



Biotechnological approaches for suppressing *Microcystis* blooms: insights and challenges

Mingyeong Kang^{1,2} · Seonah Jeong¹ · So-Ra Ko¹ · Min-Seong Kim^{1,2} · Chi-Yong Ahn^{1,2}

Received: 13 July 2024 / Revised: 13 July 2024 / Accepted: 17 July 2024
© The Author(s) 2024

Abstract

Cyanobacterial harmful algal blooms, particularly those dominated by *Microcystis*, pose significant ecological and health risks worldwide. This review provides an overview of the latest advances in biotechnological approaches for mitigating *Microcystis* blooms, focusing on cyanobactericidal bacteria, fungi, eukaryotic microalgae, zooplankton, aquatic plants, and cyanophages. Recently, promising results have been obtained using cyanobactericidal bacteria: not through the inoculation of cultured bacteria, but rather by nurturing those already present in the periphyton or biofilms of aquatic plants. Fungi and eukaryotic microalgae also exhibit algicidal properties; however, their practical applications still face challenges. Zooplankton grazing on *Microcystis* can improve water quality, but hurdles exist because of the colonial form and toxin production of *Microcystis*. Aquatic plants control blooms through allelopathy and nutrient absorption. Although cyanophages hold promise for *Microcystis* control, their strain-specificity hinders widespread use. Despite successful laboratory validation, field applications of biological methods are limited. Future research should leverage advanced molecular and bioinformatic techniques to understand microbial interactions during blooms and offer insights into innovative control strategies. Despite progress, the efficacy of biological methods under field conditions requires further verification, emphasizing the importance of integrating advanced multi-meta-omics techniques with practical applications to address the challenges posed by *Microcystis* blooms.

Key points

- A diverse range of biotechnological methods is presented for suppressing *Microcystis* blooms.
- Efficacy in laboratory experiments needs to be proved further in field applications.
- Multi-meta-omics techniques offer novel insights into *Microcystis* dynamics and interactions.

Keywords *Microcystis* · Cyanobacterial bloom · Biotechnological control · Field application · Multi-meta-omics

Introduction

Cyanobacterial harmful algal blooms (cyanoHABs) refer to the rapid proliferation of cyanobacteria in water systems that cause disturbances in ecosystems. Some cyanobacteria produce diverse toxins that pose threats to aquatic animals, livestock, and even humans (Shahmohammadloo

et al. 2023, 2020; Zeng et al. 2021a). Among the globally prevalent cyanoHABs, *Microcystis* is the most dominant in Asia, North America, South America, and Europe (Arif et al. 2023; Den Uyl et al. 2021; Huo et al. 2021; Mânica and Lima 2023; Park et al. 2021; Schweitzer-Natan et al. 2023). For instance, Lake Taihu, China, has been famous worldwide for *Microcystis* blooms since the shutdown of the water-supply system in Wuxi in 2007, prompting intensive research (Chen et al. 2024; Huang et al. 2024). *Microcystis* blooms are also prevalent in freshwater systems in Korea, such as the Nakdong River and Daechung Reservoir (Chun et al. 2019, 2020; Le et al. 2023a), particularly after the completion of the Four Major Rivers Restoration Project (Park 2012). In Lake Erie, a significant cyanoHAB in 2014 led to the suspension of the water supply for more than 500,000 residents in Toledo, Ohio (Steffen et al. 2017).

✉ Chi-Yong Ahn
cyahn@kribb.re.kr

¹ Cell Factory Research Center, Korea Research Institute of Bioscience and Biotechnology (KRIBB), 125 Gwahak-Ro, Yuseong-Gu, Daejeon 34141, Republic of Korea

² Department of Environmental Biotechnology, KRIBB School of Biotechnology, University of Science and Technology (UST), 217 Gajeong-Ro, Yuseong-Gu, Daejeon 34113, Republic of Korea

The intensification of cyanoHABs has been attributed to the combined effects of eutrophication and climate change (Burford et al. 2020; Geletu 2023; Thomalla et al. 2023). In particular, cyanobacteria are adapting better to elevated temperatures caused by global warming (Guo et al. 2023; Wang et al. 2023; Yang et al. 2023). In addition, cyanoHABs promote the production of methane, a greenhouse gas (Li et al. 2021; Wang et al. 2022b). Increased methane oxidation by *Methylomonas* during the post-bloom period can facilitate the recovery of water quality in eutrophicated reservoirs (Yu et al. 2023), but cyanoHABs still stimulate methylotrophic methanogenesis and accelerate global warming (Zhu et al. 2022). Therefore, increased methanogenesis by cyanobacteria coupled with rising temperatures synergistically exacerbate cyanoHABs.

Various approaches, including physical, chemical, and biological methods, have been proposed to suppress *Microcystis* blooms and improve water quality (Lusty and Gobler 2020; Zang et al. 2020; Zhang et al. 2023c). However, physical methods for *Microcystis* removal are generally costly, and chemical methods can leave persistent substances that pose toxicity risks to water quality, aquaculture facilities, and drinking-water sources (Buley et al. 2021; Santos et al. 2021). In contrast, biological methods are regarded as more

favorable owing to their nontoxic nature and highly specific effects on the target cyanobacteria. Furthermore, the recent integration of high-throughput sequencing and bioinformatic/ecoinformatic techniques has created an opportunity to obtain novel insights and enhance the reliability and effectiveness of biological methods. This review focuses on analyzing biotechnological approaches for suppressing *Microcystis* blooms, assessing their field applicability, and prospecting innovative techniques based on genomics and multi-meta-omics.

Biotechnological approaches for *Microcystis* suppression using diverse biotic agents

Biotechnological methods for suppressing *Microcystis* can be categorized into microorganism- and macroorganism-based methods. Microorganisms comprise bacteria, fungi, eukaryotic microalgae, zooplankton, and viruses, whereas macroorganisms include aquatic plants. Each organism either directly attacks *Microcystis* or indirectly influences it by releasing allelopathic compounds. This review focuses on biotic agents that have been isolated and used to suppress *Microcystis* (Fig. 1).

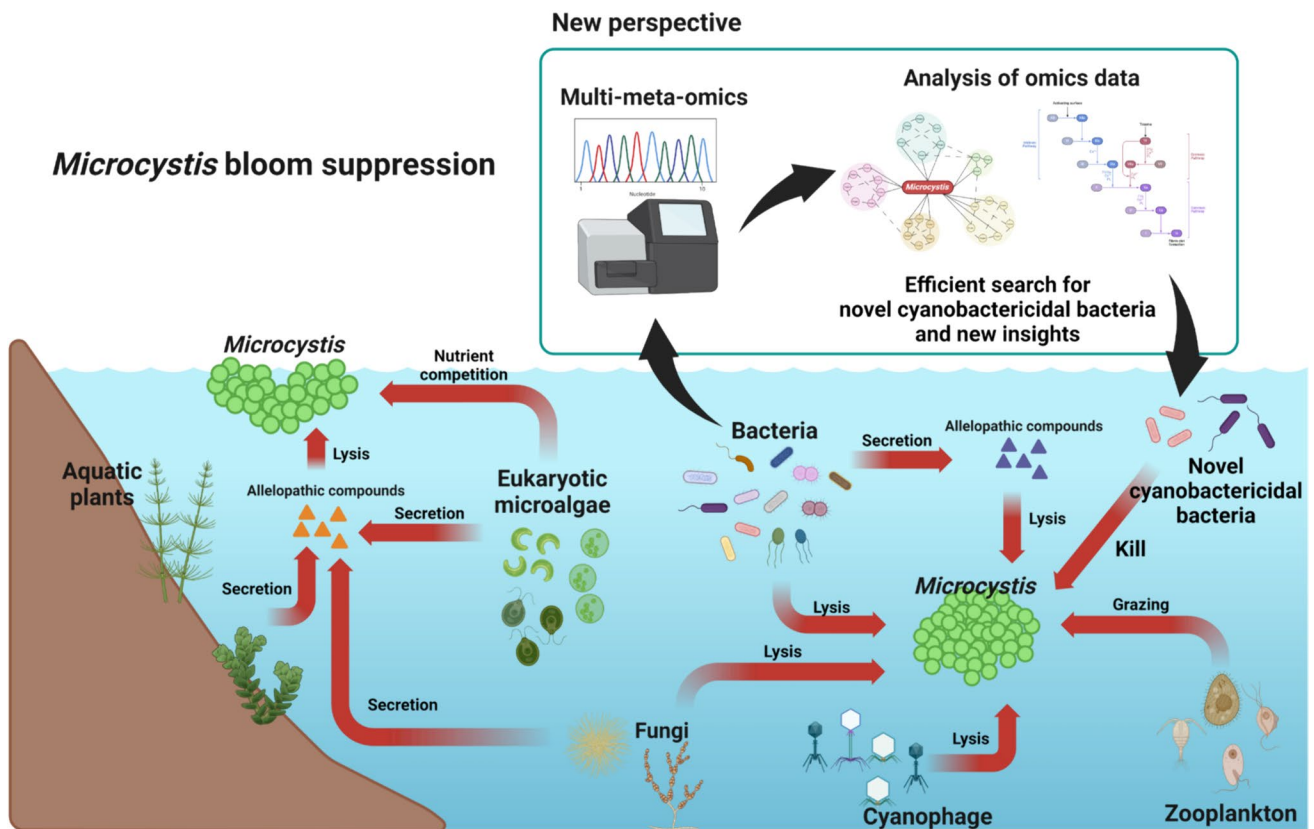


Fig. 1 Overview of diverse biotechnological approaches for suppressing *Microcystis*

Cyanophages

Cyanobactericidal bacteria are considered to be crucial biological facilitators for *Microcystis* suppression. These bacteria exploit both direct and indirect modes of action against *Microcystis*. Direct activity involves physical contact between cyanobactericidal bacteria and *Microcystis*, whereas indirect activity involves the secretion of secondary

metabolites (Table 1). *Streptomyces globisporus* G9 and *Stenotrophomonas* sp. KT48 kill *Microcystis aeruginosa* by direct cell-to-cell attack (Lyu et al. 2022; Zeng et al. 2021b). However, direct cyanobactericidal bacteria have been scarcely reported when compared with indirect ones. The multifaceted effects of indirect activity, mediated by allelopathic compounds, often surpass those of direct activity. Indirect mechanisms involve the degradation of cell

Table 1 Summary of control mechanisms for *Microcystis* bloom using cyanobactericidal bacteria

Mechanism	Mode of action	Species	Effective concentration	Initial cell density of <i>Microcystis</i>	Growth inhibition	Duration	Reference	
Direct	Cell-to-cell contact and lysis	<i>Aeromonas bestiarum</i> HYD0802-MK36	1×10^7 cells/mL	5×10^4 cells/mL	91.0%	2 days	Park et al. (2022)	
	Cell-to-cell contact and lysis	<i>Streptomyces globisporus</i> G9	5% (v/v)	1×10^6 cells/mL	96.7%	6 days	Zeng et al. (2021b)	
	Lysis	<i>Stenotrophomonas</i> sp. KT48	10% (v/v)	5.2×10^6 cells/mL	95.2%	10 days	Lyu et al. (2022)	
Indirect	Secretion of algicidal compounds in filtrate	<i>Bacillus</i> sp. YZ1 and <i>Brevibacillus</i> sp. CBS	10% (v/v)	1×10^7 cells/mL	95.0%	5 days	Liu et al. (2022)	
		<i>Bacillus altitudinis</i> G3	5% (v/v)	4.0×10^6 cells/mL	99.8%	72 h	Hou et al. (2023)	
		<i>Brevibacillus</i> sp.	3% (v/v)	7×10^7 cells/mL	100.0%	96 h	Liu et al. (2023)	
	Secretion of seven algicidal compounds in cell-free supernatant (cyclo (leu-pro), cyclo (phe-pro), norharman, trans-3-indoleacrylic acid, hypoxanthine, kanosamine, and betaine)	<i>Bacillus</i> sp. AK3	5% (v/v)	2.59×10^6 cells/mL	82.6%	3 days	Boonbangkeng et al. (2022)	
		<i>Morganella morganii</i>	10% (v/v) 5.65×10^7 cells/mL	1.07×10^7 cells/mL	98.5%	6 days	Mankiewicz-Boczek et al. (2022)	
		<i>Pseudomonas</i> sp. Go58	3.1×10^8 cells/mL	1.83×10^5 cells/mL	> 95.0%	2 days	Chen et al. (2023)	
		Flocculation and lysis by algicidal compounds	<i>Paenibacillus</i> sp. A9	6% (v/v)	-	80.9%	96 h	Jia et al. (2023)
	Secretion of algicidal compounds in filtrate	<i>Streptomyces</i> sp. HY	5% (v/v)	5×10^6 cells/mL	93.0%	2 days	Zhang et al. (2023a)	
	Direct/indirect	Secretion of paucibactin A and direct lysis	<i>Paucibacter aquatile</i> DH15	2.1×10^4 CFU/mL	2×10^6 cells/mL	94.9%	36 h	(Le et al. 2022a, 2023b)

wall components, modulation of gene expression, and disruption of antioxidants or photosynthetic systems (Zhang et al. 2022b). For example, *Bacillus altitudinis* G3 secretes both thermolabile and thermostable algicidal substances that affect photosynthetic activity and reactive oxygen species production, selectively killing *M. aeruginosa* (Hou et al. 2023). The filtrate of *Bacillus* sp. YZ1 and *Brevibacillus* sp. CBS, when applied at a density of 1×10^7 cells/mL, caused more than 95% lysis of *M. aeruginosa* cells within 5 days (Liu et al. 2022). Similarly, the filtrate of a novel *Brevibacillus* sp. caused complete cell lysis within 4 days at a concentration of 2.1×10^5 cells/mL (Liu et al. 2023). *Paenibacillus* sp. A9 uses a “flocculation-lysis-degradation” mechanism, where it initially secretes polysaccharides containing carboxyl groups to flocculate *Microcystis*, followed by lysing it with algicidal active compounds (Jia et al. 2023). In contrast, *Bacillus* sp. AK3 secretes seven antimicrobial compounds into the cell-free supernatant (Boonbangkeng et al. 2022). This supernatant, when inoculated into *Microcystis* bloom water, strongly inhibited the growth of *Microcystis* and *Pseudanabaena* and promoted the growth of *Chlorella*, indicating a specific inhibitory effect. Recently, *Paucibacter* has emerged as a dual-acting bacterium against *Microcystis*, exerting both direct and indirect effects with a high cyanobactericidal effect of 94.9% within 36 h (Le et al. 2022a). Through indirect action, *Paucibacter* secretes paucibactin A, which exhibits an algicidal effect of 81.6% within 24 h. Moreover, paucibactin A undergoes 87.4% photolysis within 24 h, rendering it an environment-friendly substance without a persistent impact on aquatic ecosystems (Le et al. 2023b). Additionally, various bacteria such as *Paucibacter aquatile* DH15, *Paenibacillus* sp. A9, and *Stenotrophomonas geniculata* can degrade microcystin, a toxin produced by *Microcystis* (Jia et al. 2023; Le et al. 2022a; Xie et al. 2023).

Cyanobactericidal bacteria are more abundant during bloom-declining periods, but they are often successfully isolated during bloom periods (Le et al. 2022a; Mankiewicz-Boczek et al. 2022; Zhang et al. 2019). Therefore, periphyton, which consists of diverse attached eukaryotic microalgae and bacteria, has been suggested as a promising strategy to reduce cyanobacterial blooms owing to its ability to stimulate the growth of cyanobactericidal bacteria (Le et al. 2023c). Biofilms on aquatic plants may serve as reservoirs of algicidal bacteria in the natural environment (Miyashita et al. 2019). These approaches can enhance the control of *Microcystis* blooms by fostering the growth of only periphyton or aquatic plants, without the inoculation of cultured bacteria or allelopathic compounds and. Because such methods promote already existing cyanobactericidal bacteria and organic matter-degrading bacteria in the water column, they can achieve eco-friendly bloom control at a lower cost.

Fungi

The process of eliminating cyanobacterial cells and their degradation by fungal strains remain largely unknown. Currently, only a few species with the ability to inhibit and lyse cyanobacterial cells have been identified. Direct and indirect attacks are the modes of fungal action used to lyse *Microcystis* species. For example, *Trichaptum abietinum* and *Lopharia spadicea* degrade *M. aeruginosa* and *M. flos-aquae*, and the lysis mechanism involves mucus secretion by fungal mycelia upon direct contact with cyanobacterial cells (Jia et al. 2010; Wang et al. 2010). *Irpex lacteus*, *Trametes versicolor*, and *Bjerkandera adusta* also successfully eliminate *Microcystis* cells by direct attack (Han et al. 2011). In addition, algicidal fungi can indirectly attack cyanobacteria by releasing algicidal compounds that inhibit growth or by secreting lytic enzymes that damage the cell wall and plasma membrane. *T. versicolor* also inhibits *M. aeruginosa* by producing decomposing enzymes such as cellulase, β -glucanase, and protease (Dai et al. 2018). *Trichoderma citrinoviride* culture filtrate inhibits the growth of *M. aeruginosa*, indicating algicidal activity through fungal secretions rather than a direct attack (Mohamed et al. 2014). *Aureobasidium pullulans* produces β -*N*-acetylglucosaminidase, an enzyme capable of breaking down bacterial peptidoglycan, a major component of the cyanobacterial cell wall (Mohamed et al. 2020). Recent studies have shown that certain fungal species can degrade microcystins. *Phanerochaete chrysosporium*, a white-rot fungus, not only destroys algal cells but also reduces the expression of microcystin genes (Zeng et al. 2020). *Penicillium chrysogenum* inhibits the growth and antioxidant system of *M. aeruginosa* by secreting extracellular substances, specifically penicillin V and G (Han et al. 2021b). This interaction leads to the altered expression of genes involved in microcystin synthesis and photosynthesis in *M. aeruginosa*. Moreover, *Penicillium* sp. GF3 effectively degrades microcystin-LR (Kuzikova et al. 2023). Algicidal fungi are expected to be an environment-friendly control method because they can decompose toxins and cells simultaneously (Mohamed et al. 2014; Kuzikova et al. 2023). However, there are numerous challenges in directly using them for onsite treatment, so the use of fungal extracts is now regarded as a more practical method.

Eukaryotic microalgae

Microcystis and eukaryotic microalgae compete under different environmental conditions, such as temperature, nutrients, and light (Hu et al. 2021). The colonial *Microcystis* exhibits more resistance to light stress and chemical

materials than eukaryotic algae (Fang et al. 2018; Zhang and Benoit 2019), and *Microcystis* and its exudates have allelopathic effects on *Scenedesmus quadricauda* and *Chlorella pyrenoidosa* (Wang et al. 2017). However, recent studies indicate a decline in the competitive ability of colonial *M. aeruginosa* against *Scenedesmus obliquus* with respect to the macro-nutrient phosphorus (P) (Wang et al. 2022d). Furthermore, *S. obliquus* exhibits greater resistance and outcompetes *M. aeruginosa* in freshwater salinization caused by climate change, agriculture, and use of deicing salts (Gao et al. 2023). At different temperatures and P concentrations, *M. aeruginosa* and *C. pyrenoidosa* showed different patterns of competition (Ren et al. 2021). Although *C. pyrenoidosa* predominated at low temperatures and high P concentrations, *M. aeruginosa* suppressed *C. pyrenoidosa* at higher temperatures through more efficient P-uptake systems and allelopathic effects.

Microcystis can be inhibited by the allelopathic effects of eukaryotic microalgae. *Oocystis borgei* competes with *M. aeruginosa* for nutrients and hinders its growth through allelopathic effects, thereby disrupting the membrane system and esterase activity (Wang et al. 2022c). *Scenedesmus* sp. FACHB-1229 produces allelochemicals 1,2-benzenedicarboxylic acid and bis(2-methoxyethyl) ester that suppress *M. aeruginosa* FACHB-3550 and FACHB-905, respectively (Song et al. 2022). However, *Microcystis* also has allelopathic effects on eukaryotic algae such as *S. quadricauda*, *C. pyrenoidosa*, and *Cyclotella meneghiniana* (Wang et al. 2017). Furthermore, the allelopathic effects vary depending on the growth phase of *M. aeruginosa* and species of microalgae, which complicates the practical applications of eukaryotic microalgae in inhibiting *Microcystis* in the field (Wang et al. 2022c).

Zooplankton

Zooplankton and *Microcystis* have miscellaneous interactions, involving not only the grazing of *Microcystis* but also defense against zooplankton (Davis and Gobler 2010; Ger et al. 2014). *Daphnia pulex*, *Hyalella azteca* (Davis and Gobler 2010), *Notodiaptomus iheringi* (Leitao et al. 2018), cyclopoid copepods (Urrutia-Cordero et al. 2015), *Eudiaptomus gracilis*, and *Daphnia magna* (Ger et al. 2018a) are known to graze on *Microcystis*. According to Mohamed et al. (2018), *M. aeruginosa* is completely consumed by *Cyclops vicinus*. The highest grazing rate of *C. vicinus* was observed when the cell density of *M. aeruginosa* peaked. In a hypereutrophic pond, *Daphnia pulicaria* reduced the biomass of *Microcystis* by up to 19.7 times when compared with that of the control (Chislock et al. 2013). However, many zooplankton species cannot graze on *Microcystis* because of three main reasons: (1) As *Microcystis* does not

provide key nutrients (particularly essential fatty acids) to zooplankton, *Cladocera* and *Copepoda* prefer nutrient-rich eukaryotic microalgae over *Microcystis* (Ger et al. 2018a). (2) Zooplankton have difficulty ingesting *Microcystis* cells because of its colonial forms (Geng et al. 2013; Xiao et al. 2018). *Pseudodiaptomus hessei*, *Moina micrura*, *Ceriodaphnia cornuta*, *Brachionus angularis*, *Brachionus falcatulus*, and *Keratella* sp. can digest filamentous cyanobacteria but not the colonial forms (Kâ et al. 2012). (3) *Microcystis* produces various secondary metabolites as a defense mechanism against zooplankton (Harke et al. 2016). For example, trypsin and chymotrypsin derived from *M. aeruginosa* PCC 7806 suppress the activity of digestive proteases in *Daphnia magna* (Agrawal et al. 2005). Xu et al. (2023) observed that *Microcystis* exudates damaged the mitochondrial membrane potential of *Daphnia*, causing impaired mitochondrial function. Microcystin, a notorious cyanobacterial toxin, is also lethal to *Daphnia* (Bownik 2016).

Zooplankton contribute to improved water quality by directly grazing on *Microcystis*, but *Microcystis* colonization presents a significant challenge to this grazing activity (Chislock et al. 2013; Xiao et al. 2018). Under continuous disturbances, *Microcystis* cells form small colonies that are easy to ingest, whereas intermittent disturbances cause them to form larger colonies that are difficult for zooplankton to consume (Yang et al. 2020). Thus, successful control necessitates the simultaneous optimization of numerous environmental conditions (Ger et al. 2018b).

Aquatic plants

Aquatic plants are fundamental primary producers that play a key role in maintaining water clearance in aquatic ecosystems. Macrophytes are regarded as prospective tools for controlling cyanobacterial blooms because they produce chemical compounds that can suppress bloom-forming cyanobacteria (Maredova et al. 2021; Nezbrtytska et al. 2022; Wang and Liu 2023). However, the detailed mechanisms underlying the cyanobactericidal effects have not yet been fully identified. Submerged macrophytes possess distinct allelopathic properties, along with effective nutrient absorption (Maredova et al. 2021; Nezbrtytska et al. 2022; Wang and Liu 2023). The various aquatic plants recognized for their ability to inhibit the growth of *M. aeruginosa* are listed in Table 2.

Among emergent macrophytes, *Typha angustifolia* exhibits its more pronounced inhibitory effects on *M. aeruginosa* than *Acorus calamus* and *Phragmites australis* (Kang et al. 2020; Maredova et al. 2021). *Pistia stratiotes*, a free-floating macrophyte, demonstrates substantial growth inhibition with both aqueous and ethanolic extracts (Lourenção et al. 2021). However, the study conducted by Maredova

Table 2 Summary of *Microcystis* bloom control using aquatic plants

Habitat	Species	Types used in experiments	Effective concentration	Initial cell density of <i>Microcystis</i>	Growth inhibition ^a	Duration	Reference	
Emergent	<i>Acorus calamus</i>	Ethanollic extracts	1% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Phragmites australis</i>	Extracts at different decomposition stages (fresh and dead)	Various levels of EC ₅₀ (mg C/L)		H	0.2, 10, 30, 50, 100 days	Kang et al. (2020)	
	<i>Typha angustifolia</i>	Extracts at different decomposition stages (fresh and dead)	Various levels of EC ₅₀ (mg C/L)		H	0.2, 10, 30, 50, 100 days	Kang et al. (2020)	
Free-floating	<i>Pistia stratiotes</i>	Ethanollic extracts	25 mg/L	2.3 × 10 ⁵ cells/mL	H	6 days	Lourenção et al. (2021)	
		Aqueous extracts	3% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
Rooted floating	<i>Nymphaoides peltata</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
Submerged and floating-leaves	<i>Potamogeton natans</i>	Aqueous extracts	1% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Stratiotes aloides</i>	Ethanollic extracts	3% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h		
Submerged	<i>Ceratophyllum</i>	Ultrasonic cellulose extraction	5 g/L	Around 50 µg Chl- <i>a</i> /L	H	120 h	Li et al. (2023)	
	<i>Ceratophyllum demersum</i>	Aqueous extracts (anaerobic soaking)	3 g/L	1–2 × 10 ⁶ cells/mL	H	15 days	Han et al. (2021a)	
	<i>Ceratophyllum submersum</i>	Ethanollic extracts	1% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Chara globularis</i>	Aqueous extracts	0.1% (200 µL)	1.2 × 10 ⁶ cells/mL	H	72 h	Marekova et al. (2021)	
	<i>Chara tomentosa</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Egeria densa</i>	Organic extracts	0.5, 1, 3, 6 g/L	10 ⁵ cells/mL	H, M, P, P	10 days	Wijesinghe et al. (2023)	
	<i>Elodea canadensis</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Elodea nuttallii</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Hydrilla verticillata</i>	Ethanollic extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Hydrocleys nymphaoides</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Myriophyllum alterniflorum</i>	Aqueous extracts	1% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Myriophyllum heterophyllum</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Myriophyllum spicatum</i>	Extracts	100 mg/L	10 ⁶ cells/mL	H	9 days	Kitamura et al. (2023)	
			Ultrasonic cellulose extraction	5 g/L	Around 50 µg Chl- <i>a</i> /L	H	120 h	Li et al. (2023)
			Ethanollic extracts	100% (200 µL)	1.2 × 10 ⁶ cells/mL	H	72 h	Marekova et al. (2021)
			Plant	5 cm apical shoot (0.42 g dw/L)	471 µg Chl- <i>a</i> /L	H	7 days	Jeong et al. (2021)
			Plant	5 g fw/L	1 × 10 ⁶ cells/mL	H	3 days	Zhu et al. (2010)
			Plant	1 g fw/L	1 × 10 ⁶ cells/mL	H	7 days	He et al. (2016)
			Plant	12 cm apical shoot (2 g fw/L)	4.5 × 10 ⁶ cells/mL	H	12 days	Gao et al. (2022)
		<i>Potamogeton crispus</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)
	<i>Potamogeton praelongus</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Potamogeton pusillus</i>	Aqueous extracts	10% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Vallisneria</i> sp.	Ultrasonic cellulose extraction	5 g/L	Around 50 µg Chl- <i>a</i> /L	H	120 h	Li et al. (2023)	
		Ultrasonic cellulase extraction	5 g/L	Around 50 µg Chl- <i>a</i> /L	H	5 days	Wang et al. (2022a)	
	<i>Vallisneria americana</i>	Aqueous extracts	0.3% (200 µL)	1.2 × 10 ⁶ cells/mL	M	72 h	Marekova et al. (2021)	
	<i>Vallisneria natans</i>	Aqueous extracts (anaerobic soaking)	3 g/L	100–200 × 10 ⁴ cells/mL	H	15 days	Han et al. (2021a)	

^aH, inhibition rate of > 50%; M, inhibition rate < 50%; P, promoting

et al. (2021) indicated that *P. stratiotes*, *Nymphoides peltata*, and *Stratiotes aloides* have only stimulatory effects on cyanobacteria. *Ceratophyllum* and *Chara*, which are submerged macrophytes, exhibit high allelopathic abilities, except *Chara tomentosa*, which has a stimulatory effect (Han et al. 2021a; Li et al. 2023; Maredova et al. 2021). *Egeria*, *Elodea*, and *Hydrocleys* do not hinder the growth of *M. aeruginosa*, whereas *Elodea nuttallii* and *Hydrilla verticillata* have algicidal abilities against *Aphanizomenon gracile* (Maredova et al. 2021; Wijesinghe et al. 2023). Within the genus *Myriophyllum*, *M. spicatum* has strong algicidal effects, whereas *M. alterniflorum* has a stimulatory effect on *Microcystis* (Gao et al. 2022; He et al. 2016; Jeong et al. 2021; Kitamura et al. 2023; Li et al. 2023; Maredova et al. 2021; Zhu et al. 2010). Of the studies on *M. spicatum*, Gao et al. (2022), He et al. (2016), Jeong et al. (2021), and Zhu et al. (2010) directly treated the plant itself. Moreover, *M. spicatum* selectively inhibits the growth of *M. aeruginosa*, exerting a robust effect especially on unicellular cyanobacterial strains, including various *M. aeruginosa* strains and *Synechocystis* sp. (Jeong et al. 2021). *Potamogeton praelongus* is the only species with inhibitory effects in its genus, whereas three other species, including *P. natans* with floating leaves, exhibit stimulatory effects (Maredova et al. 2021). *Vallisneria* demonstrates high growth inhibition of *M. aeruginosa*, except for *V. americana*, which has a stimulatory effect on *Microcystis* but an algicidal effect on *Aphanizomenon* (Han et al. 2021a; Li et al. 2023; Maredova et al. 2021; Wang et al. 2022a).

Most studies have verified the algicidal effects of allelopathic substances extracted from aquatic plants. Whole plants were also effective in controlling blooms in some experiments. To obtain more consistent results for comparison, it is necessary to establish standardized criteria in experimental settings, such as substance concentration, mesocosm volume, and treatment duration. Several recent studies have reported algicidal bacteria isolated from the symbiotic microbiota of aquatic plants (Chen et al. 2023; Imai et al. 2021; Jiang et al. 2019; Miyashita et al. 2019). Further research should consider both the allelopathic effects of the plant and the effects of algicidal bacteria originating from plant biofilms.

Cyanophages

Cyanophages are viruses with a specific affinity for cyanobacteria. Since the identification of SM-1 in 1969, more than 10 cyanophages that infect *Microcystis* have been identified to date (Aranda et al. 2023; Safferman et al. 1969). These cyanophages are categorized into three families: *Myoviridae*, *Siphoviridae*, and *Podoviridae* (Aranda et al. 2023;

Zhu et al. 2023). Previously identified cyanophages such as Ma-LMM01, MaMV-DC, and MaCV-L exhibit highly strain-specific lysis of *Microcystis* (Li et al. 2013; Ou et al. 2013; Yoshida et al. 2006). However, new findings indicate that MaMV-DC infects not only *Microcystis aeruginosa* FACHB-524 but also *M. flos-aquae* TF09 and *M. wesenbergii* DW09 (Wang et al. 2019). Me-ZS1, MinS1, and Mae-Yong924-1 also infect various *Microcystis* species via lysis (Lin et al. 2020; Qian et al. 2022; Zhang et al. 2022a). Morimoto et al. (2023) reported that *M. aeruginosa* interacts with both broad and narrow host-range cyanophages. Broad host-range cyanophages increase with *Microcystis* abundance, whereas narrow host-range cyanophages are less abundant and fluctuate less. Because *Microcystis* blooms typically consist of multiple *Microcystis* strains, strain-specific cyanophages could reveal this issue in field applications. However, the potential of cyanophages for bloom control is increasing, considering the recent isolation of novel broad host-range cyanophages and their observed increase even during the bloom period.

Field applications and limitations of biotechnological approaches

Several biotechnological approaches for inhibiting *Microcystis* have been extensively validated in the laboratory. However, it is crucial to apply these results in the field under varying environmental conditions to determine their efficacy against natural *Microcystis* blooms. Nevertheless, biological methods have fewer field application reports and less impact on controlling natural *Microcystis* blooms than chemical methods. Among the few field applications, *Paucibacter aquatile* DH15, a cyanobactericidal bacterium, successfully removed 90.7% natural *Microcystis* blooms in a 1000-L-scale mesocosm within 2 days, with the microbial and eukaryotic communities monitored during this process (Le et al. 2022b). Notably, an increase in eukaryotic algae was observed following *Microcystis* decline, contributing to the long-term inhibition of *Microcystis* and maintaining a healthy ecosystem by preserving primary production. In addition, periphyton, a mixture of heterotrophic and photoautotrophic microorganisms, effectively reduced *Microcystis* blooms in a field experiment (Le et al. 2023c). This study demonstrated the effectiveness of periphyton not only against *Microcystis* but also against *Dolichospermum* blooms, offering a wide-range potential for various cyanobacterial blooms. Biological algicides derived from cyanobactericidal bacteria are also being used to control *Microcystis* in the field. For example, using biological algicides derived from *Bacillus* sp. T4 as an adsorbent, Park et al. (2024) confirmed the removal of *Microcystis aeruginosa* in

50-L and 10-ton reactors. Paucibactin A produced by *Paucibacter aquatile* DH15 was 91.6% efficient in removing natural *Microcystis* in a 12-L microcosm (Le et al. 2023b).

Field applications to control *Microcystis* blooms using other organisms are less common. Ger et al. (2018b) proved that *Pseudodiaptomus forbesi* ingests *Microcystis* by identifying the microcystin synthase E (*mcyE*) gene in the gut of *P. forbesi* from the upper San Francisco Estuary. Additionally, the *Microcystis mcyE* gene has been detected in the guts of various zooplankton species (*Bosmina* spp., *Daphnia* spp., *Bythotrephes longimanus*, and *Eudiaptomus gracilis*) in the eutrophic Lake Peipsi, Estonia (Agasild et al. 2019). These findings suggest the possibility of using zooplankton to control *Microcystis* in the field. Amorim and Moura (2020) conducted 100-L-scale mesocosms in the Tapacurá reservoir in Brazil, manipulating submerged macrophytes (*Ceratophyllum demersum*), large herbivorous zooplankton, and nutrients. They discovered that the presence of macrophytes, both alone and in combination with zooplankton, significantly reduced cyanobacterial biomass by up to 84.8%. In Chagan Lake, China, the combined restoration of filter-feeding bivalves and submerged macrophyte (*Hydrilla verticillate*) effectively reduced nutrient concentrations and cyanobacterial biomass, thereby alleviating eutrophication (Du et al. 2023).

Through a meta-analysis of field experiments utilizing chemical, bacterial, physical, and/or plant-based treatments, Anantapantula and Wilson (2023) evaluated their effectiveness on the water quality, including parameters such as phytoplankton pigment, cell density, cyanobacterial toxins, and taste/odor compounds. They concluded that only four chemicals, namely, copper sulfate, hydrogen peroxide, peracetic acid, and simazine, were significantly effective in controlling natural blooms and improving water quality. None of the bacterial, physical, or plant treatments alone showed a statistically significant effect. However, the authors emphasized that field data are still limited for drawing firm conclusions. This indicates that sufficient data from large-scale field experiments have not yet been accumulated enough. Therefore, more field experiments are needed to understand the current limitations of each method and to search for better alternatives.

Future directions with genome sequencing and multi-meta-omics

Various biological methods have been introduced, yet their application and success rates in the field remain limited when compared with those of chemical and physical methods. Nevertheless, advances in biotechnological techniques are paving the way for novel approaches to suppress *Microcystis*

from a unique perspective. For instance, *Roseomonas* and *Rhodobacter*, which exhibit a phylosymbiotic pattern with *Microcystis* genotypes, can enrich the metabolic potential of *Microcystis* (Perez-Carrascal et al. 2021). Controlling these symbiotic bacteria could indirectly contribute to reducing *Microcystis* blooms. Furthermore, genome sequencing of *Microcystis* allows for the identification of genetic diversity by examining variations in gene repertoires among different strains, thereby elucidating functional differentiation along the evolutionary route (Zhang et al. 2023b). Moreover, it facilitates the identification of algicidal substances and their mechanisms. For example, lysine is toxic to *Microcystis*, as it blocks peptidoglycan biosynthesis (Kim et al. 2023). Cai et al. (2024) analyzed the gene composition in metagenome-assembled genomes of bloom microbiome in comparison with complete *Microcystis* genomes. They reported that the microbiome and *Microcystis* had complementary biochemical pathways involved in C, N, S, and P cycling.

Research on the periodic succession in microbial communities during *Microcystis* blooms has increased in recent years (Chen et al. 2024; Le et al. 2023a; Smith et al. 2021). These findings offer new insights into the interactions within cyanobacteria-associated bacterial communities, including the specific bacterial communities associated with *Microcystis* genotypes and the diverse responses of successive free-living and particle-attached bacterial communities during different stages of bloom development (Chun et al. 2020; Liu et al. 2019). Network and indicator analyses permit the straightforward identification of bacterial species that interact closely with *Microcystis* and have a high potential for bloom control. This approach is expected to provide innovative strategies for combating blooms effectively. For example, *Vampirovibrionales*, a non-photosynthetic obligate-parasitic cyanobacterium, was first proposed as a bloom terminator on the basis of a network analysis (Chun et al. 2020).

Multi-meta-omics techniques, along with microbial community analyses, allow us to understand the detailed mechanisms underlying cyanobacterial bloom formation and extinction (Wang et al. 2021; Yan et al. 2022). Proteomic and metabolomic studies have identified the metabolic processes of *Microcystis* under various environmental conditions (Huang et al. 2024). Transcriptomics has revealed that allelopathic chemicals derived from plants notably down-regulate essential genes related to biosynthetic pathways for carbohydrate assembly during the carbon fixation cycle and peptidoglycan construction in *M. aeruginosa* (Gil and Eom 2023). In addition, the transcriptomic study by Wang et al. (2024) discovered that *Microcystis* exposed to β -cyclocitral exhibit reduced photosynthetic activity and upregulation of stress-related genes, leading to cell death pathways. These results provide insight into the potential role of biological

metabolites in inducing programmed cell death *Microcystis* to control blooms. Using a multi-meta-omics approach is expected to enhance our understanding of how *M. aeruginosa* responds to different environmental conditions, distinct microbial communities, and coexisting aquatic plants, thereby contributing to breakthroughs in cyanobacterial bloom control.

Concluding remarks

CyanoHABs pose a significant threat to freshwater ecosystems by adversely affecting drinking water quality and agricultural activities. *Microcystis* is responsible for most cyanoHABs globally. This review presents recent findings in biotechnological research on *Microcystis* control, weighs the advantages and disadvantages of each method, and suggests future directions. The biotic agents examined in this review include cyanobactericidal bacteria, fungi, eukaryotic microalgae, zooplankton, aquatic plants, and cyanophages. Among these agents, cyanobactericidal bacteria use both direct lysis of cells and secretion of algicidal compounds to indirectly kill bacteria. Furthermore, newly reported bacteria that use both methods enable the highly efficient control of *Microcystis*. Although numerous biological methods have demonstrated success, their control efficiencies in field applications are generally lower than those of chemical and physical methods. Therefore, a future approach to control *Microcystis* was proposed: a comprehensive understanding of microbial interactions during *Microcystis* blooms by using advanced molecular and bioinformatic/ecoinformatic tools, such as high-throughput sequencing and multi-meta-omics. It is imperative to adopt the latest techniques and apply them more frequently in the field to achieve tangible advancements. Ultimately, we anticipate new insights into the unknown mechanisms surrounding *Microcystis* outbreaks.

Author contribution MK designed the concepts, wrote the manuscripts, and revised it. SJ, SRK, and MSK wrote the sections of diverse biotic agents. CYA designed the concepts, guided the manuscript writing, and revised it. All authors read and approved the manuscript.

Funding This research was supported by the Korea Environmental Industry & Technology Institute (KEITI) through the Aquatic Ecosystem Conservation Research Program (2022003050004), National Research Foundation of Korea (2023R1A2C1003308), and Korea Research Institute of Bioscience and Biotechnology (KRIBB) Research Initiative Program (KGM5252322).

Data Availability Data sharing is not suitable for this mini-review paper because no new data was created.

Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

References

- Agasild H, Panksep K, Tonno I, Blank K, Koiv T, Freiberg R, Laugaste R, Jones RI, Noges P, Noges T (2019) Role of potentially toxic cyanobacteria in crustacean zooplankton diet in a eutrophic lake. *Harmful Algae* 89:101688. <https://doi.org/10.1016/j.hal.2019.101688>
- Agrawal MK, Zitt A, Bagchi D, Weckesser J, Bagchi SN, von Elert E (2005) Characterization of proteases in guts of *Daphnia magna* and their inhibition by *Microcystis aeruginosa* PCC 7806. *Environ Toxicol* 20(3):314–322. <https://doi.org/10.1002/tox.20123>
- Amorim CA, Moura AN (2020) Effects of the manipulation of submerged macrophytes, large zooplankton, and nutrients on a cyanobacterial bloom: a mesocosm study in a tropical shallow reservoir. *Environ Pollut* 265:114997. <https://doi.org/10.1016/j.envpol.2020.114997>
- Anantapantula SS, Wilson AE (2023) Most treatments to control freshwater algal blooms are not effective: meta-analysis of field experiments. *Water Res* 243:120342. <https://doi.org/10.1016/j.watres.2023.120342>
- Aranda YN, Bhatt P, Ates N, Engel BA, Simsek H (2023) Cyanophage-cyanobacterial interactions for sustainable aquatic environment. *Environ Res* 229:115728. <https://doi.org/10.1016/j.envres.2023.115728>
- Arif S, Djebbari N, Belhaoues S, Touati H, Bensouilah M (2023) Spatio-temporal dynamics of cyanobacterial abundance and toxicity in a Mediterranean hypereutrophic lake. *J Oceanol Limnol* 41(5):1834–1848. <https://doi.org/10.1007/s00343-022-1313-0>
- Boonbangkeng D, Treesubsuntorn C, Krobthong S, Yingchutrakul Y, Pekkoh J, Thiravetyan P (2022) Using cell-free supernatant of *Bacillus* sp AK3 in combination with *Chlorella* to remove harmful algal bloom species, TP, TN, and COD from water. *J Environ Chem Eng* 10(6):108645. <https://doi.org/10.1016/j.jece.2022.108645>
- Bownik A (2016) Harmful algae: Effects of cyanobacterial cyclic peptides on aquatic invertebrates—a short review. *Toxicol* 124:26–35. <https://doi.org/10.1016/j.toxicol.2016.10.017>

- Buley RP, Adams C, Belfiore AP, Fernandez-Figueroa EG, Gladfelter MF, Garner B, Wilson AE (2021) Field evaluation of seven products to control cyanobacterial blooms in aquaculture. *Environ Sci Pollut Res* 28(23):29971–29983. <https://doi.org/10.1007/s11356-021-12708-0>
- Burford MA, Carey CC, Hamilton DP, Huisman J, Paerl HW, Wood SA, Wulff A (2020) Perspective: Advancing the research agenda for improving understanding of cyanobacteria in a future of global change. *Harmful Algae* 91:101601. <https://doi.org/10.1016/j.hal.2019.04.004>
- Cai H, McLimans CJ, Jiang H, Chen F, Krumholz LR, Hambright KD (2024) Aerobic anoxygenic phototrophs play important roles in nutrient cycling within cyanobacterial *Microcystis* bloom microbiomes. *Microbiome* 12(1):88. <https://doi.org/10.1186/s40168-024-01801-4>
- Chen S, Haga M, Imai I, Sakai R, Fujita MJ (2023) Function of the algicidal bacterium *Pseudomonas* sp. Go58 isolated from the biofilm on a water plant, and its active compounds, pyoluteorins. *Sci Total Environ* 872:162088. <https://doi.org/10.1016/j.scitotenv.2023.162088>
- Chen Y, Yue Y, Wang J, Li H, Wang Z, Zheng Z (2024) Microbial community dynamics and assembly mechanisms across different stages of cyanobacterial bloom in a large freshwater lake. *Sci Total Environ* 907:168207. <https://doi.org/10.1016/j.scitotenv.2023.168207>
- Chislock MF, Sarnelle O, Jernigan LM, Wilson AE (2013) Do high concentrations of microcystin prevent *Daphnia* control of phytoplankton? *Water Res* 47(6):1961–1970. <https://doi.org/10.1016/j.watres.2012.12.038>
- Chun S-J, Cui Y, Lee CS, Cho AR, Baek K, Choi A, Ko S-R, Lee H-G, Hwang S, Oh H-M, Ahn C-Y (2019) Characterization of distinct cyanoHABs-related modules in microbial recurrent association network. *Front Microbiol* 10:1637. <https://doi.org/10.3389/fmicb.2019.01637>
- Chun S-J, Cui Y, Lee JJ, Choi I-C, Oh H-M, Ahn C-Y (2020) Network analysis reveals succession of *Microcystis* genotypes accompanying distinctive microbial modules with recurrent patterns. *Water Res* 170:115326. <https://doi.org/10.1016/j.watres.2019.115326>
- Dai W, Chen X, Wang X, Xu Z, Gao X, Jiang C, Deng R, Han G (2018) The Algicidal fungus *Trametes versicolor* F21a eliminating blue algae via genes encoding degradation enzymes and metabolic pathways revealed by transcriptomic analysis. *Front Microbiol* 9:826. <https://doi.org/10.3389/fmicb.2018.00826>
- Davis TW, Gobler CJ (2010) Grazing by mesozooplankton and microzooplankton on toxic and non-toxic strains of *Microcystis* in the Transquaking River, a tributary of Chesapeake Bay. *J Plankton Res* 33(3):415–430. <https://doi.org/10.1093/plankt/fbq109>
- Den Uyl PA, Harrison SB, Godwin CM, Rowe MD, Strickler JR, Vanderploeg HA (2021) Comparative analysis of *Microcystis* buoyancy in western Lake Erie and Saginaw Bay of Lake Huron. *Harmful Algae* 108:102102. <https://doi.org/10.1016/j.hal.2021.102102>
- Du X, Song D, Wang H, Yang J, Liu H, Huo T (2023) The combined effects of filter-feeding bivalves (*Cristaria plicata*) and submerged macrophytes (*Hydrilla verticillate*) on phytoplankton assemblages in nutrient-enriched freshwater mesocosms. *Front Plant Sci* 14:1069593. <https://doi.org/10.3389/fpls.2023.1069593>
- Fang F, Gao Y, Gan L, He X, Yang L (2018) Effects of different initial pH and irradiance levels on cyanobacterial colonies from Lake Taihu. *China J Appl Phycol* 30(3):1777–1793. <https://doi.org/10.1007/s10811-018-1394-5>
- Gao Y, Yang H, Dong J, Zhang M, Gao X, Zhang J, Li M, Li X (2022) Growth and photosynthesis responses of microcystin (MC)- and non-MC-producing *Microcystis* strains during co-culture with the submerged macrophyte *Myriophyllum spicatum*. *Water Sci Technol* 86(1):56–65. <https://doi.org/10.2166/wst.2022.166>
- Gao T, Li Y, Xue W, Pan Y, Zhu X (2023) Freshwater salinization impacts the interspecific competition between *Microcystis* and *Scenedesmus*. *Water (Switzerland)* 15(7):1331. <https://doi.org/10.3390/w15071331>
- Geletu TT (2023) Lake eutrophication: control of phytoplankton overgrowth and invasive aquatic weeds. *Lakes Reserv: Sci, Policy Manage Sustain Use* 28(1):e12425. <https://doi.org/10.1111/lre.12425>
- Geng L, Qin B, Yang Z (2013) Unicellular *Microcystis aeruginosa* cannot revert back to colonial form after short-term exposure to natural conditions. *Biochem Syst Ecol* 51:104–108. <https://doi.org/10.1016/j.bse.2013.08.027>
- Ger KA, Hansson LA, Lürling M (2014) Understanding cyanobacteria-zooplankton interactions in a more eutrophic world. *Freshwat Biol* 59(9):1783–1798. <https://doi.org/10.1111/fwb.12393>
- Ger KA, Naus-Wiezer S, De Meester L, Lürling M (2018a) Zooplankton grazing selectivity regulates herbivory and dominance of toxic phytoplankton over multiple prey generations. *Limnol Oceanogr* 64(3):1214–1227. <https://doi.org/10.1002/lno.11108>
- Ger KA, Otten TG, DuMais R, Ignoffo T, Kimmerer W (2018b) In situ ingestion of *Microcystis* is negatively related to copepod abundance in the upper San Francisco Estuary. *Limnol Oceanogr* 63(6):2394–2410. <https://doi.org/10.1002/lno.10946>
- Gil CS, Eom SH (2023) Two different anti-algal control mechanisms in *Microcystis aeruginosa* induced by robinin or tannin rich plants. *Chemosphere* 323:138202. <https://doi.org/10.1016/j.chemosphere.2023.138202>
- Guo Y, Meng H, Zhao S, Wang Z, Zhu L, Deng D, Liu J, He H, Xie W, Wang G, Zhang L (2023) How does *Microcystis aeruginosa* respond to elevated temperature? *Sci Total Environ* 889:164277. <https://doi.org/10.1016/j.scitotenv.2023.164277>
- Han G, Feng X, Jia Y, Wang C, He X, Zhou Q, Tian X (2011) Isolation and evaluation of terrestrial fungi with algicidal ability from Zijin Mountain, Nanjing, China. *J Microbiol* 49(4):562–567. <https://doi.org/10.1007/s12275-011-0496-4>
- Han J, Yin Y, Xu D, Wang H, Yu S, Han D, Niu Y, Xu R (2021a) Growth inhibition and oxidative damage of *Microcystis aeruginosa* induced by aqueous extract of different submerged macrophytes. *Environ Sci Pollut Res* 28(38):53224–53238. <https://doi.org/10.1007/s11356-021-14459-4>
- Han S, Zhou Q, Lilje O, Xu W, Zhu Y, van Ogtrop FF (2021b) Inhibition mechanism of *Penicillium chrysogenum* on *Microcystis aeruginosa* in aquaculture water. *J Clean Prod* 299:126829. <https://doi.org/10.1016/j.jclepro.2021.126829>
- Harke MJ, Steffen MM, Gobler CJ, Otten TG, Wilhelm SW, Wood SA, Paerl HW (2016) A review of the global ecology, genomics, and biogeography of the toxic cyanobacterium, *Microcystis* spp. *Harmful Algae* 54:4–20. <https://doi.org/10.1016/j.hal.2015.12.007>
- He Y, Zhou Q-H, Liu B-Y, Cheng L, Tian Y, Zhang Y-Y, Wu Z-B (2016) Programmed cell death in the cyanobacterium *Microcystis aeruginosa* induced by allelopathic effect of submerged macrophyte *Myriophyllum spicatum* in co-culture system. *J Appl Phycol* 28(5):2805–2814. <https://doi.org/10.1007/s10811-016-0814-7>
- Hou X, Yan Y, Wang Y, Jiang T, Zhang X, Dai X, Igarashi Y, Luo F, Yang C (2023) An insight into algicidal characteristics of *Bacillus altitudinis* G3 from dysfunctional photosystem and overproduction of reactive oxygen species. *Chemosphere* 310:136767. <https://doi.org/10.1016/j.chemosphere.2022.136767>
- Hu L, Shan K, Huang L, Li Y, Zhao L, Zhou Q, Song L (2021) Environmental factors associated with cyanobacterial assemblages in a mesotrophic subtropical plateau lake: a focus on bloom toxicity. *Sci Total Environ* 777:146052. <https://doi.org/10.1016/j.scitotenv.2021.146052>
- Huang S, Chen Y, Wang J, Lao A, Huang H, Wang Z, Luo X, Zheng Z (2024) Understanding the dynamics of *Microcystis* bloom:

- unraveling the influence of suspended solids through proteomics and metabolomics approaches. *Sci Total Environ* 908:168079. <https://doi.org/10.1016/j.scitotenv.2023.168079>
- Huo D, Gan N, Geng R, Cao Q, Song L, Yu G, Li R (2021) Cyanobacterial blooms in China: diversity, distribution, and cyanotoxins. *Harmful Algae* 109:102106. <https://doi.org/10.1016/j.hal.2021.102106>
- Imai I, Inaba N, Yamamoto K (2021) Harmful algal blooms and environmentally friendly control strategies in Japan. *Fish Sci* 87(4):437–464. <https://doi.org/10.1007/s12562-021-01524-7>
- Jeong S, Yang D, Joo S, Park S (2021) Allelopathic inhibition effects of *Myriophyllum spicatum* on growths of bloom-forming cyanobacteria and other phytoplankton species in coexistence experiments. *J Plant Biol* 64(6):501–510. <https://doi.org/10.1007/s12374-021-09322-5>
- Jia Y, Han G, Wang C, Guo P, Jiang W, Li X, Tian X (2010) The efficacy and mechanisms of fungal suppression of freshwater harmful algal bloom species. *J Hazard Mater* 183(1–3):176–181. <https://doi.org/10.1016/j.jhazmat.2010.07.009>
- Jia L, Cheng X, Fang L, Huang X (2023) Flocculation and lysis of *Microcystis aeruginosa* by *Paebubacillus* sp. A9 and inhibition of microcystin release. *Environ Technol Innov* 31:103152. <https://doi.org/10.1016/j.eti.2023.103152>
- Jiang M, Zhou Y, Ji X, Li H, Zheng Z, Zhang J (2019) Responses of leaf-associated biofilms on the submerged macrophyte *Valisneria natans* during harmful algal blooms. *Environ Pollut* 246:819–826. <https://doi.org/10.1016/j.envpol.2018.12.081>
- Kâ S, Mendoza-Vera JM, Bouvy M, Champalbert G, N'Gom-Kâ R, Pagano M (2012) Can tropical freshwater zooplankton graze efficiently on cyanobacteria? *Hydrobiologia* 679:119–138. <https://doi.org/10.1007/s10750-011-0860-8>
- Kang P-G, Hong J, Kim E, Kim B (2020) Effects of extracts of reed and cattail on the growth of a cyanobacterium, *Microcystis aeruginosa*. *J Freshwat Ecol* 35(1):123–134. <https://doi.org/10.1080/02705060.2020.1748128>
- Kim W, Kim M, Park W (2023) Unlocking the mystery of lysine toxicity on *Microcystis aeruginosa*. *J Hazard Mater* 448:130932. <https://doi.org/10.1016/j.jhazmat.2023.130932>
- Kitamura RSA, da Silva ARS, Pagioro TA, Martins LRR (2023) Enhancing biocontrol of harmful algae blooms: seasonal variation in allelopathic capacity of *Myriophyllum aquaticum*. *Water* 15(13):2344. <https://doi.org/10.3390/w15132344>
- Kuzikova I, Zaytseva T, Chernova E, Sazanova A, Sharov A, Medvedeva N (2023) Algicidal activity and microcystin-LR destruction by a novel strain *Penicillium* sp. GF3 isolated from the Gulf of Finland (Baltic Sea). *Toxins* 15(10):607. <https://doi.org/10.3390/toxins15100607>
- Le VV, Ko S-R, Kang M, Lee S-A, Oh H-M, Ahn C-Y (2022a) Algicide capacity of *Paucibacter aquatilis* DH15 on *Microcystis aeruginosa* by attachment and non-attachment effects. *Environ Pollut* 302:119079. <https://doi.org/10.1016/j.envpol.2022.119079>
- Le VV, Ko S-R, Kang M, Park C-Y, Lee S-A, Oh H-M, Ahn C-Y (2022b) The cyanobactericidal bacterium *Paucibacter aquatilis* DH15 caused the decline of *Microcystis* and aquatic microbial community succession: a mesocosm study. *Environ Pollut* 311:119849. <https://doi.org/10.1016/j.envpol.2022.119849>
- Le VV, Kang M, Ko S-R, Jeong S, Park C-Y, Lee JJ, Choi I-C, Oh H-M, Ahn C-Y (2023a) Dynamic response of bacterial communities to *Microcystis* blooms: a three-year study. *Sci Total Environ* 902:165888. <https://doi.org/10.1016/j.scitotenv.2023.165888>
- Le VV, Ko S-R, Kang M, Oh H-M, Ahn C-Y (2023b) Effective control of harmful *Microcystis* blooms by paucibactin A, a novel macrocyclic tambjamine, isolated from *Paucibacter aquatilis* DH15. *J Clean Prod* 383:135408. <https://doi.org/10.1016/j.jclepro.2022.135408>
- Le VV, Ko S-R, Kang M, Shin Y, Lim B, Kang Y-H, Oh H-M, Ahn C-Y (2023c) Periphyton reduces cyanobacterial blooms by promoting potentially cyanobactericidal bacteria. *J Appl Phycol* 35:1285–1299. <https://doi.org/10.1007/s10811-023-02949-6>
- Leitao E, Ger KA, Panosso R (2018) Selective grazing by a tropical Copepod (*Notodiaptomus iheringi*) facilitates *Microcystis* dominance. *Front Microbiol* 9:301. <https://doi.org/10.3389/fmicb.2018.00301>
- Li S, Ou T, Zhang Q (2013) Two virus-like particles that cause lytic infections in freshwater cyanobacteria. *Virologia Sin* 28(5):303–305. <https://doi.org/10.1007/s12250-013-3339-0>
- Li C, Hambright KD, Bowen HG, Trammell MA, Grossart HP, Burford MA, Hamilton DP, Jiang H, Latour D, Meyer EI, Padišák J, Zamor RM, Krumholz LR (2021) Global co-occurrence of methanogenic archaea and methanotrophic bacteria in *Microcystis* aggregates. *Environ Microbiol* 23(11):6503–6519. <https://doi.org/10.1111/1462-2920.15691>
- Li X, Zhao W, Chen J, Wang F (2023) Dosage impact of submerged plants extracts on *Microcystis aeruginosa* growth: from hormesis to inhibition. *Ecotoxicol Environ Saf* 268:115703. <https://doi.org/10.1016/j.ecoenv.2023.115703>
- Lin W, Li D, Sun Z, Tong Y, Yan X, Wang C, Zhang X, Pei G (2020) A novel freshwater cyanophage vB_MelS-Me-ZS1 infecting bloom-forming cyanobacterium *Microcystis elabens*. *Mol Biol Rep* 47(10):7979–7989. <https://doi.org/10.1007/s11033-020-05876-8>
- Liu M, Liu L, Chen H, Yu Z, Yang JR, Xue Y, Huang B, Yang J (2019) Community dynamics of free-living and particle-attached bacteria following a reservoir *Microcystis* bloom. *Sci Total Environ* 660:501–511. <https://doi.org/10.1016/j.scitotenv.2018.12.414>
- Liu F, Zhu S, Qin L, Feng P, Xu J, Zhou W, Wang Z (2022) Isolation, identification of algicidal bacteria and contrastive study on algicidal properties against *Microcystis aeruginosa*. *Biochem Eng J* 185:108525. <https://doi.org/10.1016/j.bej.2022.108525>
- Liu F, Qin L, Zhu S, Chen H, Al-Haimi AANM, Xu J, Zhou W, Wang Z (2023) Applications-oriented algicidal efficacy research and in-depth mechanism of a novel strain *Brevibacillus* sp. on *Microcystis aeruginosa*. *Environ Pollut* 330:121812. <https://doi.org/10.1016/j.envpol.2023.121812>
- Lourenção A, Mecina GF, Cordeiro-Araújo MK, Bittencourt-Oliveira MC, Chia MA, Bronzel-Júnior JL, Granero FO, Silva LP, da Silva RMG (2021) Characterization of allelochemicals from *Pistia stratiotes* extracts and their effects on the growth and physiology of *Microcystis aeruginosa*. *Environ Sci Pollut Res* 28(40):57248–57259. <https://doi.org/10.1007/s11356-021-14658-z>
- Lusty MW, Gobler CJ (2020) The efficacy of hydrogen peroxide in mitigating cyanobacterial blooms and altering microbial communities across four Lakes in NY, USA. *Toxins (Basel)* 12(7):428. <https://doi.org/10.3390/toxins12070428>
- Lyu P, Li H, Zheng X, Zhang H, Wang C, Qin Y, Xia B, Wang D, Xu S, Zhuang X (2022) Oxidative stress of *Microcystis aeruginosa* induced by algicidal bacterium *Stenotrophomonas* sp. KT48. *Appl Microbiol Biotechnol* 106(11):4329–4340. <https://doi.org/10.1007/s00253-022-11959-2>
- Mânica AN, de Lima IR (2023) Seasonal dynamics and diversity of cyanobacteria in a eutrophied Urban River in Brazil. *Water Supply* 23(9):3868–3880. <https://doi.org/10.2166/ws.2023.216>
- Mankiewicz-Boczek J, Morón-López J, Serwecińska L, Font-Nájera A, Gałczowska G, Jurczak T, Kokociński M, Wolska L (2022) Algicidal activity of *Morganella morganii* against axenic and environmental strains of *Microcystis aeruginosa*: compound combination effects. *Chemosphere* 309:136609. <https://doi.org/10.1016/j.chemosphere.2022.136609>
- Maredova N, Altman J, Kastovsky J (2021) The effects of macrophytes on the growth of bloom-forming cyanobacteria: systematic review and experiment. *Sci Total Environ* 792:148413. <https://doi.org/10.1016/j.scitotenv.2021.148413>

- Miyashita Y, Hagiwara T, Imai I (2019) The existence of cyanobactericidal bacteria and growth-inhibiting bacteria on water plants in Lake Ohnuma, Japan. *Limnology* 20(1):39–53. <https://doi.org/10.1007/s10201-018-0542-6>
- Mohamed ZA, Hashem M, Alamri SA (2014) Growth inhibition of the cyanobacterium *Microcystis aeruginosa* and degradation of its microcystin toxins by the fungus *Trichoderma citrinoviride*. *Toxicol* 86:51–58. <https://doi.org/10.1016/j.toxicol.2014.05.008>
- Mohamed ZA, Bakr AA, Ghramh HA (2018) Grazing of the copepod *Cyclops vicinus* on toxic *Microcystis aeruginosa*: potential for controlling cyanobacterial blooms and transfer of toxins. *Oceanol Hydrobiol Stud* 47(3):296–302. <https://doi.org/10.1515/ohs-2018-0028>
- Mohamed ZA, Alamri S, Hashem M, Mostafa Y (2020) Growth inhibition of *Microcystis aeruginosa* and adsorption of microcystin toxin by the yeast *Aureobasidium pullulans*, with no effect on microalgae. *Environ Sci Pollut Res* 27(30):38038–38046. <https://doi.org/10.1007/s11356-020-09902-x>
- Morimoto D, Yoshida N, Sasaki A, Nakagawa S, Sako Y, Yoshida T (2023) Ecological dynamics of broad- and narrow-host-range viruses infecting the bloom-forming toxic cyanobacterium *Microcystis aeruginosa*. *Appl Environ Microbiol* 89(2):1–9. <https://doi.org/10.1128/aem.02111-22>
- Nezbrytska I, Usenko O, Konovets I, Leontieva T, Abramiuk I, Goncharova M, Bilous O (2022) Potential use of aquatic vascular plants to control cyanobacterial blooms: a review. *Water* 14(11):1727. <https://doi.org/10.3390/w14111727>
- Ou T, Li S, Liao X, Zhang Q (2013) Cultivation and characterization of the MaMV-DC cyanophage that infects bloom-forming cyanobacterium *Microcystis aeruginosa*. *Virol Sin* 28(5):266–271. <https://doi.org/10.1007/s12250-013-3340-7>
- Park SB (2012) Algal blooms hit South Korean rivers. *Nature*. <https://doi.org/10.1038/nature.2012.11221>
- Park HK, Lee HJ, Heo J, Yun JH, Kim YJ, Kim HM, Hong DG, Lee IJ (2021) Deciphering the key factors determining spatio-temporal heterogeneity of cyanobacterial bloom dynamics in the Nakdong River with consecutive large weirs. *Sci Total Environ* 755:143079. <https://doi.org/10.1016/j.scitotenv.2020.143079>
- Park BS, Park CS, Shin Y, Yoon S, Han MS, Kang YH (2022) Different algicidal modes of the two bacteria *Aeromonas bestiarum* HYD0802-MK36 and *Pseudomonas syringae* KACC10292^T against harmful cyanobacteria *Microcystis aeruginosa*. *Toxins (Basel)* 14(2):1–12. <https://doi.org/10.3390/toxins14020128>
- Park YH, Kim S, Yun S, Choi Y-E (2024) Enhancement of adsorption of cyanobacteria, *Microcystis aeruginosa* by bacterial-based compounds. *Chemosphere* 361:142430. <https://doi.org/10.1016/j.chemosphere.2024.142430>
- Perez-Carrascal OM, Tromas N, Terrat Y, Moreno E, Giani A, Correa Braga Marques L, Fortin N, Shapiro BJ (2021) Single-colony sequencing reveals microbe-by-microbiome phylosymbiosis between the cyanobacterium *Microcystis* and its associated bacteria. *Microbiome* 9(1):194. <https://doi.org/10.1186/s40168-021-01140-8>
- Qian M, Li D, Lin W, Pan L, Liu W, Zhou Q, Cai R, Wang F, Zhu J, Tong Y (2022) A novel freshwater cyanophage, Mae-Yong924-1, reveals a new family. *Viruses* 14(2):283. <https://doi.org/10.3390/v14020283>
- Ren L, Huang J, Wang B, Wang H, Gong R, Hu Z (2021) Effects of temperature on the growth and competition between *Microcystis aeruginosa* and *Chlorella pyrenoidosa* with different phosphorus availabilities. *Desalin Water Treat* 241:87–111. <https://doi.org/10.5004/dwt.2021.27819>
- Safferman RS, Schneider IR, Steere RL, Morris ME, Diener TO (1969) Phycovirus SM-1: a virus infecting unicellular blue-green algae. *Virology* 37(3):386–395. [https://doi.org/10.1016/0042-6822\(69\)90222-0](https://doi.org/10.1016/0042-6822(69)90222-0)
- Santos AA, Guedes DO, Barros MUG, Oliveira S, Pacheco ABF, Azevedo SMFO, Magalhães VF, Pestana CJ, Edwards C, Lawton LA, Capelo-Neto J (2021) Effect of hydrogen peroxide on natural phytoplankton and bacterioplankton in a drinking water reservoir: Mesocosm-scale study. *Water Res* 197:117069. <https://doi.org/10.1016/j.watres.2021.117069>
- Schweitzer-Natan O, Ofek-Lalzar M, Sher D, Sukenik A (2023) The microbial community spatially varies during a *Microcystis* bloom event in Lake Kinneret. *Freshwat Biol* 68(2):349–363. <https://doi.org/10.1111/fwb.14030>
- Shahmohamadloo RS, Poirier DG, Ortiz Almirall X, Bhavsar SP, Sibley PK (2020) Assessing the toxicity of cell-bound microcystins on freshwater pelagic and benthic invertebrates. *Ecotoxicol Environ Saf* 188:109945. <https://doi.org/10.1016/j.ecoenv.2019.109945>
- Shahmohamadloo RS, Bhavsar SP, Ortiz Almirall X, Marklevitz SAC, Rudman SM, Sibley PK (2023) Lake Erie fish safe to eat yet afflicted by algal hepatotoxins. *Sci Total Environ* 861:160474. <https://doi.org/10.1016/j.scitotenv.2022.160474>
- Smith DJ, Tan JY, Powers MA, Lin XN, Davis TW, Dick GJ (2021) Individual *Microcystis* colonies harbour distinct bacterial communities that differ by *Microcystis* oligotype and with time. *Environ Microbiol* 23(6):3020–3036. <https://doi.org/10.1111/1462-2920.15514>
- Song CY, Bai F, Li TL, Song LR (2022) Inhibitory effect of *Scenedesmus* sp. on *Microcystis aeruginosa* and its evaluation. *Acta Hydrobiologica Sinica* 46(12):1916–1923. <https://doi.org/10.7541/2023.2022.0042>
- Steffen MM, Davis TW, McKay RML, Bullerjahn GS, Krausfeldt LE, Stough JMA, Neitzey ML, Gilbert NE, Boyer GL, Johengen TH, Gossiaux DC, Burtner AM, Palladino D, Rowe MD, Dick GJ, Meyer KA, Levy S, Boone BE, Stumpf RP, Wynne TT, Zimba PV, Gutierrez D, Wilhelm SW (2017) Ecophysiological examination of the Lake Erie *Microcystis* bloom in 2014: Linkages between biology and the water supply shutdown of Toledo, OH. *Environ Sci Technol* 51(12):6745–6755. <https://doi.org/10.1021/acs.est.7b00856>
- Thomalla SJ, Nicholson S-A, Ryan-Keogh TJ, Smith ME (2023) Widespread changes in Southern Ocean phytoplankton blooms linked to climate drivers. *Nat Clim Change* 13(9):975–984. <https://doi.org/10.1038/s41558-023-01768-4>
- Urrutia-Cordero P, Ekvall MK, Hansson LA (2015) Responses of cyanobacteria to herbivorous zooplankton across predator regimes: who mows the bloom? *Freshwat Biol* 60(5):960–972. <https://doi.org/10.1111/fwb.12555>
- Wang T, Liu H (2023) Aquatic plant allelochemicals inhibit the growth of microalgae and cyanobacteria in aquatic environments. *Environ Sci Pollut Res* 30(48):105084–105098. <https://doi.org/10.1007/s11356-023-29994-5>
- Wang Q, Su M, Zhu W, Li X, Jia Y, Guo P, Chen Z, Jiang W, Tian X (2010) Growth inhibition of *Microcystis aeruginosa* by white-rot fungus *Lopharia spadicea*. *Water Sci Technol* 62(2):317–323. <https://doi.org/10.2166/wst.2010.214>
- Wang L, Zi J, Xu R, Hilt S, Hou X, Chang X (2017) Allelopathic effects of *Microcystis aeruginosa* on green algae and a diatom: evidence from exudates addition and co-culturing. *Harmful Algae* 61:56–62. <https://doi.org/10.1016/j.hal.2016.11.010>
- Wang J, Bai P, Li Q, Lin Y, Huo D, Ke F, Zhang Q, Li T, Zhao J (2019) Interaction between cyanophage MaMV-DC and eight *Microcystis* strains, revealed by genetic defense systems. *Harmful Algae* 85:101699. <https://doi.org/10.1016/j.hal.2019.101699>
- Wang Z, Akbar S, Sun Y, Gu L, Zhang L, Lyu K, Huang Y, Yang Z (2021) Cyanobacterial dominance and succession: factors, mechanisms, predictions, and managements. *J Environ Manage* 297:113281. <https://doi.org/10.1016/j.jenvman.2021.113281>
- Wang F, Zhao W, Chen J, Zhou Y (2022a) Allelopathic inhibitory effect on the growth of *Microcystis aeruginosa* by improved ultrasonic-cellulase extract of *Vallisneria*. *Chemosphere*

- 298:134245. <https://doi.org/10.1016/j.chemosphere.2022.134245>
- Wang J, Wei Z-P, Chu Y-X, Tian G, He R (2022b) Eutrophic levels and algae growth increase emissions of methane and volatile sulfur compounds from lakes. *Environ Pollut* 306:119435. <https://doi.org/10.1016/j.envpol.2022.119435>
- Wang X, Zhang Y, Li C, Huang X, Li F, Wang X, Li G (2022c) Allelopathic effect of *Oocystis borgei* culture on *Microcystis aeruginosa*. *Environ Technol* 43(11):1662–1671. <https://doi.org/10.1080/09593330.2020.1847202>
- Wang Z, Xu Y, Yang J, Li Y, Sun Y, Zhang L, Yang Z (2022d) Adverse role of colonial morphology and favorable function of microcystins for *Microcystis* to compete with *Scenedesmus*. *Harmful Algae* 117:102293. <https://doi.org/10.1016/j.hal.2022.102293>
- Wang Z, Lei Y, Liu Q, Sun Y, Zhang L, Huang Y, Yang Z (2023) Long-term acclimation to warming improves the adaptive ability of *Microcystis aeruginosa* to high temperature: Based on growth, photosynthetic activity, and microcystin production. *Environ Pollut* 338:122727. <https://doi.org/10.1016/j.envpol.2023.122727>
- Wang X, Cao H, Zhu Y, Zhou T, Teng F, Tao Y (2024) β -cyclocitral induced rapid cell death of *Microcystis aeruginosa*. *Environ Pollut* 348:123824. <https://doi.org/10.1016/j.envpol.2024.123824>
- Wijesinghe A, Senavirathna M, Fujino T (2023) *Egeria densa* organic extracts: an eco-friendly approach to suppress *Microcystis aeruginosa* growth through allelopathy. *Water Sci Technol* 88(11):2955–2973. <https://doi.org/10.2166/wst.2023.387>
- Xiao M, Li M, Reynolds CS (2018) Colony formation in the cyanobacterium *Microcystis*. *Biol Rev Cambridge Philos Soc* 93(3):1399–1420. <https://doi.org/10.1111/brv.12401>
- Xie W, Li B, Qu J, Zhou X, Su S, Wu C, Xu H (2023) Biodegradation of microcystin using free and alginate-immobilized *Stenotrophomonas geniculata* DMC-X3 bacterium. *Environ Technol Innov* 32:103440. <https://doi.org/10.1016/j.eti.2023.103440>
- Xu J, Chang X, MacIsaac HJ, Zhou Y, Li J, Wang T, Zhang J, Wen J, Xu D, Zhang H, Xu R (2023) Is a lower-toxicity strain of *Microcystis aeruginosa* really less toxic? *Aquat Toxicol* 263:106705. <https://doi.org/10.1016/j.aquatox.2023.106705>
- Yan X, Zhao F, Wang G, Wang Z, Zhou M, Zhang L, Wang G, Chen Y (2022) Metabolomic analysis of *Microcystis aeruginosa* after exposure to the algicide L-lysine. *Bull Environ Contam Toxicol* 110(1):12. <https://doi.org/10.1007/s00128-022-03658-5>
- Yang G, Tang X, Wilhelm SW, Pan W, Rui Z, Xu L, Zhong C, Hu X (2020) Intermittent disturbance benefits colony size, biomass and dominance of *Microcystis* in Lake Taihu under field simulation condition. *Harmful Algae* 99:101909. <https://doi.org/10.1016/j.hal.2020.101909>
- Yang Y, Wang H, Yan S, Wang T, Zhang P, Zhang H, Wang H, Hansson LA, Xu J (2023) Chemodiversity of cyanobacterial toxins driven by future scenarios of climate warming and eutrophication. *Environ Sci Technol* 57(32):11767–11778. <https://doi.org/10.1021/acs.est.3c02257>
- Yoshida T, Takashima Y, Tomaru Y, Shirai Y, Takao Y, Hiroishi S, Nagasaki K (2006) Isolation and characterization of a cyanophage infecting the toxic cyanobacterium *Microcystis aeruginosa*. *Appl Environ Microbiol* 72(2):1239–1247. <https://doi.org/10.1128/AEM.72.2.1239-1247.2006>
- Yu Z, Peng X, Liu L, Yang JR, Zhai X, Xue Y, Mo Y, Yang J (2023) Microbial one-carbon and nitrogen metabolisms are beneficial to the reservoir recovery after cyanobacterial bloom. *Sci Total Environ* 856(Pt 1):159004. <https://doi.org/10.1016/j.scitotenv.2022.159004>
- Zang X, Zhang H, Liu Q, Li L, Li L, Zhang X (2020) Harvesting of *Microcystis flos-aquae* using chitosan coagulation: influence of proton-active functional groups originating from extracellular and intracellular organic matter. *Water Res* 185:116272. <https://doi.org/10.1016/j.watres.2020.116272>
- Zeng G, Gao P, Wang J, Zhang J, Zhang M, Sun D (2020) Algicidal molecular mechanism and toxicological degradation of *Microcystis aeruginosa* by white-rot fungi. *Toxins* 12(6):406. <https://doi.org/10.3390/toxins12060406>
- Zeng H, Tan Y, Wang L, Xiang M, Zhou Z, Chen J-a, Wang J, Zhang R, Tian Y, Luo J, Huang Y, Lv C, Shu W, Qiu Z (2021a) Association of serum microcystin levels with neurobehavior of school-age children in rural area of Southwest China: a cross-sectional study. *Ecotoxicol Environ Saf* 212:111990. <https://doi.org/10.1016/j.ecoenv.2021.111990>
- Zeng Y, Wang J, Yang C, Ding M, Hamilton PB, Zhang X, Yang C, Zhnag L, Dai X (2021b) A *Streptomyces globisporus* strain kills *Microcystis aeruginosa* via cell-to-cell contact. *Sci Total Environ* 769:144489. <https://doi.org/10.1016/j.scitotenv.2020.144489>
- Zhang S, Benoit G (2019) Comparative physiological tolerance of unicellular and colonial *Microcystis aeruginosa* to extract from *Acorus calamus* rhizome. *Aquat Toxicol* 215:105271. <https://doi.org/10.1016/j.aquatox.2019.105271>
- Zhang C, Massey IY, Liu Y, Huang F, Gao R, Ding M, Xiang L, He C, Wei J, Li Y, Ge Y, Yang F (2019) Identification and characterization of a novel indigenous algicidal bacterium *Chryseobacterium* species against *Microcystis aeruginosa*. *J Toxicol Environ Health, A* 82(15):845–853. <https://doi.org/10.1080/15287394.2019.1660466>
- Zhang S, He X, Cao L, Tong Y, Zhao B, An W (2022a) A novel wide-range freshwater cyanophage MinS1 infecting the harmful cyanobacterium *Microcystis aeruginosa*. *Viruses* 14(2):433. <https://doi.org/10.3390/v14020433>
- Zhang Y, Li J, Hu Z, Chen D, Li F, Huang X, Li C (2022b) Transcriptome analysis reveals the algicidal mechanism of *Brevibacillus laterosporus* against *Microcystis aeruginosa* through multiple metabolic pathways. *Toxins (Basel)* 14(7):492. <https://doi.org/10.3390/toxins14070492>
- Zhang H, Xie Y, Zhang R, Zhang Z, Hu X, Cheng Y, Geng R, Ma Z, Li R (2023a) Discovery of a high-efficient algicidal bacterium against *Microcystis aeruginosa* based on examinations toward culture strains and natural bloom samples. *Toxins (Basel)* 15(3):220. <https://doi.org/10.3390/toxins15030220>
- Zhang X, Xiao L, Liu J, Tian Q, Xie J (2023b) Trade-off in genome turnover events leading to adaptive evolution of *Microcystis aeruginosa* species complex. *BMC Genomics* 24(1):462. <https://doi.org/10.1186/s12864-023-09555-3>
- Zhang Y, Lin L, Jia D, Dong L, Pan X, Liu M, Huang H, Hu Y, Crittenden JC (2023c) Inactivation of *Microcystis aeruginosa* by H₂O₂ generated from a carbon black polytetrafluoroethylene gas diffusion electrode in electrolysis by low-amperage electric current. *Environ Pollut* 324:121316. <https://doi.org/10.1016/j.envpol.2023.121316>
- Zhu J, Liu B, Wang J, Gao Y, Wu Z (2010) Study on the mechanism of allelopathic influence on cyanobacteria and chlorophytes by submerged macrophyte (*Myriophyllum spicatum*) and its secretion. *Aquat Toxicol* 98(2):196–203. <https://doi.org/10.1016/j.aquatox.2010.02.011>
- Zhu Y, Chen X, Yang Y, Xie S (2022) Impacts of cyanobacterial biomass and nitrate nitrogen on methanogens in eutrophic lakes. *Sci Total Environ* 848:157570. <https://doi.org/10.1016/j.scitotenv.2022.157570>
- Zhu X, Li Z, Tong Y, Chen L, Sun T, Zhang W (2023) From natural to artificial cyanophages: current progress and application prospects. *Environ Res* 223:115428. <https://doi.org/10.1016/j.envres.2023.115428>