



Review

Biotic control of harmful algal blooms (HABs): A brief review

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ABSTRACT

The water bodies, mainly coastal and lake, remain tainted worldwide, mostly because of the Cyanobacteria harbored in Harmful Algal Blooms (HABs). The main reason for the flourishing of blooms depends on the eutrophication. Blooms could be toxic as well as non-toxic, depending on the bloom-forming species. The blooms affect the water body, aquatic ecosystem and also dependents like human. A large number of organisms, including bacteria, viruses, fungi, fish and zooplankton have adverse effects on Cyanobacteria either through infection, predation or by the production of the algicidal compounds. It was reported, these microorganisms have species-specific interactions and hence differ in their interaction mechanism. The present review emphasises on the role of selected microbial species and the mechanism they follow for mitigation of HABs. Generally lab-scale entities were reported to involve lytic agents, like cyanobacteriolytic substances, released by bacteria. Cyanobacterial species release Cyanotoxins which may affect the water quality. Growing biotic factors in a large quantity and discharging it into the water-body needs excessive efficacy and economic requisite and hence the feasibility of extrapolation of the laboratory results in the field still finds promiscuity towards mitigation of HABs.

1. Introduction

HABs consist of organisms which can severely deplete oxygen levels in natural water systems; it also kills coastal as well as lake life (Anderson et al., 2008). It can last days to months. They are considered to be harmful due to the production of massive biomass and toxins. Therefore, its mitigation measures are catching the eye of environmentalists. A large amount of cell biomass produced due to HABs hinders the light penetration results into decreased density of submerged aquatic vegetation (Anderson, 2009). When these algal blooms start decaying, oxygen consumption increases and also leads to the mortality of aquatic life in the affected area (Berdalet, E et al., 2016). The economic loss due to the presence of HAB occurs over millions of US dollars (Glibert and Pitcher, 2001). Due to the consumption of released algal toxins, about 2000 cases of human poisoning have been reported yearly (Zingone and Enevoldsen, 2000). Although to control HABs, some practices have been recommended up till now. Still, secondary pollution, high cost, and or impracticality, only a few of them are applicable on a larger scale (Anderson, 1997). These toxins could also transmit through the blood-brain barrier as well as the cell membranes and skin

tissue, which makes them even more lethal for life (Kemppainen et al., 1991). Algal blooms can grow fast under some specific conditions. Fig. 1 illustrates intense bloom and poor bloom conditions, where intense bloom required eutrophication, warm water (>15 °C), steady water, little wind, high light, and low salinity. In contrast, poor bloom needs a low flow of nitrogen and phosphorous, cooler water temperature (<15 °C), mixed water, wind, and high salinity.

Blooms are formed in both, marine and freshwater by wide-range of phytoplankton including diatoms, dinoflagellates, and cyanobacteria (Sangolkar et al., 2006; Sangolkar et al., 2009) that float to the surface and accumulate, eliciting water discoloration ranging from greenish to red depending on their species (Bibak and Hosseini, 2013; Sellner et al., 2003). Martin County tests confirmed the presence of algal toxins in St. Lucie River, Florida, United States. These HABs are also found to contaminate the air by the release of toxins (Martin County, 2016 web data). Cyanobacteria, which are already present into the water body, consume nitrogen and phosphorous to flourish. Fig. 2 demonstrates that pollution can affect the submerged water environment due to eutrophication of nitrogen and phosphorus levels. Flourishing algal blooms result in the depletion of oxygen levels, which affects the environment of

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the water body (Wells et al., 2015). Fish and bacteria consume the toxic flourishing algal blooms (Abeyasiriwardena et al., 2018). In such events, many fishes die due to oxygen depletion and toxin production by blooms. The present review is carried out with an objective to focus mainly on different organisms that are used to mitigate different HABs and the possibilities to make it feasible at a larger scale.

It is impervious to develop new techniques to mitigate the harmful effects of HABs (Sun et al., 2004). Solving the problem of HAB mitigation needs numerous regulating methods to be applied (Choi et al., 1998). Chemical agents such as triosyn, hydrogen peroxide (Kim et al., 2007), copper sulfate (Kim et al., 2007) were found competent in a small period of application. Still, it affects aquatic ecosystems (Jeong et al., 2000). Whereas, the biotic factors were favorable for the removal of HABs. In the prevention, termination, and regulation of HABs, they can play a significant role. These microbial populations termed microbial herbicides (Atlas and Bartha, 1986). So, viruses (Garry et al., 1998), protozoa (Sigee et al., 1999), and bacteria (Imai et al., 1995; Kim et al., 2007) are used as biological control agents for specific consideration. It has now broadly acknowledged that bacteria play an important role in regulating the phytoplanktonic biomass in freshwater environments (Maske et al., 2010). Many associated bacteria have algicidal properties and have been responsible for the execution and putrefaction of algal blooms, and many have been responsible for bloom formation (Choi et al., 2005).

The effects of the blooms have been identified in many ways, even in the marine ecosystem. Marine life gets exposed to toxins by ingestion. Therefore, to predict and eliminate the impacts of HABs, some useful techniques are required. Biological control of HABs is seen to be an economically and environment-friendly solution and causes no secondary pollution (Yang et al., 2012). The present review focuses on the different biotic organisms, which were isolated and used to remove HABs (Fig. 3), along with their mode of action. Bacteria are found to use several modes of actions, such as secretion of cyanobacteriolytic substances (Nakamura et al., 2003). Cell to cell contact mechanism (Shunyu et al., 2006), by producing acyl-homoserine lactone signals (Zheng et al., 2015), creating antagonistic volatiles (Wright and Thompson, 1985), by inhibiting photosynthetic electron transport reactions and glycolate dehydrogenase and nitrogenase activity (Sallal, 1993), producing secondary metabolites (Kim et al., 2015), mucous-like secretion from cyanobacteria for self-defense (Yang et al., 2012) and entrapment which brings the lysis of cyanobacteria (Burnham et al., 1984). The advantage of bacterial degradation is that it can target only the prey organisms. The virus typically uses species-specific interaction (Mankiewicz-Boczek et al., 2016), the bursting of cells, and the virus lytic cycle (Pollard and Young, 2010). Viral degradation has the advantage of the

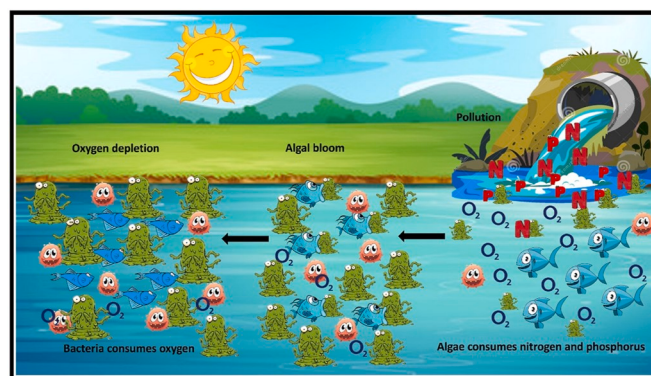


Fig. 2. Illustration of algal bloom formation and oxygen depletion by the end.

species-specific attack. In the case of fungi, direct attack (Han et al., 2011) has been reported. Zooplanktons use grazing (Urrutia-Cordero; et al., 2015) phenomena. Grazing offers the benefit of the removal of invasive species, so fish and zooplankton have the advantage of that. Fishes were used for the ingestion and digestion mechanism and grazing (Xie and Liu, 2001; Görgényi et al., 2016). Ingestion and digestion give the assurance of toxin removal as fish can digest the toxin. Algae have also been reported for bloom control by bio flocculation (Salim et al., 2011). Golden algae have also been reported as a mitigator of Microcystis cells as well as toxin degraders (Zhang et al., 2017). Bio-Flocculation is the method that barely causes any harm to other present entities, so it is also the best way to remove HABs.

Biotic mitigation approach involves several drawbacks, which include in principle, damage restricted to the target organism, the survival of the predator organism, or presence of other predatory organisms, large-scale production of the microbial agent remains a problem, storage and application especially applying a single microbial agent in a field environment (Gumbo et al., 2008). The main challenge of the biotic factor for mitigation is to extrapolate the laboratory proved work into the environment. Different biological factors have their distinct life cycle, hence consigning these biological entities into an environment remains a challenge.

In this review, we are focusing on the factors affecting phytoplanktonic growth, biotic mitigation measures of blooms. Some global success stories of HAB removal and reasons for difficulties in HAB mitigation are also discussed.

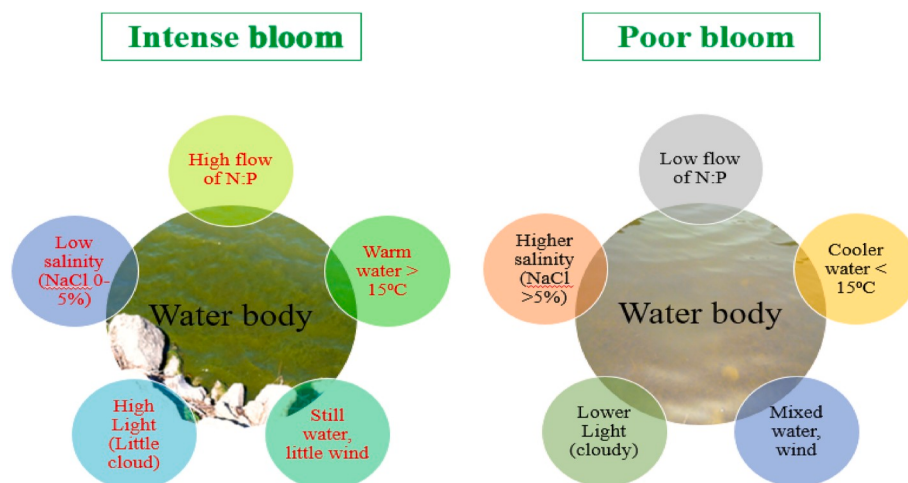


Fig. 1. Prevalence of different conditions for the generation of intense and poor blooms in water bodies.

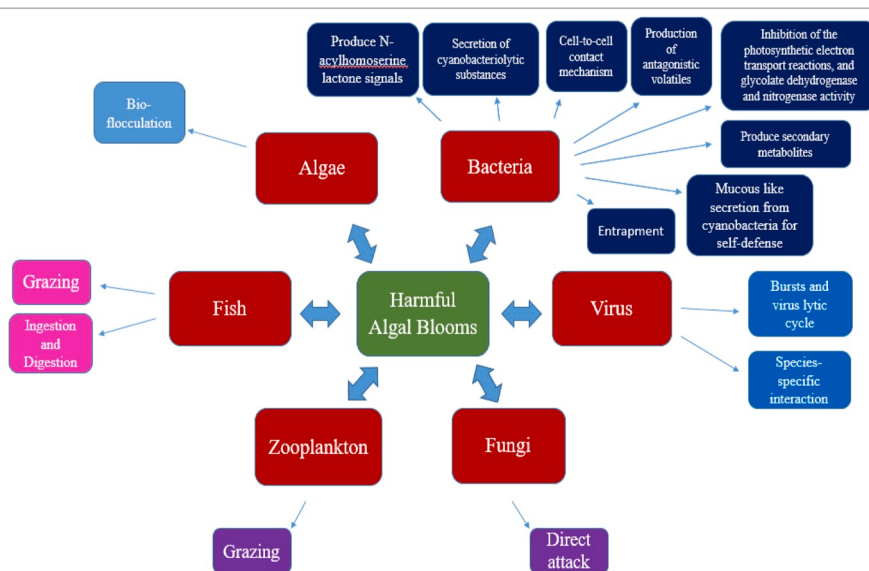


Fig. 3. Interaction events of microorganism with Harmful Algal Blooms for mitigation.

2. Purpose of the research

The present review mainly focuses on different organisms that are used to mitigate different HABs and the possibilities to make it feasible at a larger scale. There are many factors to consider when it comes to field trials, such as an area of the experimental site, location, and climatic conditions, etc. It is highly challenging to maintain laboratory conditions such as temperature, pH, etc. during field trials, and hindrance caused by the presence of other inhibitory biological factors affects the mitigation process.

Another fact is that before taking all the results to extrapolate into the field level, microcosm (<1000litres) or mesocosm (>1000litres) level setup needs to study for feasible assessment. Several studies also reported that the algae cultures cultivated in laboratory conditions are difficult to grow in an open environment. These facts cannot be ignored when discussing environmental issues related to mitigation of HABs.

3. Scope in the optimization of factors associated with cyanobacterial control

While designing effective management strategies for the lake ecosystem, many components need to be taken into consideration such as interannual variability, evaluation of the regional differences in agents and factors that perturb the accessibility of nutrients to bloom (Huo et al., 2019). It was recommended from previous studies that HAB management is challenging for scientists and managers due to rapid changes in the world. Population growth is one of the essential reason which will increase the nutrient enrichment in coastal water for providing food for 30% more people in next 3 decades, resulting in more HABs in some areas also its impacts due to expansion of aquaculture in those reasons which are affected (Anderson, D. 2014).

Suggestions have been made by resource managers and funding agencies regarding the repercussion of the changing perceptions of HABs, which might potentially lead to migration of funds from certain topics such as fundamental ecology, physiology, and others (e.g., prevention, control, and mitigation). Also, the requirements for cost-effective and accurate monitoring data are compulsory. Technological advancement will gradually improve with time for toxin detection and cell, which will facilitate valuable real-time data resulting in improvement in detection and forecasting efforts. There would still be shortcomings when the application of HABs models for long-standing predictions are considered, which can divulge these intricacies and

include the coming climate predictions with precision and accuracy. Gradual improvement in forecasting is needed, but due to its high unreliability, it should not be discouraged at present (Anderson, D. 2014). Overall challenges in research and management of HAB will be there. Still, its impact can be minimized by incorporating tools, technologies, and skilled personnel, and public health and marine resources can be protected like never before (Anderson, D. 2014).

Some of the reports suggest that the relationship between primary productivity and nutrients could be altered by meteorological conditions, which leads to a change in the availability of nutrients to cyanobacteria. There is still scope for optimizing these factors, which include nutrient load, temperature, and geographic regions.

3.1. Nutrient load and temperature

The temperature always plays an essential role in the water-ecosystem (Aljerf, L. 2017). Water temperature correlates with the primary productivity of HABs, which affects the lgTN/lgTP, lgChla relationship (Wang et al., 2016; Liu et al., 2018). An increase in temperature could significantly augment Chlorophyll-a concentration, suggesting that under warmer conditions, lakes could develop a dominant population of cyanobacteria (Liu et al., 2018). In a study, it is reported that temperature variation affects the interaction of physical, chemical, and biological parameters in shallow lakes. In the cyanobacteria communities also, these factors imitate their fluctuating physiological changes (e.g., N-fixation, nutrient uptake capacity, and temperature optima), resulting in consistent differences. It is also reported that microcystin quota shows a positive correlation with the temperature. Understanding the factors that alter *Microcystis aeruginosa* (*M. aeruginosa*) biomass production and to predict its variation along with the genotype composition shifting with climate change are extremely challenging (Wood et al., 2017).

For the prediction of the *M. aeruginosa* growth, various dependable factors such as temperature variations, water quality, nutrient concentration, and molecular quantification of *M. aeruginosa* were measured (Li and Li, 2012). Among all these factors, molecular analysis has been found to be a better predictor of the presence of microcystin (Davis et al., 2009).

3.2. Geographical factors

Many geographic regions are reported where HABs were found like

Great lakes, which includes Lake Erie (US) (Scavia et al., 2019), Ontario (Hanief and Laursen, 2019), Superior, Michigan, Huron (Verschoor et al., 2017). In Huon Estuary in southern Tasmania, Australia, the harmful cyanobacterial bloom of genera *Chattonella* was found (Lovejoy et al., 1998). *Gymnodiniumbreve* Davis, and in the Gulf of Mexico, dinoflagellate was responsible for protracted red tides, were present in the waters of the west Florida shelf (Doucette et al., 1999). It is evident that there is an increase and spreading of phytoplankton bloom globally in the sea; it is also observed that nutrient loading is dependent on biomass composition. Since this autotrophic growth can result only from increased photosynthesis, increased primary production should be a consequence of increased nutrient levels. During nitrification, alteration in the ratio of nutrients was observed, which encourages competition for nutrient-resources among community structure and species. Coastal nutrient enrichment is caused due to riverine inputs in association with different discharge, resulting in new nutrient input eliciting new species/bloom. Therefore the global epidemic of marine phytoplankton blooms occurring presently can be linked to increased primary production rates (= "new" production) accompanying increased nutrient enrichment of coastal waters and inland seas. Global epidemic of phytoplankton was firstly reported on dino-flagellate *Gyrodinium aureolum* European waters, which was previously present in the north-east coast of the U.S. Likewise, there are many species, spread

globally and caused shellfish poisoning and were responsible for global epidemic (Smayda, T. J. 1989). Lake Taihu was also reported for annual cyanobacteria occurrence (Lin et al., 2016). The geographical location generally influences nutrient availability in the lakes, which is an important factor in defining their eutrophication status. Geographical factors (like latitude, altitude, and longitude) could also affect the accessibility of nutrients to algal blooms. Altitude is exceedingly associated with light intensity and human interference. Nutritional availability is found to be higher in the lakes at higher elevations (Huo et al., 2014).

3.2.1. Control agents related to HABs

Many studies have been carried out worldwide to find a better way of controlling HABs. Different biotic factors have been identified to mitigate the option of HABs in the lab scale.

3.3. Bacteria used to mitigate HABs

Phytoplankton and bacterioplankton statistically dominate the coastal and freshwater community (Sarmiento and Gasol, 2012). The most abundant toxic algal strain is *M. aeruginosa*, which always produces microcystins, harmful to aquatic organisms and humans. Microcystins have been reported as tumor-promoting compounds (Zurawell et al.,

Table 1
Removal of harmful algal blooms (HABs) using bacterial control agents.

Predatory bacteria	Habitat/culture bank	Mode of action	Major host phytoplankton	Reference
<i>Bacillus cereus</i>	Lake	Secretion of cyanobacteriolytic substances	<i>Microcystis aeruginosa</i>	Nakamura et al. (2003)
<i>Bacillus</i> sp.	Lake Dianchi China	Cell-to-cell contact mechanism	<i>Aphanizomenon Flos-aquae</i>	Shunyu et al. (2006)
<i>Bacillus</i> sp.	Biosystems immobilized on a sponge	Production of an extracellular product	<i>M. aeruginosa</i>	Pei and Hu (2006)
<i>Bacillus</i> sp.	coastal waters of Zhuhai in China	Secretion of algalytic substance	<i>Phaeocystis globosa</i>	Gerphagnon et al. (2015)
<i>Bdellovibrio</i> -like bacteria	Lake Varese	Penetration	<i>Microcystis aeruginosa</i> (lake)	Caiola and Pellegrini (1984)
<i>Brachy bacterium</i>	Seawater sample	Produce secondary metabolites	<i>A. catenella</i>	Kim et al. (2015)
<i>Cytophaga</i>	Lake Brome Lake, a shallow eutrophic lake in the St. Lawrence Lowlands (72–30' W, 45–15' N;	Direct contact	<i>Microcystis aeruginosa</i>	Rashidan and Bird (2001)
<i>F. flexilis</i> , <i>F. sancti</i>	Domestic sewage.	Inhibition of the photosynthetic electron transport reactions, and glycolate dehydrogenase and nitrogenase activity	<i>Oscillatoria williamsii</i>	Sallal (1993)
<i>M. fulvus</i> BGO2	The roadside ditch on Route 2, Port Clinton, Ohio	Entrapment	<i>Phormidium luridum</i>	Burnham et al. (1984)
<i>M. xanthus</i> PCO2	The roadside ditch on Route 2, Port Clinton, Ohio	Entrapment		Burnham et al. (1981)
<i>Pseudomonas fluorescens</i>	Masan bay of Korea	Indirect attack by alga-lytic substances	<i>Heterosigmaakashio</i>	Kim et al. (2007)
<i>Pseudomonas putida</i>	Lake Chaohu of Anhui Province, China	Inhibit the synthesis of the photosynthetic apparatus.	<i>Microcystis aeruginosa</i>	Zhang et al. (2011)
<i>Pedobacter</i> sp.(Ma11-5)	Lake and water treatment plant	Mucous-like secretion from cyanobacteria for self-defense	<i>Microcystis aeruginosa</i>	Yang et al. (2012)
<i>Raoultella</i> sp. R11	Lake	Dissolved microbial metabolites and humic acid		Su et al. (2016)
<i>Rhodobacteraceae</i> Strain PD-2	Marine	Produce N-acyl-homoserine lactone signals	<i>Prorocentrumdonghaiense</i>	Zheng et al. (2015)
<i>S. neyagawaensis</i>	Sediment of a eutrophic lake (Lake Juam, Korea)	Secretion of extracellular antialgal substances	<i>Microcystis aeruginosa</i>	Choi et al. (2005)
<i>Saprospiraalbida</i>	Lake basin south Africa	Parasitic lysis	<i>Microcystis aeruginosa</i>	Ashton and Robarts (1987)
<i>Streptomyces</i>	Lake of Guangzhou Higher Education Mega Center	Indirect attack by producing algicidal compounds	<i>Microcystis aeruginosa</i>	Luo et al. (2013)
<i>Agrobacterium vitis</i>	Biofilm on the surface of water plants such as <i>Egeria dense</i> and <i>Ceratophyllumdemersum</i> Lake Biwa, Japan	Quorum sensing	<i>Microcystis aeruginosa</i>	Imai et al. (2010)
<i>Rhizobium</i> sp.	Ambazari Lake, Nagpur India	Lysis	<i>Microcystis aeruginosa</i>	Pal et al. (2018)
<i>Methylobacterium zatmanii</i>				
<i>Sandaracinobacter sibiricus</i>				
<i>Halobacillus</i> sp.		bioflocculation	<i>Microcystis aeruginosa</i>	Zhang et al. (2019)

2005). It is found that bacterial agents were genus-specific or species-specific (Rashidan and Bird, 2001), while other predators attack in different diversity of cyanobacteria (Daft et al., 1975). After isolation of first algicidal bacteria, many researchers have focused on finding algicidal bacteria against marine (Kim et al., 2009) and freshwater (Ren et al., 2010) algae. Due to fast reproduction, high efficiency, and host specificity (MU et al., 2007), it is the most promising solution for the removal of HABs.

Two types of bacteria were reported, one as antagonistic towards cyanobacteria called predatory bacteria, and another as toxin-degrading (Table 1). Predatory bacteria make an environmentally friendly solution to HABs. Some factors, like the number of prey-predator and the mechanism of cyanobacterial lysis, were effective biological control approaches (Gumbo et al., 2008). In the laboratory scenario, consortia also show algicidal properties; one study confirmed that, three bacterial strains were showing better algicidal properties as a consortium, whereas one single species alone could show the algicidal property as well as toxin degradation capability (Pal et al., 2018).

Some Cyanobacteria was mitigated using the secretion of cyanobacteriolytic substances by some *Bacillus* sp. Mostly *Bacillus cereus* and (Nakamura et al., 2003), *S. neyagawaensis* (Choi et al., 2005), *Streptomyces* (Luo et al., 2013), *Pseudomonas fluorescens* (Kim et al., 2007) species. *Bdellovibrio*-like bacteria (Caiola and Pellegrini, 1984) use the penetration method to remove *M. aeruginosa*. *Brachy bacterium* (Kim et al., 2015) produce secondary metabolites to lyse *A. catenella*. *F. flexilis*, *F. sancti*, and *Pseudomonas putida* (Zhang et al., 2011) which stops the growth of *Oscillatoria williamsii* (Sallal, 1993) by inhibition of the photosynthetic electron transport reactions, and glycolate dehydrogenase and nitrogenase activity. *M. fulvus* and *M. xanthus* kill *Phormidium luridum* by entrapment of cells. *Pedobacter* sp. secretes some mucus-like secretion as self-defence against *M. aeruginosa*. *Raoultella* sp. removes *M. aeruginosa* by dissolving microbial metabolites and humic acid (Su et al., 2016). *Rhodobacteraceae* strain Produce N-acyl-homoserine lactone signalsto lyse *Prorocentrum donghaiense* (Zheng et al., 2015). *Saprospira albida* uses paracytic lysis to kill *M. aeruginosa* (Ashton and Robarts, 1987). *Agrobacterium vitis* use Quorum sensing to lyse *M. aeruginosa* (Imai et al., 2010). *Sandaracinobacter sibiricus*, *Methyl-obacterium zatmanii* and *Rhizobium* sp. use lytic mechanism to remove *M. aeruginosa* (Pal et al., 2018). Some *Bacillus* sp. use cell-to-cell contact mechanism and production of an extracellular product to remove *Aphanizomenon flos-aquae* (Shunyu et al., 2006) and *M. aeruginosa* (Pei and Hu, 2006; Zhang et al., 2019). Table 1 summarizes about bacterial strains used to remove HABs.

3.4. Cyanophage used to mitigate HABs

Viral treatment may be one of the important factors that can control the HABs (Tucker and Pollard, 2005) both in freshwater and marine water (Bergh et al., 1989), and it is assumed that these are infectious for cyanobacteria (Proctor and Fuhrman, 1990). First isolated cyanophage

was reported about 40 years ago, and after that, several cyanophage strains were isolated. Phage has been mainly responsible for controlling the dynamics of the most abundant aquatic prime producers. Table 2 showed the phage species used to remove HABs. Some cyanophage named SM-1, SM-2, Ma-LBP, Ma-LMM01, MaMV-DC, MaCV-L, and type *Myoviridae* kills *M. aeruginosa* by species-specific interactions (Safferman et al., 1969)(Tucker and Pollard, 2005)(Mankiewicz-Boczek et al., 2016). *Siphoviridae* uses bursts and the virus lytic cycle to lyse *C. raciborskii* (Pollard and Young, 2010). One virus named SAM-1 use to remove broader host by species-specific interaction (Parker et al., 1977). *Cyanostyloviridae* genus and S-PM2 also remove *Lyngbya majuscula* (Hewson et al., 2001) and *Synechococcus* sp. (Mann, 2003) by species-specific interaction. Ma-LEP is the highest lytic cyanophage isolated from Lake Erie, LE (Jiang et al., 2019). A study conducted by (Yoshida et al., 2006) concluded that few phages were reported to be lytic to *M. aeruginosa* (Fox et al., 1976a; Safferman et al., 1969) but were sensitive to *Synechococcus* strain. It is due to the misidentification of *Cyanobacterium*.

Many biological phenomena related to viruses were poorly understood because of host specificity and seasonal issues. For example, several reports suggested that algal viruses often existed at stable numbers, even when their hosts were absent (Suttle, 2000). Reports claimed that summer and spring seasons are showing the high decay rates of cultivated viruses after four-seasons of analysis (Short, 2012). The seasonal study found that the low decay rates of the algal virus during the winter that allowed for the survival of about 126 days under the ice-cover in a frozen freshwater pond (Long, 2017). Another thing is, these agents show high specificity and high efficiency, but it has the limitation of high cost, and it requires upscaled level experiment confirmation (Rashidan and Bird, 2001).

3.5. Fish species used to mitigate HABs

Fish species have always used an option for bloom removal as some fishes can ingest and digest the toxin itself. Bio-manipulation is a promising tool to control HABs for the lake-ecosystem. (Shapiro et al., 1975). Many attempts have been made to decrease cyanobacterial blooms in China and other countries by using filter-feeding fish, like bighead carp, silver carp, which has been proven effective sometimes (Starling, 1993; Xie and Liu, 2001). Ingestion and digestion mechanism used by Tilapia (*Oreochromis niloticus*) for removal of *M. aeruginosa* was studied (Lu et al., 2006; Torres et al., 2016; Moriarty, 1973). Bighead (*Aristichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), and a freshwater mussel (*Hyriopsis cumingii*) use grazing for *M. aeruginosa* removal (Görgényi et al., 2016). Feeding experiments were conducted under laboratory conditions and field testing in Lake Yuehu and other polluted waters in Ningbo China by stocking tilapia showed decreased *M. aeruginosa* blooms. It was observed that Tilapia could ingest and digest a large amount of *M. aeruginosa*. Equivalent results were detected in some other eutrophic waters. Reported studies discovered that

Table 2
Removal of harmful algal blooms (HABs) using phage.

Cyanophage	Habitat	Mode of action	Algae	Reference
SM-1	Lake	Species-specific interaction	<i>M. aeruginosa</i>	Safferman et al. (1969)
SM-2	Lake (Nebraska)	Species-specific interaction	<i>M. aeruginosa</i>	Fox et al. (1976b)
Ma-LBP	Lake baron South	Species-specific interaction	<i>M. aeruginosa</i>	Tucker and Pollard (2005)
<i>Cyanostyloviridae</i> genus	East Queensland, Australia (26° 42'50S, 152° 52'30E)	Species-specific interaction	<i>Lyngbya majuscula</i>	Hewson et al. (2001)
Ma-LMM01	Shallow water regions of Moreton Bay, Australia	Species-specific interaction	<i>M. aeruginosa</i>	Yoshida et al. (2006)
S-PM2	Lake Mikata in Fukui Prefecture, Japan	Species-specific interaction	<i>Synechococcus</i>	Mann (2003)
MaMV-DC	Marine	Species-specific interaction	<i>M. aeruginosa</i>	Ou et al. (2013)
MaCV-L	Lake Dianchi, Kunming, China	Species-specific interaction	<i>M. aeruginosa</i>	Zhang et al. (2013)
SAM-1	Lake Donghu China	Species-specific interaction	<i>M. aeruginosa</i>	Parker et al. (1977)
<i>Myoviridae</i>	Sewage	Species-specific interaction	Broader host range	Mankiewicz-Boczek et al. (2016)
<i>Siphoviridae</i>	Shallow lowland dam reservoir in Central Poland	Species specific interaction	<i>M. aeruginosa</i>	Pollard and Young (2010)
Ma-LEP	Australian freshwater lake	Bursts and virus lytic cycle	<i>C. raciborskii</i>	Jiang et al. (2019)
	Western Lake Erie	mechanical stiffness	<i>M. aeruginosa</i>	

stocking tilapia is an effective way to control algal blooms in eutrophic waters, particularly in lakes where nutrient loading cannot be reduced sufficiently (Lu et al., 2006). Consumption of sea-food is a major source of food-borne illness, due to the activity of HAB-related toxins. The approximate annual budget for acute care for the seafood-borne disease is reported to be two-thirds of a billion dollars (US). The budgetary estimates are conservative as the diagnostic uncertainty and lack of significant data regarding seafood-related illnesses (Grattan et al., 2016). But due to the high toxin production during bloom conditions (Loai and Nuha, 2018), the massive fish kill was reported, as its challenging for fishes to survive in oxygen-poor conditions, which suggest finding another option to remove HABs (Sun et al., 2018). Table 3 showed the fish species used to remove HABs.

3.6. Zooplanktons used to mitigate HABs

Some natural grazing environment is having selective herbivores like cyclopoid, copepods, and calanoid, which affects cyanobacterial growth by lowering cyanobacterial densities (Urrutia-Cordero et al., 2015). Zooplankton shows eco-friendly, contamination-free, and low-cost removal, but it will not use at oxygen-poor conditions. It was found that *Daphnia longispina* can ingest various Cyanobacteria (Urrutia-Cordero et al., 2016). Grazing is one of the main mitigation options for zooplankton, *Daphnia ambigua*, *Eudiaptomus gracilis* shows graze on *M. aeruginosa* (Fulton III and Paerl, 1988; Urrutia-Cordero et al., 2015). *Daphnia hyaline* and *Eudiaptomus gracilis* graze on *Chtorella* (Knisely and Geller, 1986). *Cyclops* sp. and *D. galeata* graze on *Scenedesmus* (Knisely and Geller, 1986). Cyclopoid copepods graze on *Anabaena*, *Microcystis*, and *Planktothrix* species (Urrutia-Cordero et al., 2015). Table 4 showed the zooplankton species able to remove HABs. Some data support the result of grazing experiments related to the suppression of cyanobacterial growth, especially the dominant taxon like *M. aeruginosa* by the potential ability of the natural zooplankton community. It is suggested that lake where algal blooms are present, already present zooplankton community as a grazer could be an intense bloom regulating factor.

3.7. Fungi used to mitigate HABs

Search for fungi with the algicidal ability on cyanobacteria has not been given too much consideration compared to cyanophage and bacteria. In some studies, it was seen that some fungi have algicidal activity, and some findings showed fungi could produce antibiotics to lyse HABs (Jia et al., 2010). For fungal species, direct attack is the mode of action for lysis of Cyanobacterial or algal species (Jia et al., 2010). *Trichaptum abietinum*, *Lopharia spadicea*, *Irpex lacteus*, *Trametes hirsuta*, *Trametes versicolor* and *Bjerkandera adusta* was used to remove *Microcystis* and *Oocystis borgei* (Jia et al., 2010). It was seen that some of the fungal species have the ability to lyse the *M. aeruginosa* in 2 days completely and the degradation of microcystin in 3 days (Han et al., 2011). One marine genetic study shows that different fungal species are responsible for Cyanobacterial formation and collapse. Throughout the initial bloom stage *Hysteropatella*, *Malassezia*, and *Saitoella* were found to be present dominantly, among which *Malassezia* was present abundantly at the onset and peak bloom stage. But at the time of the declined stage, *Saitoella* and *Lipomyces* were found abundant. At the time of termination of

Table 3

Removal of harmful algal blooms (HABs) using fish species.

Fish species	Habitat	Mode of action	Algae	References
Silver carp	Oligo-mesotrophic Lake Balaton (Hungary)	Grazing	<i>Microcystis aeruginosa</i>	(Hui, 1982; Xie and Liu, 2001; Görgényi et al., 2016)
Bighead carp	Lake Donghu	Grazing	<i>Microcystis aeruginosa</i>	(Xie and Liu, 2001; Görgényi et al., 2016)
Tilapia (<i>Oreochromis niloticus</i>)	Lake	Ingestion and digestion	<i>Microcystis aeruginosa</i>	(Lu et al., 2006; Torres et al., 2016; Moriarty, 1973)

Table 4

Removal of harmful algal blooms (HABs) using zooplanktons.

Zooplankton	Habitat	Mode of action	Algae	References
<i>Daphnia ambigua</i>	Lake Ringsjon southern Sweden	Grazing	<i>Microcystis aeruginosa</i>	(Fulton III and Paerl, 1988; Urrutia-Cordero et al., 2015)
<i>Daphnia hyaline</i>	Oberlingersee Lake Constance	Grazing	<i>Chtorella</i>	Knisely and Geller (1986)
<i>D. galeata</i>	Oberlingersee Lake Constance	Grazing	<i>Scenedesmus</i>	Knisely and Geller (1986)
<i>Cyclops</i> sp.	Oberlingersee Lake Constance	Grazing	<i>Chtorella</i>	Knisely and Geller (1986)
<i>Eudiaptomus gracilis</i>	Lake Constance	Grazing	<i>Microcystis aeruginosa</i>	Ger et al. (2016)
<i>Eudiaptomus gracilis</i>	Rauwbraken	Grazing	<i>Anabaena</i> , <i>Microcystis</i> and <i>Planktothrix</i> species	Urrutia-Cordero et al. (2015)
Cyclopoid copepods	Lake Ringsjon southern Sweden	Grazing		

bloom *Rozella* rapidly increased up to 50-60% (Gerphagnon et al., 2015). Table 5 showed some fungi species which have algicidal activity.

3.8. Algae used to mitigate HABs

Algae, as a control agent, uses the bio-flocculation method (Salim et al., 2011). Reports showed that flocculating microalga could be used to concentrate non-flocculating alga of interest. The advantage of this method is that it requires non-addition of any flocculating agent (Salim et al., 2011). In Table 6, species used for algal bloom removal are mention, where *Ankistrodesmus falcatus*, *Scenedesmus obliquus* flocculate *Chlorella vulgaris*, and *Tetraselmis suecica* flocculates *Neochloris oleoabundans* (Salim et al., 2011). A species of golden alga

Table 5

Removal of harmful algal blooms (HABs) using fungi species.

Fungi	Habitat	Mode of action	Algae	References
<i>Trichaptum abietinum</i>	The soil of bamboo forests (Hangzhou, China)	Direct attack	<i>Microcystis aeruginosa</i> , <i>Microcystis flos-aquae</i> , <i>Oocystis borgei</i>	Jia et al. (2010)
<i>Lopharia spadicea</i>	The soil of bamboo forests (Hangzhou, China)	Direct attack	<i>Microcystis aeruginosa</i>	Jia et al. (2010)
<i>Irpex lacteus</i> , <i>Trametes hirsuta</i> , <i>Trametes versicolor</i> , <i>Bjerkandera adusta</i>	Mountain (Nanjing China)	Direct attack	<i>Microcystis aeruginosa</i>	Han et al. (2011)

Table 6
Removal of harmful algal blooms (HABs) using algal species.

Microalgae (floculant)	Habitat	Mode of action	Algae	Reference
<i>Ankistrodesmus falcatus</i>	Freshwater	Bio-flocculation	<i>Chlorella vulgaris</i>	Salim et al. (2011)
<i>Scenedesmus obliquus</i>	Freshwater	Bio-flocculation	<i>Chlorella vulgaris</i>	Salim et al. (2011)
<i>Tetraselmis suecica</i>	Marine	Bio-flocculation	<i>Neochloris oleabundans</i>	Salim et al. (2011)
<i>Poteroiochromonas</i> sp.	Algal repository (FACHB) (Wuhan, Hubei Province, China)	Grazing	<i>M. aeruginosa</i>	Görgényi et al. (2016)

(*Poteroiochromonas* sp. strain ZX1), is identified as a feeding agent for toxic *M. aeruginosa* and also does not affected by cyanotoxin. Densities of *M. aeruginosa* below 10^7 cells mL^{-1} was grazed down by *Poteroiochromonas* sp. (GenBank accession: EU586184), but no significant decrease was reported when the initial density was 3.2×10^7 cells mL^{-1} . The light intensity (0.5 - 2500 lx) and pH of the medium (pH = 5.0 - 9.5) were reported to influence the ZX1 grazing. ZX1 could not survive in continuous darkness for longer than 10 days (Zhang et al., 2009). *Poteroiochromonas* sp. was identified as capable of feeding on the cyanobacterial toxic *Microcystis* sp. (Yang and Kong, 2012; Zhang et al., 2017). The study shows that the feeding experiments of ZX1 could clear high densities of *M. aeruginosa* (7.3×10^5 – 4.3×10^6 cells mL^{-1}) in a short time (40 h), with inhibition ratios higher than 99.9%. ZX1 grew during the feeding processes and achieved a maximum density of 10–20% of the initial *M. aeruginosa* density. Furthermore, the first-ever report on ZX1 reveals that ZX1 can degrade microcystin-LR (MC-LR) in cells of *M. aeruginosa*. For a total MC-LR (intra- and extracellular) concentration of up to 114 mg L^{-1} , 82.7% was removed in 40 h. This reveals that golden algae play an important role in the MC-LR natural transportation/transformation in aquatic microbial ecosystems (Zhang et al., 2008).

4. Some global success stories

Declination in nutrient availability is the key to control cyanobacterial loads for HAB in nutrient-rich waters (Paerl, H. W. 2018), but if eutrophication could be controlled, the story of success will increase up to several folds. Technical and economic incapability's restricts its feasibility in the surface water. There is a requirement of substitutes, which can be fast-acting because cyanobacterial bloom affects the water adversely which is used for drinking, irrigation, aquaculture, industry, and recreation. The inclusion of biological control to mitigation strategies is one of the ways where microbial consortia mainly comprised of *Lactobacillus*, *Lactococcus*, and *Saccharomyces*, which, in conjunction with submerged plants reduces total phosphates, and nitrogen in water (Higa and Parr, 1994). Other ways include plant/tree extracts, golden algae (*Ochromonas*), ultrasonication, and artificial mixing of non-stratifying waters. But these mitigation strategies are mainly sustainable symptomatic treatments of HABs and not for eutrophication relief (Lürling et al., 2016). Golden algae act as a source of nutrition for cyanobacteria (Glimn-Lacy, J., & Kaufman, P. B. 2006). Chrysomonads (*Ochromonas Danica*, *O. minuta*, and *Poteroiochromonas malhamensis*) can be other class of biological control agent that are said to degrade microcystins as they can consume food particles several times bigger in diameter than their own (Zhang et al., 1996) and utilizes cyanobacteria as food (Zhang and Watanabe, 2001). (Park et al., 2017) have suggested that most of the control measure for cyanobacterial bloom has been in controlled laboratory conditions, where ultra-sonication of

Aphanizomenon culture has been proposed in a field reservoir, which reduced up to 90% of the blooms. The study also suggests the difference in effectiveness in laboratory conditions and field conditions. Past studies have enlightened the utility of metabolites from bacteria to up-scale the treatment of HABs (PEI et al., 2007). It has also reported that microcystins in the environment were normally degraded in 5–21 days, though in laboratory experiments, it takes more than five days to detect cyanobacteria (Welker et al., 2001). Few control agents such as L-lysine, anthraquinone-59 (2-[methylaminoN-(10-methylethyl)]- 9,10-anthraquinone monophosphate), biocide Sea Kleen, leachates of *E. equisetina* root and barley straw all are reported to control the target cyanobacteria successfully in the field tests. At the same time, ferulic acid, 9,10 anthraquinone failed to achieve the same (Shao et al., 2013).

5. Some reason for possible pitfalls

It is observed that the relationship between the prey and predator with variation in culture methods found to be the area that required more attention. It has been seen that bacterial cell concentration remains the critical point to consider for control of HABs, which indicates the estimated time (6–7days) to damage the cyanobacteria with a particular cell concentration. But the main fact has been the use of axenic strains of bacteria as well as cyanobacteria for biological control studies, which is feasible in the laboratory. But when it comes to the assessment in the natural environment, similar results could not be achieved, because the isolated candidates never remain in axenic forms in the environment. In field applications, ferulic acid failed to control the cyanobacteria in catfish ponds by spraying at a rate of 0.97 mg L^{-1} . However, the LOEC (lowest-observed-effect concentration) on musty odor cyanobacterium *oscillatoria* cf. *chalybea* (O. cf. *chalybea*) was reported as low as 0.19 mg L^{-1} . The rapid dissipation of this compound from pond waters may be the reason for its failed action. Evaluation of ferulic acid for controlling the musty-odor cyanobacterium, *Oscillatoria perornata*, in aquaculture ponds (Ndlela, L. L et al., 2018). Schrader et al. (1998) reported that the lowest complete inhibition concentration (LCIC) for ferulic acid on O. cf. *chalybea* was 190 mg L^{-1} , three orders of magnitude larger than its LOEC (Shao et al., 2013). The isolates grown in laboratory conditions differ from wild strains, and thus the possible outcomes vary in the environment. Therefore further research on the efficacy of control agents, especially in blooms and its interaction with other species and aquatic lives, is the need of the hour. There is a wide variety of Cyanobacteria species that remains unexplored. It is observed that there are common phyla Firmicutes which has been a control agent, but not reported as frequently as copious under bloom conditions. It has not been extensively explored beyond laboratory conditions while it has some augmentative approach as control agents. To mitigate these bloom, if the mechanism of interaction of cyanobacteria and bio-control agents like the release of lytic substances or extracellular secretion are used, which are biologically derived substances, it could be a good alternative, because it will not grow and disturb the environment, only targeted control will be done (Shao et al., 2013).

6. Conclusion

For the mitigation of HABs, many biological control agents existed that includes bacteria, fungi, phages, zooplankton, etc. The role of selective organisms for remediation of HABs has been imperative, as each organism has a species-specific mode of interaction with algal blooms. However, extrapolation of the biological entities in the environment needs to be addressed. Many reports of laboratory success have been reported, but when it comes to field management, the success rate appears quite low. In conclusion, the present review indicates the possible approach beyond the laboratory application. The progress rate of the biological control agents is at the stall because HABs release a toxin when lysed and adversely affect biological control. This review highlights environmental factors like nutrient conditions, temperatures, and

turbulence as scorable factors that can act as a positive force to enhance mitigation of HABs and control of cyanobacteria. The idea to mitigate such bloom is to use the lytic substances or extracellular secretion, which are biologically derived substances released from bacteria, which in turn could not grow and disturb the environment.

Main finding

Biological options for removal of harmful algal blooms (HABs).

Declaration of competing interest

All authors have mutually agreed to submit this manuscript to this Journal. All the authors declare that they have no conflict of interest.

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