an increase in bioavailable P concentration. As *R. raciborskii* has a higher uptake affinity of dissolved inorganic P than other algal species (61), it could outcompete other taxa and uptake more P-released consequence of ALP. A field study also revealed that the production of CYN is in line with P-deficient conditions, suggesting that CYN acts as an infochemical to trigger ALP secretion by competing phytoplankton species and that CYN-induced ALP secretion is facilitated upon P deficiency, thus supporting the dominance of its producer *R. raciborskii* (62).

Recruitment: overwintering (or dormant) algal cells activated by suitable environmental conditions for proliferating and recovering its buoyancy activity

3. MECHANISMS DRIVING THE RECRUITMENT, PROLIFERATION, AND PERSISTENCE OF BLOOMS

In general, the life cycle of a bloom can be defined from the onset of the bloom to the disappearance from the water body. An annual life cycle of the bloom can be divided into four stages/phases: recruitment, outbreak, persistence/duration, and decline.

During the recruitment stage, overwintering (or dormant) cells on the surface of the bottom sediment (or suspended in the water column) are activated and recover their activity to provide an inoculum to support cell germination and initiate bloom proliferation. The process is usually associated with an increase of buoyancy ability. There is uncertainty/debate as to whether recruitment is an active process triggered by internal changes in buoyancy or a passive process induced by resuspension. Borges et al. (63) demonstrated that allopathic interactions, ammonium, light, and temperature can individually and synergistically regulate gas vesicle synthesis and affect *Microcystis* recruitment. It was shown that photosynthetic activity, colony size, and intracellular MC content are associated with the performance of the recruitment of *Microcystis* (64). Misson & Latour (65), however, indicated that passive resuspension plays a much more critical role in the recruitment of *Microcystis* than light and temperature, as sediment mixing was shown to be the only physical factor in promoting recruitment. Controversially, a study in Lake Chaohu, China, suggested that the contribution of the recruitment of cyanobacteria from sediment could be negligible (66). To date, most research on cyanobacterial blooms in freshwater lakes has been focused on the pelagic life stage. However, the benthic life stages are important components of the life cycle of cyanobacteria and need further investigation (67) if we are to have the whole picture concerning dynamics for accurate prediction of blooms.

The proliferation of cyanobacteria is often characterized by a rapid increase in the biomass of a single species to create high density populations, leading to a visible surface bloom under favorable circumstances. Factors contributing to the formation or initiation of blooms include warm temperatures, high nutrient levels, and low water flow (68, 69). It is widely accepted that the combination of biological traits and environmental factors determines the magnitude, frequency, and duration of blooms in waters.

Temperature is strongly associated with cell growth rate and related performances that determine cell density and persistence in the water column. Many bloom-forming cyanobacteria can reach their maximal growth rates at relatively high temperatures, often over 25°C (38, 70, 71). Thomas & Litchman (71) showed that optimum growth rates of 12 strains of *Microcystis*, *Raphidiopsis*, and *Dolichopsermum* are in the range of 27–37°C. Paerl & Otten (70) compiled data from nine studies showing maximum growth rates of cyanobacteria between 25 and 35°C.

During the past two decades, lake temperatures have increased globally (72). Generally speaking, warmer temperatures might lead to a higher biomass of cyanobacteria in the water column (68, 69, 73). First, warmer temperatures lead to a prolonged open-water season duration and strengthen the water column's stratification during the growing season (74). Second, warmer temperatures could enhance the stratification of the water column and cause depletion of bottom dissolved oxygen and release of dissolved nutrients (75).

The persistence of blooms depends heavily on the supply of major nutrients. The availability of nutrients could be sustained by the changes in rainfall patterns under the changing climate. Higher rainfall could lead to more significant nutrient inputs to water bodies through surface runoff within the watershed (76, 77). In addition, heavy storms can play a vital role for destratification of the water column and may enhance flushing (78). However, heavy rainfall would decrease lake temperatures, dilute nutrient concentrations, and suppress phytoplankton growth, which are unfavorable for bloom formation (79). Qin et al. (80) indicated that regional climate anomalies exacerbated eutrophication via a positive feedback mechanism by intensifying internal nutrient cycling and aggravating cyanobacterial blooms. Atmospheric nitrogen deposition may supplement the supply of nitrogen in sustaining blooms, therefore offsetting the effect of nitrogen loading reduction (81, 82). Under the joint impact of weather and hydrological disturbance, the phytoplankton community in the reservoirs shifted quickly from a non-cyanobacterial taxa-dominated to a cyanobacteria-dominated state over six years of a case study (83).

The interaction between external drivers and biological traits is well reflected during the formation (84, 85), maintenance (86), and vertical movement (87–89) of colonial *Microcystis*. These abilities to adapt to the ever-changing environment enable colonial *Microcystis*'s stronger competition over other species.

Growing evidence showed that the bacterial microbiome associated with bloom-forming cyanobacteria has the functional potential to contribute to nutrient exchange within bloom communities and interact with important bloom formers like *Microcystis* in Lake Erie (90) and Lake Taihu (91, 92). The role of the α-proteobacteria *Phenylobacterium* in maintaining toxic *Microcystis* dominance was illustrated via both field monitoring and chemostats experiments (93). Considerable reconstructed genomes (6 *Microcystis* and 28 bacteria) revealed the functional complementation between *Microcystis* and its epibionts at genetic and metabolic levels (91). Note that *Microcystis* must rely on bacteria to obtain vitamin B12, and heterotrophic bacteria need carbon and energy provided by *Microcystis* (94). Moreover, compared to N_2-fixing cyanobacteria, metagenomics data indicated that *Microcystis* exuded more complex bound extracellular metabolites, which facilitated bacterial colonization and provided sufficient substrates for ammonium production (95). Hence, the supply of bioavailable essential molecules from microorganisms plays a vital role in the growth and proliferation of *Microcystis*.

4. CYANOBACTERIAL BLOOMS AT REGIONAL AND GLOBAL SCALE

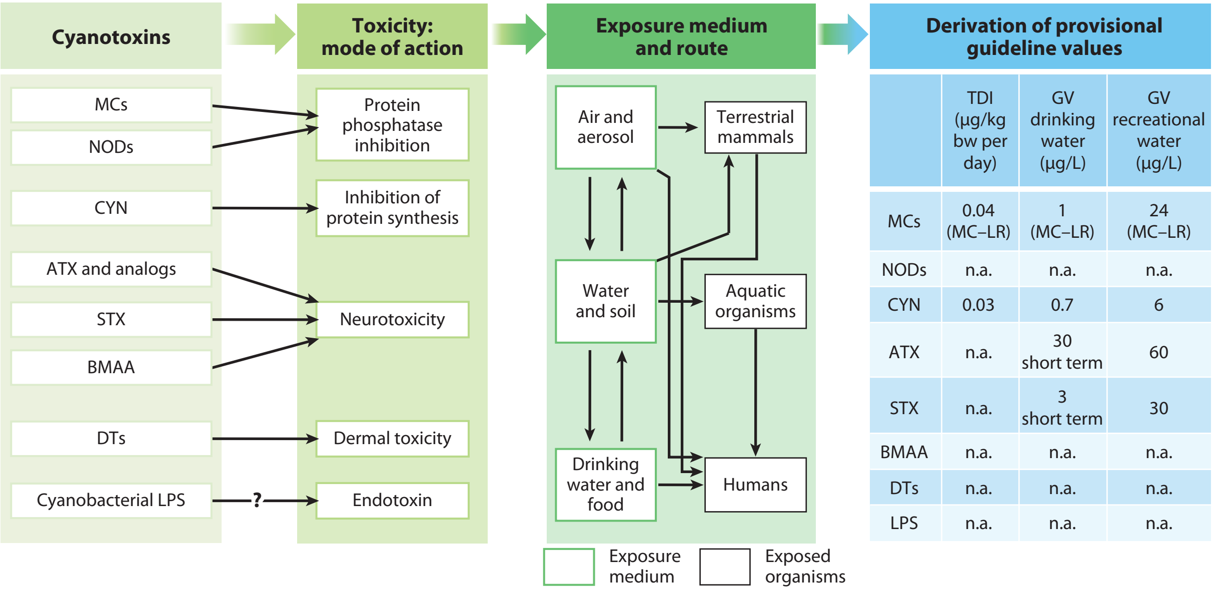
4.1. Geographic Distribution

Recent studies have shown that the intensity, frequency, and duration of cyanobacterial blooms have increased in many lakes due to the unceasing anthropogenic activities (agricultural and industrial production, urbanization, and population growth, among others) and climate change (global warming, rising CO_2 concentrations, high-intensity rainfall events, and longer dry periods) (78). A global biogeographic analysis showed *Microcystis* spp. blooms were recorded in at least 108 countries, 79 of which have also reported the presence of MCs (21). Cirés & Ballot (96) compiled the global record on bloom-forming *Aphnaizomenon* spp. Five species, *Aphanizomenon flos-aquae*, *A. gracile*, *Cuspidothrix issatschenkoi*, *Chrysosporum ovalisporum*, and *Sphaerospermopsis aphanizomenoides*, were also widely distributed and experienced a geographic expansion. Based on results of 41 peer-reviewed publications before May 2021, Wang et al. (97) conducted a global-scale meta-analysis of the relationships between driving factors and CyanoHABs. From a global-scale analysis, water quality, hydraulic conditions, meteorological conditions, and nutrient loading were often considered the driving forces of CyanoHABs. Interestingly, meteorological parameters were negatively related to the occurrence of CyanoHABs, while other driving forces were positively correlated. Based on the satellite survey of 248,243 freshwater lakes globally over 38 years (1982–2019), 21,878 lakes (8.8%) have experienced algal blooms, and the most pronounced increases were found in developing countries (1, 5). At the regional level, the features of CyanoHABs might be masked in global-scale analysis due to scale effects (3). Small water bodies are susceptible to even short-term changes in land-use and climate conditions. Unfortunately, current monitoring programs have largely ignored small water bodies. Regional features of CyanoHABs may further challenge the effectiveness of management and policy that are derived from large-scale study of CyanoHABs.

4.2. Monitoring and Modeling

To describe the trend of CyanoHABs' distribution and expansion, long-term and large-scale monitoring are gaining traction, owing to fast advances in technologies and devices (98). Microscopy and pigment analytical analysis are traditional monitoring methodologies commonly applied to collect data for cyanobacteria and develop data-driver forecasting models (99). However, microscopic assessment and pigment analytical techniques require skilled personnel and are highly time-consuming (100). In situ fluorescence probes and remote sensing have been increasingly used for CyanoHAB monitoring in recent years due to their low-cost, high-efficiency data collection at higher temporal and spatial resolution. For example, Kutser et al. (101) evaluated and confirmed the potential of satellite remote sensing technology in monitoring cyanobacterial blooms. These studies suggested that the forecasting performance of the models would be higher if high-frequency data were available (102, 103). The combination of data from different monitoring methodologies has also been shown to improve prediction performance (104). Bertani et al. (105) developed a boosted regression tree model to predict cyanobacteria dynamics to evaluate whether different monitoring methodologies would affect the performance of models and show that monitoring methodologies are critical for assessing model accuracy. However, only a few studies have coupled both remote sensing and in situ fluorescence monitoring techniques, and further efforts should be made to explore multisource data fusion models. Recently, scientists have tried to predict cyanobacterial blooms by integrating satellite remote sensing, in situ observations, and process-based models (106). For example, satellite imagery can provide information about the present location and extent of cyanobacteria and then predict short-term bloom dynamics considering hydrodynamic and future meteorological conditions (107, 108). In practice, these strategies are always data-demanding and time-consuming to calibrate parameters. As an alternative, artificial intelligence modeling, especially deep learning, has received great attention recently (103). The Deep Neural Networks (DNN), Convolutional Neural Network (CNN), and Long Short-Term Memory (LSTM) have proved their superiority in predicting algal parameters. More specifically, efforts have been made to fuse data from different sources to develop a hybrid deep learning framework in predicting cyanobacterial blooms, including wavelet transform+LSTM (109), CNN+LSTM (110), and environmental fluid dynamics code (EFDC)+LSTM (111). However, more work is needed for meaningful interpretation of the proposed models according to ecological principles.

Exploring the driving factors of cyanobacterial blooms is the key to controlling bloom outbreaks effectively. In recent years, data-intensive machine learning models have been developed to illuminate the external drivers for bloom-forming taxa, including tree-based ensemble models (112), Bayesian networks (113), and genetic programming (114). Nevertheless, it is still difficult to determine the relative importance of environmental factors, because the bloom formation results from complex and synergistic effects rather than a single dominant factor.



	TDI (μg/kg bw per day)	GV drinking water (μg/L)	GV recreational water (μg/L)
MCs	0.04 (MC–LR)	1 (MC–LR)	24 (MC–LR)
NODs	n.a.	n.a.	n.a.
CYN	0.03	0.7	6
ATX	n.a.	30 short term	60
STX	n.a.	3 short term	30
BMAA	n.a.	n.a.	n.a.
DTs	n.a.	n.a.	n.a.
LPS	n.a.	n.a.	n.a.

Figure 3

The aggregated exposure pathways of cyanotoxins. The provisional GVs for MCs, NODs, CYN, ATX, and STX are presented according to current WHO GVs. Note that these GVs are provisional due to limitations of the toxicological data, including data being available for only one congener. Abbreviations: ATX, anatoxins; BMAA, β-methylamino-L-alanine; CYN, cylindrospermopsin; DT, dermatoxin; GV, guideline value; LPS, lipopolysaccharide; MC, microcystin; MC–LR, microcystin-leucine-arginine; NOD, nodularin; STX, saxitoxin; T&O, taste and odor; TDI, tolerable daily intake; WHO, World Health Organization.

5. RISK ASSESSMENT OF CYANOHABS AND CYANOTOXINS

CyanoHABs pose serious risks toward the health of humans and animals, ecosystem sustainability, and economic vitality related to aquatic systems, as depicted in **Figure 3**. Risk assessment of CyanoHABs is often associated with toxic secondary metabolites, i.e., cyanotoxins. However, the scientific knowledge on cyanotoxins is still insufficient for correctly assessing the risk of CyanoHABs. The major toxicological aspects remain to be elucidated; particularly, epidemiological data are largely unknown and the exposomics of cyanotoxins is a very complex task. The number of reported CyanoHAB incidents has risen notably over the past few decades, and these incidents have affected public health and ecosystem services worldwide (4). Not only is the nuisance of such blooms esthetical, but also concomitant environmental stressors (such as low dissolved oxygen and high particle/dissolved organic substances) can lead to a decrease in biodiversity and food web alterations (69). In particular, cyanobacteria are most feared due to their production of cyanotoxins and off-flavor compounds that restrict the safety of freshwater and usage of water for a range of ecosystem services of considerable importance for societal and economic interest, including drinking water, irrigation, aquaculture, fish breeding, tourism, and recreation (11, 115). These include strains of cyanobacteria from different genera, which produce a variety of cyanotoxins (**Figure 3**).

Toxicological data have linked poisonings to cyanotoxins, which is of great concern for human and animal health. For human health, several regions of the world provide epidemiological evidence (116). One example is the fatal hepatotoxin MC intoxication that occurred in 1996 at a hemodialysis center in Brazil and resulted in 50 patient deaths (117). Another example is associated with *R. raciborskii*. In 1979, a bloom of *R. raciborskii* occurred in Lake Solomon on Palm Island near

Townsville, Queensland, Australia, and resulted in one of the world's most significant cyanotoxin direct acute intoxication events. Ten adults and 140 children suffered a range of severe illnesses, including gastroenteritis, which became known as the Palm Island Mystery Disease (118). This cyanobacterium can produce CYN. Genetic analysis has linked the CYN biosynthesis gene cluster and the strain's toxicity (119). Additional examples were from the United States, Africa, and Europe, where gastroenteritis reports have been made following cyanobacterial blooms in drinking water (11). Svirčev et al. (120) compiled the toxicological data on MCs, indicating that the limitations in current epidemiological studies include a lack of use of long-term, standardized, environmental monitoring and cyanobacterial quantification methods and of systematic and specific cyanotoxin analysis methods.

The exposure pathways (the exposure medium and route panel) of cyanotoxins are described in **Figure 3**. The two well-documented routes of exposure to cyanobacteria and cyanotoxins are incidental consumption of contaminated water and direct dermatological contact through recreational activities (121). Dietary consumption of cyanotoxin-contaminated fish is an important exposure route as well (122, 123). Other routes include intake of supposedly beneficial cyanobacterial supplements (124). In the past few years, exposure through aerosol is of growing concern. Evidence indicates that living within 0.5 miles of a waterbody affected by frequent CyanoHABs appears to be a significant risk factor for amyotrophic lateral sclerosis in Northern New England (125). Humans inhale aerosolized cyanobacteria, which can be harbored in the nostrils and the lungs. Future classification of cyanobacterial species in human biosamples may provide insight into clinically relevant aerosolized cyanobacteria with cyanotoxin exposure and the potential for associated human disease (126).

Despite accumulating toxicological and epidemiological data on cyanotoxins, current guidelines and regulations for these toxins are still insufficient. As shown in **Figure 3**, the guideline values for the majority of cyanotoxins are not provided. The current World Health Organization (WHO) guideline values for MC and CYN are provisional due to limitations of toxicological data, including data being available for only one congener for each type of cyanotoxin. For anatoxin-a (ATX-a), in an experiment designed to derive the no-observed-adverse-effect level (NOAEL), none of the dose levels tested indicated damage due to ATX-a, and thus no NOAEL value could be calculated. The data do allow giving an upper limit below which adverse effects are unlikely, termed health-based reference value. For saxitoxins (STXs), toxicological data for chronic exposure are unavailable, but for acute exposure they were reported in cases of food poisoning with marine shellfish. Note that the guideline value of acute exposure for STXs in drinking water is calculated based on the bodyweight of an infant and all recreational values are based on the bodyweight of a child. Note also that while the derivation is based on toxicological data for one main congener (due to lack of data for the others), WHO recommends application to the sum of all congeners present in one sample (11). In addition, although the levels of cyanotoxins were relatively lower than the provisional guideline values in many waterbodies, CyanoHABs cause a high load of organic matters, which can provide a precursor of chlorination by-products during drinking water treatment. These by-products are suspected of being carcinogenic and causing off-flavor taste and odor, thus resulting in future health risks (11).

Evidence of animal poisonings by cyanotoxins is emerging (127). A recent review provides a systematic map of freshwater cyanobacterial poisonings in terrestrial wildlife (128). In 2020, approximately 400 elephants died in the Okavango Delta region in Botswana, which coincided with an exceptional landscape-wide cyanobacterial bloom event. Therefore, toxic cyanobacterial blooms were widely blamed for this catastrophic event (9). A recent study demonstrated that the neurotoxin aetokthonotoxin produced by the cyanobacterium *Aetokthonos hydrillicola* growing on aquatic vegetation is responsible for a mysterious mass mortality of bald eagles in Arkansas (129).

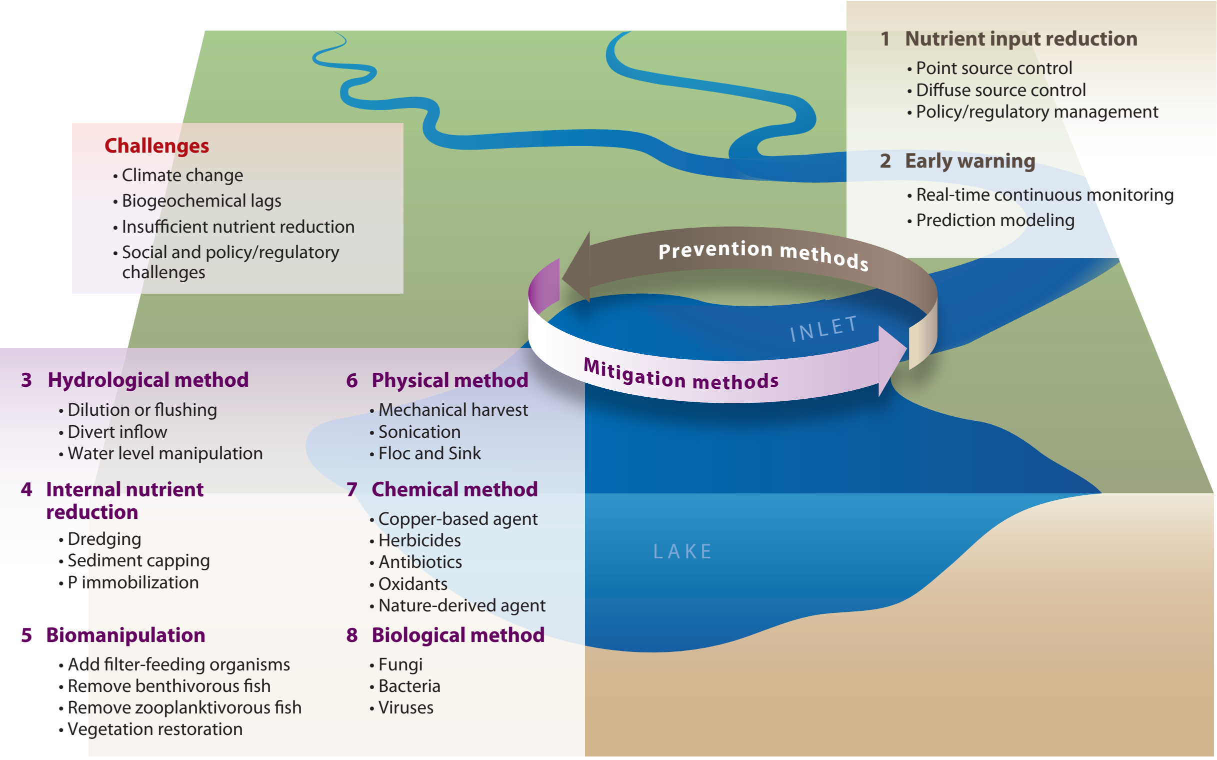


Figure 4

Conceptual overview of prevention and mitigation methods for harmful cyanobacterial blooms (CyanoHABs). The strategies for combating CyanoHABs can be categorized into two groups generally, i.e., prevention and mitigation. The prevention methods include (1) nutrient input reduction and (2) early warning; the mitigation methods include (3) hydrological methods, (4) internal nutrient reduction, (5) biomanipulation, (6) physical methods, (7) chemical methods, and (8) biological methods. The red text suggests current challenges to control CyanoHABs. The background picture is used to visualize catchment-wide strategies, including out- and in-lake measures. Note that some in-lake measures (e.g., 3, 4, and 5) are also implemented as prevention methods.

6. PREVENTION AND CONTROL OF CYANOHABS

The increased incidence of toxic and unsightly nuisance CyanoHABs calls for reliable methods to prevent, mitigate, eliminate, and control risks of CyanoHABs during emergency events or extended persistence in freshwater systems, as illustrated in **Figure 4**. These methods can be categorized as prevention and mitigation approaches. The prevention approaches include both in-lake and out-lake measures, whereas the mitigation approaches are often implemented as emergency strategies in a lake.

6.1. Prevention Methods

The prevention methods will allow us to target the root causes of CyanoHABs and leverage the power of nature's self-regulating and self-renewing ecological processes. Nutrient input reduction, early warning of CyanoHABs, and hydrological manipulation approaches are often employed as proactive prevention strategies.

6.1.1. Nutrient input reduction. Nutrient input reductions are the fundamental prevention and controlling strategy for CyanoHABs. During past decades, P input restrictions have been implemented widely (39). It is assumed that P is the limiting nutrient, whereas N limitation could induce the dominance of N-fixing cyanobacteria to meet the N requirements of the ecosystem by N_2 fixation (130). P reduction has been successful in controlling CyanoHABs in some deep and/or low-nutrient lakes (39, 131) but has failed in many large, shallow eutrophic lakes (131). When developing N and P control strategies, we have to consider the lake morphology, hydrological processes, and nutrient status of the lakes (131). In vertically stratified deep lakes, residual P is "trapped" as settling particles are often buried in sediments (132). The resultant released P can be used by phytoplankton only following autumn turnover. However, in shallow well-mixed lakes, frequent hydrodynamic disturbances effectively resuspend P in surficial sediments into the water column, maintaining relatively high total P concentrations and P availability in the water column (132). In Lake Taihu (China), the seasonal sediment P release contributed 23%–90% P demand from CyanoHABs (133). Therefore, internal nutrient cycling can modify nutrient availability and limitation, and legacy P loads in the sediments would be expected to delay recovery of the lake (133). This helps explain why some longstanding efforts to control lake eutrophication have resulted in frustratingly slow or modest effects in shallow productive lakes and why P-only reduction strategies are more effective in deep lakes.

The N cycle also has natural removal mechanisms at whole-lake scales, such as denitrification. In eutrophic shallow lakes with relatively long hydraulic residence time, reduction in external N loading would result in a quick response of in-lake total nitrogen concentration, because N loss by denitrification greatly reduces internal N loading (132). It was estimated that 50% of the external N load was "lost" through denitrification in Lake Taihu (133). Recent studies have shown that N_2 fixation does not compensate for N losses in eutrophic lakes (134, 135). Therefore, reducing N inputs, along with P, will yield a more rapid and sustainable reversal of eutrophication and bloom potentials than reducing P inputs alone (133). Nutrient inputs primarily originate from external sources within the catchment, such as point and nonpoint source inputs of nutrients from anthropogenic activities. Water discharged from wastewater treatment plants has very high nutrient concentrations that can be the source of pollution for lakes, even though they are within the national wastewater discharge limits. These limit values historically were a compromise between what was achievable at wastewater treatment plants and what was economically acceptable. In addition, nonpoint pollution sources from agricultural operations, small municipalities, and rural areas, as well as atmospheric deposition have often not been collected and/or treated/reduced, especially in developing countries and regions. The reduction of external loading often depends on water resource management and policy and regulatory legislation by national and local governments. Nutrient reduction from large lake watersheds can best be achieved by advanced wastewater treatment, establishing riparian buffers around agricultural lands, artificial wetlands, agronomic use of fertilizers, treatment and recycling of animal waste, improved stormwater management (retention ponds), and reduction of atmospheric emissions (132).

6.1.2. Early warning. Establishing a comprehensive monitoring system can facilitate early warning and prevention of CyanoHABs. Almuhtaram et al. (136) suggested that early warning tools for cyanobacteria detection consists of three tiered tasks: detecting biological activity, confirming the presence of cyanobacteria, and monitoring cyanobacteria metabolites. A variety of techniques and devices have been used by water authorities and managers, such as fluorescence probes–equipped online monitoring systems, hyperspectral remote sensing, or next-generation sequencing (12). No single tool, however, can provide all needed information for early detection of cyanobacteria, and therefore multibarrier approaches are needed (136).

6.1.3. Hydrological manipulation. Hydrological manipulations, such as water level manipulation and reducing retention time, are another effective strategy to prevent CyanoHABs. First, in shallow lakes, water level manipulations can mediate the nutrient cycling and biogeochemical processes, and provide optimal water levels for different groups of aquatic plants (137). Second, reducing water retention time, which may reduce cyanobacterial biomass, is suitable for small waterbodies (12). However, application of this method requires extremely high water flow rates, which may have negative effects on downstream waterbodies.

6.2. Mitigation and Remediation Strategies

It is widely accepted that rapid onset of CyanoHABs contributes to the difficulty of bloom control. In this case, relatively rapid and financially affordable approaches can be employed as emergency strategies to mitigate the socioeconomic losses resulting from the abnormal proliferation of noxious cyanobacteria in waterbodies (**Figure 4**).

Cyanocides: a group of chemical agents used to kill cyanobacteria or suppress the growth of cyanobacteria

6.2.1. Chemical methods. Chemical agglomeration principles have been applied for the removal of CyanoHABs in the water column, with aluminum or iron-based compounds being the most widely used agents. Precipitating the cyanobacterial cells with the addition of a low-dose coagulant, such as polyaluminum chloride, can reduce cyanobacterial surface scum by 90%; however, flotation blooms can quickly recover (12). Lürling et al. (138) reported the application of mineral/metal-based, natural, and organic coagulants combined with a ballast to improve the sedimentation of the cyanobacteria aggregates in the water column, generally termed the Floc and Sink approach. The use of synthetic and preferably natural polymers, such as chitosan, for CyanoHABs removal was also examined, including the impact of extracellular organic matter on flocculation efficiency (139). An alternative method suggests the use of local clay-enriched soil modified with chitosan (140). Cyanobacterial cells can form small flocs after the negative charge of the cell surface is neutralized by a positively charged macromolecule. With their long polymer chain, organic polymers such as chitosan and polysaccharides facilitate the growth of large flocs from small ones. Together with ballast, such as soil particles, a high and rapid removal efficacy of floating CyanoHABs is achieved. The Floc and Sink approach can be integrated and improved by physical field separation, such as the CyanoHABs harvest ship, which has been widely used in China. However, the potential leakage of cyanotoxins is often the cause of failure in applying these technologies. Additionally, the side-effect of chemicals and biosolid production should be examined.

Meanwhile, much work has been done on the application of CyanoHAB management that is based on general algicidal or cyanocidal methods, while specific cyanobacteria-inactivation compounds have become fashionable only recently (115). Conventional chemicals in use as algicides or cyanocides have been tested and their effectiveness in controlling cyanobacteria reported. However, their use is constrained by several critical issues: (*a*) their potential risk toward ecosystem and human health; (*b*) easy rebound of CyanoHABs after their application; and (*c*) that these agents can alleviate toxic CyanoHABs to some extent, but do not necessarily show the effect of cyanotoxin removal.

Recently, a diverse array of naturally derived chemicals has been developed and applied to inactivate toxic CyanoHABs (141). Although the prices of many naturally derived cyanocides are higher than for conventional agents, they at least have two advantages: They (*a*) provide selective suppression of the cyanobacteria population and minimized toxicity toward eukaryotic phytoplankton and non-phototropic biota and (*b*) are biodegradable, for optimal sustainability (115).

6.2.2. Internal nutrient removal. Even when external nutrient inputs are reduced, the legacy of eutrophication can perpetuate high internal nutrient loads that can perpetuate CyanoHABs.

Therefore, either removing sediments or capping them to reduce sediment–water column exchange of nutrients may help reduce CyanoHABs (12). However, sediment removal usually involves expensive dredging and extensive disturbance of lake bottoms, which can lead to additional release of nutrients and potentially toxic substances and destruction of bottom-dwelling plants and animal communities. Alternative approaches include chemical precipitation of P from affected water bodies to keep it "locked up" in the sediments. Common chemical treatments include alum, clays, and lanthanum-modified bentonite that tightly bind with phosphate anions. When applied at the surface, these treatments effectively precipitate P to concentrations that limit CyanoHAB growth. On the sediment surface, the thin layer of alum, clay, or lanthanum-modified bentonite can form an effective barrier to phosphate diffusing out of the sediments. Some of these treatments have been shown to work well in small water bodies, leading to P-limited conditions that can control algal and cyanobacterial proliferation (142). However, as with sediment removal, the efficacy of any chemical treatment is likely to be futile unless allochthonous nutrient inputs are concurrently managed. Therefore, sediment manipulation techniques are only a temporary "fix" without parallel, long-term nutrient input reductions.

6.2.3. Physical methods. A series of technologies have been developed for the removal of water surface aggregated cyanobacterial cells by mechanical harvest (139, 143). Although these technologies can remove the biomass and reduce the nutrient load simultaneously (144), the main shortcoming remains due to the ecological and economic stress from treatment of a huge amount of toxic cyanobacterial biomass. Using hydrostatic pressure and ultrasound waves to impair the stability of the gas vesicles has been tested to mitigate CyanoHABs, but the recovery of the damaged gas vesicles could affect the performance of these methods (12).

6.2.4. Biological methods and remediation. Biological and ecological strategies are intended to streamline aquatic environments and ecosystems to create unfavorable conditions for bloom-forming cyanobacteria, and consequently shift the CyanoHAB-dominant phytoplankton community to nontoxic eukaryotic species (145). For instance, filter-feeding fish can be introduced to reduce the biomass of cyanobacteria (146); from the food-chain perspective, zooplanktivorous fish should be controlled to strengthen the top-down effect on cyanobacterial blooms (147, 148). Ecological remediation strategies, such as macrophyte reestablishment, can be used to promote nutrient down-regulation and generate allelopathic effects toward CyanoHABs (149). Other biological methods, such as cyanobacteria-lysing and growth inhibition microbes (e.g., viruses, bacteria and fungi), are also among the promising strategies for CyanoHAB control; however, these strategies have not been scaled up for field applications (150).

6.2.5. Emerging technologies. New technologies for CyanoHAB control are emerging in the past few years, especially those technologies relying on chemical and physical processes. Recently, technologies based on microbubbles with diameters among 10–50 μm and nanobubbles with diameters smaller than 200 nm have attracted the attention of scientists in the field of water pollution remediation (145). When infused with oxygen or ozone, the bubbles can largely improve the removal of organic and inorganic pollutants from water. However, in situ studies are still needed to demonstrate that the implementation of oxygen and ozone-infused micro/nanobubbles to improve water quality and inactivate CyanoHABs and their harmful metabolites is practical. In addition, ecological risk toward other aquatic organisms should be addressed.

Selective inactivation of bloom-forming cyanobacteria is an anticipated approach. Understanding the biological and ecological traits of CyanoHABs helps direct the development of selective control strategies. New cyanocides originating from natural products may provide solutions for the selective control of CyanoHABs (141). From the discovery perspective, target protein–guide screening using both in silico and high-throughput bioanalytical tools is of great potential in the development of next-generation cyanocides. From the cost-effective perspective, synthetic biology and protein engineering are promising tools to establish cellular factories for nature-based cyanocide production.

7. CONCLUSIONS

Their biological traits, phenotypic plasticity, physiological acclimation, and genetic diversity allow CyanoHABs to effectively compete over other phytoplankton species. Advances in understanding the mechanism of CyanoHAB existence have been helpful in combating this global "aquatic monster" by adopting environmentally friendly and cost-effective monitoring and remediation strategies. Yet, the pace of transformation of scientific discovery into practical and safe procedures for prevention, control, and restoration technologies is seemingly lagging behind the demands of the public, regulators, and policymakers. It is now known to all that the intensification of CyanoHABs is the consequence and the direct reflection of the deterioration of aquatic systems. Both extreme weather events and human disturbances are predicted to become more frequent and severe in the future; therefore, sustainable management of cyanobacterial blooms will require consideration of the regional effects of climate anomalies and the resilience of aquatic ecosystems. No single CyanoHAB intervention strategy is effective even with recent scientific and technological advances. Therefore, a holistic approach to combine existing strategies with new technologies is needed within and outside waterbodies in an era of uncertainty surrounding CyanoHAB outbreaks.

SUMMARY POINTS

1. Cyanobacterial blooms have markedly increased over the past decades and will likely continue to increase due to the combined effects of eutrophication, rising CO_2 levels, and global warming.
2. Cyanobacteria have distinctive features and functions as revealed in phenotypic plasticity, physiological acclimation, and genetic diversity, thus offering harmful cyanobacterial blooms (CyanoHABs) effective competition over other phytoplankton taxa.
3. Interactions between cyanobacteria and bacteria in aquatic environments are complex and play a vital role in the persistence and decline of the bloom. Bacterial microbiomes associated with bloom-forming cyanobacteria have the potential to contribute to nutrient exchange within bloom communities.
4. Assessment, prediction, and management of CyanoHABs rely on real-time and rapid monitoring approaches. In addition to traditional field surveys, the application of remote sensing monitoring, DNA-based detection, and online automatic monitoring approaches have provided data-rich information to establish early warning protocols for CyanoHABs.
5. The risks of cyanobacteria and cyanotoxins initiate advances in both scientific research and technology development toward CyanoHAB management. Emerging concepts and frameworks from toxicological and epidemiological study, such as aggregated exposure pathways and adverse outcome pathways, push risk assessment of CyanoHABs into an era of precision exposomics.

6. Prevention, remediation, and control of CyanoHABs are crucial steps in management but are challenged by technical limitations, socioeconomic status and global environmental change. Currently, both cyanocides and combinations of flocculants have been used in removing cyanobacteria blooms. Physical technologies have also been practically applied in many waterbodies. Despite the performance and effectiveness, these strategies are faced with potential negative impacts on the aquatic ecosystems. Biological and ecological strategies are promising but prone to disturbance.

FUTURE ISSUES

1. Initiation, proliferation and persistence of CyanoHABs are influenced by global warming, regional climate anomalies and local eutrophication. Thus, predicting and withstanding CyanoHABs events requires local approaches based on global models and solutions. Thus, coordinated efforts of the scientific community, communities, and management authorities may provide sustainable solutions to the global issue.
2. Lack of long-term and rational monitoring might constrain our understanding of the mechanisms related to the occurrence of CyanoHABs. The future monitoring package for CyanoHABs should combine transdisciplinary solutions. The use of artificial intelligence may help integrate data from both past and present to better understand the mechanisms.
3. Comprehensive watershed management efforts will lead to a significant reduction of the CyanoHAB events and bloom intensities. This includes ecosystem-scale mitigation of nitrogen and phosphorus inputs or oligotrophication of aquatic ecosystems.
4. Innovative solutions should be developed and applied to combat CyanoHAB events via implementation of in situ scientifically proven measures to minimize cyanobacterial biomass and cyanotoxins. Physical, chemical, and biological techniques are needed to be site specific to selectively reduce cyanobacteria communities and support the domination of other nontoxic algae species.
5. Catchment conditions and human society-derived rearrangement of water resources can largely affect the water quality regionally. Although it is well perceived that maintenance of natural hydrologic connectivity is of great importance to the ecological equilibrium of these aquatic ecosystems, attention should be paid to the risk of interbasin water transfers that are being implemented worldwide but are rarely evaluated for their long-term effects, including the introduction of invasive CyanoHABs.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We would like to thank our research collaborators and students who have worked with us on cyanobacterial bloom–related topics over the years. Funding information is as follows: L.S.

was supported by the National Science Foundation of China (grant number 32061143029), the National Key R&D Programmes of the People's Republic of China (project number 2017YFE0125700), and the Biological Resources Program of the Chinese Academy of Sciences. Y.J. was supported by the National Science Foundation of China (grant number 42107150). The work of A.S. was carried out in accordance with the Lake Kinneret monitoring program sponsored by the Israel Water Authority and supported by a grant from the Ministry of Science and Technology, Israel, and the Ministry of Science and Technology of the People's Republic of China (research number 3-15707), as well as grants from the Israel Water Authority (contract number 4502268451). The work of K.S. is supported by the West Light Foundation of the Chinese Academy of Sciences (grant number E1296001).

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