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Review

Advancements in Biological Strategies for Controlling Harmful Algal Blooms (HABs)

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Abstract: Harmful algal blooms (HABs) are a primary environmental concern, threatening freshwater ecosystems and public health and causing economic damages in the billions of dollars annually. These blooms, predominantly driven by phytoplankton species like cyanobacteria, thrive in nutrient-rich, warm, and low-wind environments. Because of the adverse impacts of HABs, this review examines various control methods, focusing on biological strategies as sustainable solutions. While effective in disrupting algal populations, traditional chemical and physical interventions carry ecological risks and can be resource-intensive. Biological control methods, including biomanipulation and using algicidal microorganisms such as *Streptococcus thermophiles*, Myxobacteria, and *Lopharia spadicea*, emerge as eco-friendly alternatives offering long-term benefits. Additionally, barley and rice straw application has demonstrated efficacy in curbing HAB growth. These biological approaches work by inhibiting algal proliferation, disrupting cellular structures, and fostering algal cell aggregation. Despite their advantages over conventional methods, biological controls face challenges, including intricate ecological interactions. This article delves into the latest biological techniques aimed at eradicating HABs, intending to diminish their frequency and reduce toxin levels in aquatic environments. While most research to date has been confined to laboratory settings, scaling these methods to field applications presents hurdles due to the variability and complexity of natural ecosystems. The review underscores the need for further research and development in this critical area of environmental science.

Keywords: algicidal; biological methods; biomanipulation; chemical methods; eutrophication; freshwater ecosystems; harmful algal bloom; macrophytes; physical methods

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1. Introduction

Harmful algal blooms (HABs) are an intensive recurring issue in lakes and along coastlines. They harm aquatic life by utilizing dissolved oxygen, lasting from a few days to months. These blooms are dangerous and comprise a lot of biomass and toxins [1]. Ecologists are exploring a variety of methods to solve this problem. The high biomass content of HABs blocks light in the water, preventing submerged plants from developing. When these blooms decompose, they use even more oxygen, which can deteriorate the state of aquatic life [2]. HABs also result in significant economic distress, leading to multimillion-dollar losses on a global scale [3]. They release toxins that are capable of poisoning about 2000 people every year [4]. There are several methods for controlling HABs; however, they can be costly, pollute the environment, or be challenging to utilize in fields [5]. Only a handful of these strategies are effective on a large scale [6]. The toxins from HABs are dangerous as they can enter into the brain and skin. These HABs harm aquatic organisms and pollute the air when they release toxins [7]. Cyanobacteria, often found in these waters, grow well using nitrogen and phosphorus [8]. Fish and bacteria feed on these toxins, often leading to massive death due to insufficient oxygen and too many toxins [9].

Developing new strategies to counteract the detrimental effects of HABs is essential. Tackling the challenge of HABs mitigation necessitates the adoption of a variety of regulatory approaches [10]. Physical interventions encompass techniques such as nutrient load reduction, sonication, UV-C exposure, soil adjustments, hydrodynamic methods, and diverse filtration processes to mitigate HABs [11]. While most of these are environmentally friendly, they are energy-intensive, potentially rendering them economically impractical for large-scale applications [12]. Chemical treatments such as Triosyn, hydrogen peroxide, and copper sulfate have shown efficacy in short-term use. However, it is vital to acknowledge their adverse effects on aquatic ecosystems [13]. Conversely, biotic factors have been shown to positively influence the removal of HABs, playing a pivotal role in their prevention, cessation, and control. These microbial populations, called microbial herbicides, are instrumental in combating HABs [14].

Biological control agents like viruses, protozoa, and bacteria are utilized for targeted applications. It is now widely acknowledged that bacteria are vital in regulating phytoplankton biomass in freshwater environments [15]. Many bacteria associated with these environments possess algicidal properties, playing a crucial role in the decomposition and decay of algal blooms. In contrast, others contribute directly to bloom formation [16]. The impacts of blooms are evident in various forms, notably within marine ecosystems where marine life is at risk due to toxin exposure through ingestion. This highlights the necessity for effective methods to predict and mitigate the impacts of HABs [17]. The biological control of HABs is a standout solution for its economic and environmental benefits, and also avoids secondary pollution [18].

Bacteria, in particular, have demonstrated various strategies for combating HABs. These include the secretion of cyanobacterial substances, engaging in cell-to-cell contact mechanisms, producing acyl-homoserine lactone signals, generating antagonistic volatiles, inhibiting photosynthetic electron transport reactions and the activities of glycolate dehydrogenase and nitrogenase [19]. They also have secondary metabolites, release mucous-like secretions for self-defense, and use entrapment techniques leading to the lysis of cyanobacteria [19].

Viral degradation employs species-specific interactions, cell bursting, and the virus lytic cycle, offering the benefit of targeting specific species. Fungi have been observed to attack HABs directly [20]. Zooplankton contribute through grazing, a process that aids in removing invasive species and benefits both fish and zooplankton. Fish use an ingestion and digestion mechanism alongside grazing, which is advantageous for toxin elimination as they can digest the toxins. Algae, mainly through flocculation, have shown potential for bloom control [21]. Golden algae have been identified as mitigators of Microcystis cells and as toxin degraders. Bioflocculation is notable for its minimal harm to other organisms, making it an ideal approach for removing HABs [22].

A primary concern in this context is the potential for harm that extends beyond the intended target organism, impacting the survival of predatory organisms and the presence of other predators. Significant challenges arise in the large-scale production of microbial agents, compounded by their storage and application issues. This is particularly evident when introducing a single microbial agent into field settings. A principal obstacle in biotic mitigation lies in translating laboratory-proven methods into practical environmental applications [23]. This involves integrating various biological factors with a distinct life cycle into an ecological setting, posing considerable challenges.

This article will explore the ongoing problem of HABs, investigating their adverse effects on aquatic ecosystems and the challenges they present. While various strategies have been proposed to mitigate HABs, our primary focus will be physical, chemical, and, especially, recent advancements in biological methods. These innovative approaches aim to reduce the occurrence of HABs and effectively lower toxin levels in aquatic environments. We will explore the potential of microbial agents, viruses, fungi, zooplankton, fish, and algae in combating HABs, highlighting their ecological significance and potential benefits.

2. Materials and Methods

This review includes data from experimental research completed over the last 50 years, from 1973 to 2023. We conducted a thorough search of the literature through Scopus, including terms such as "biological control", "algal bloom control", "HAB mitigation", and "natural algae predators". Figure 1 illustrates the prevalent terms found in the studies. It is apparent from the figure that the term "algal bloom" was the most frequently utilized in the articles, appearing over 140 times. Following closely was the term "algae", mentioned approximately 120 times, and "eutrophication", cited around 115 times. The frequency gradually decreases for other terms, with words like "temperature", "physiology", and "humans" being among the least common, each occurring about 15 times, maintaining a similar pattern of presentation.

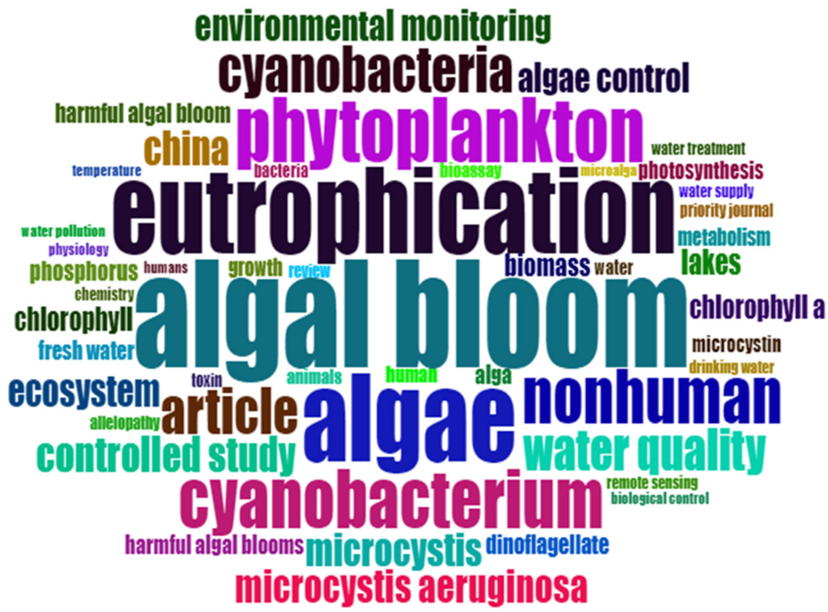

Figure 1. Word map showing the most common keywords.

Remarkably, a significant portion of the studies predominantly concentrated on measures related to biological management and the impact of toxic algal blooms. Figure 2 illustrates the distribution of publications across various journals, with the size of each bar indicating the number of articles published by the respective journals. Notably, journals such as "Phycologia", "Water Research", "Water Science and Technology", "Chemosphere", "Hydrobiologia", "Science of the Total Environment", "Journal of Eukaryotic Microbiology," and "Marine Pollution Bulletin" contributed significantly to the overall publications. Notably, the journal "Environmental Science and Technology" boasts the highest Impact Factor (IF) among the journals listed, scoring 11.4. Following closely is "Science of the Total Environment" with an (IF) of 9.8, and lastly, "Environmental Pollution" holds an (IF) of 8.9. In general, the Impact Factors (IF) across the listed journals ranged from 3.1 to 11.4. These rankings are based on data from the year 2023.

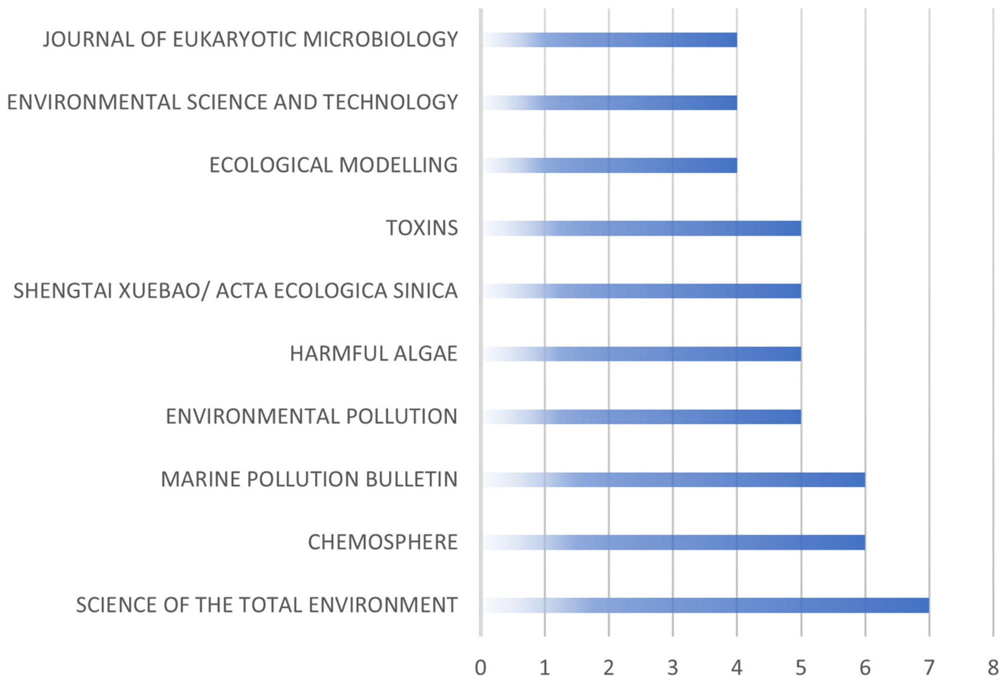

Figure 2. Journals publishing information on biological control methods of HABs.

The intricate network analysis map for publishing countries in this bibliometric analysis is depicted in Figure 3. Each box in the figure represents the number of publications, while the arcs indicate the total link strength to other publishing countries. A substantial number of publications in this study originated from countries such as the United States, China, and Japan. China emerged as the leading publishing country with 75 publications, followed by the United States with 46, and a total of 19 each for Australia and South Korea. Regarding total link strength and illustrating collaborative efforts between countries, the United States exhibited the highest number of links, followed by China, with Germany ranking third in this aspect.

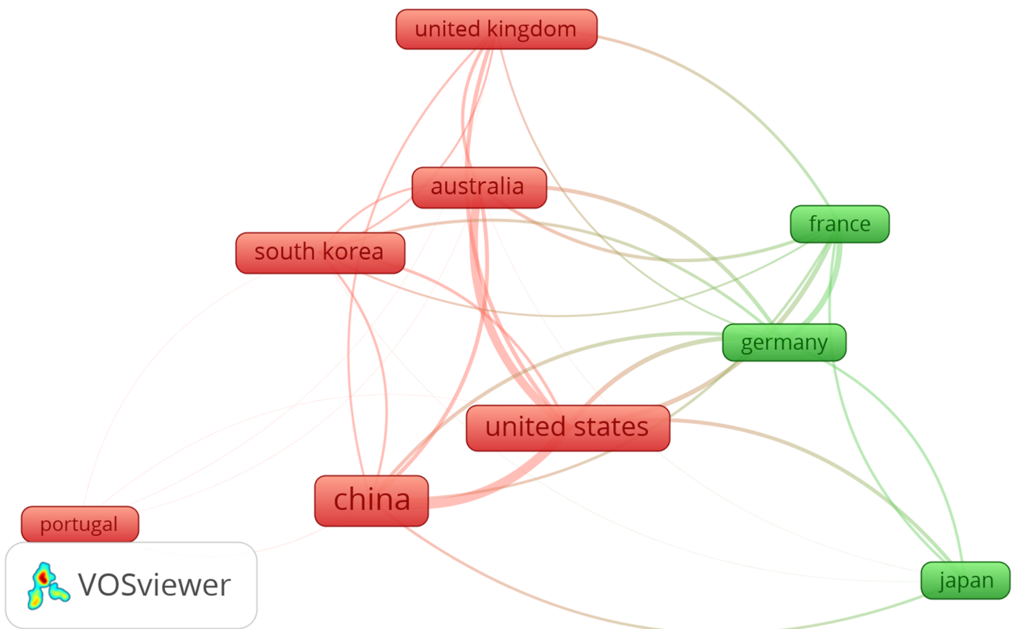

Figure 3. Map of countries with the most significant publications on the topic.

The gathered data underwent careful classification based on the specific biological strategies employed to manage HABs. Among the prominent methods, using bacteria, zooplankton, and other microorganisms to impede algal growth stands out. Toxins generated by toxic algae species, for example, can be broken down by particular bacterial strains. The primary questions driving this meta-analysis are: Which biological control strategies most effectively prevent HABs? Are there any factors in operation that increase or decrease the effectiveness of the biological controls besides environmental parameters such as pH, light intensity, and temperature? Here, our analysis primarily focused on the evaluation of biological control approaches.

3. Causes of Algal Blooms

Phytoplankton depend on light, carbon dioxide, and nutrients to generate biomass. These elements form the basis of food chains by supplying energy and resources. The growth of phytoplankton depends on the proper mix of light and nutrients. This balance in water ecosystems is vital for life support [24]. Also, blooms occur when predators fail to control rising phytoplankton numbers [25]. This can be attributed to a combination of factors that lead to their spread and specific reasons for the proliferation of different algae species [26]. Chakraborty et al. [27] have highlighted common factors like deteriorating water quality, rising eutrophication, intense aquaculture activities, transport of harmful species through ballast water, and climate change. Algal blooms proliferate under certain conditions. Figure 4 shows the difference between heavy and light bloom conditions. Heavy blooms need many nutrients, warm and calm water, little wind, bright light, and not much salt, along with a higher PH and lower dissolved oxygen. Light blooms happen with less nutrients, cooler water, turbulent water, wind, and salt, followed by a lower PH and a higher dissolved oxygen content [28]. Blooms comprise different tiny water plants like diatoms, dinoflagellates, and cyanobacteria, which can grow in the ocean and freshwater. These tiny plants float to the top of the water and gather together, changing the watercolor from green to red, depending on the type of plant [29].

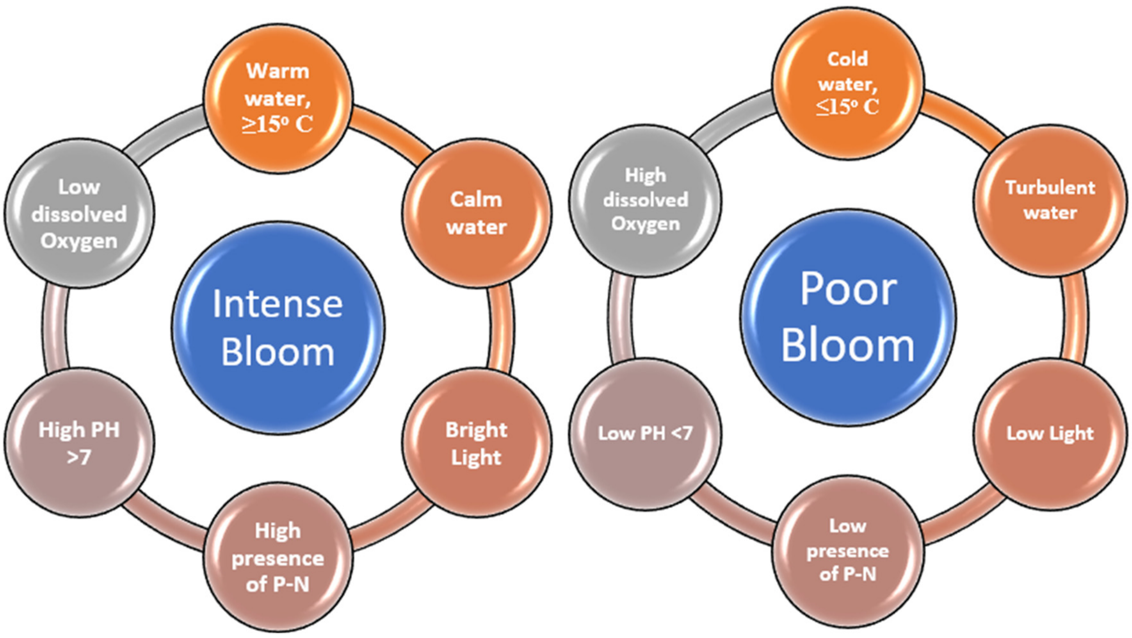

Figure 4. Difference in parameters between intense and poor blooms.

Typically, factors promoting HABs include the rate of introducing species to new areas and local environmental shifts. Such conditions boost the growth of certain species, resulting in HABs. Environmental changes might be minor, and not all factors might shift at once, causing situations where one aspect seems beneficial [30]. Adding a new species to water bodies is not always feasible, as it is contingent on environmental factors and the adaptability of the new species [31]. Human actions are the primary drivers of environmental changes, leading to a rising global trend of HABs. These changes predominantly involve nutrient variations, growth in aquaculture, and major waterway projects [32,33]. Finally, extended stratification periods, rising temperatures, and heightened nutrient input also contribute to a growing prevalence of HABs.

The endeavor to control and handle HABs has been rigorously examined due to their harmful consequences on marine ecosystems. Multiple approaches have been assessed, including chemical, physical, and biological techniques. Figure 5 illustrates a comparative flowchart of these techniques. Each possesses its unique benefits and challenges. This portion elaborates on these methods, highlighting their effectiveness, ecological implications, and practicality in managing HABs.

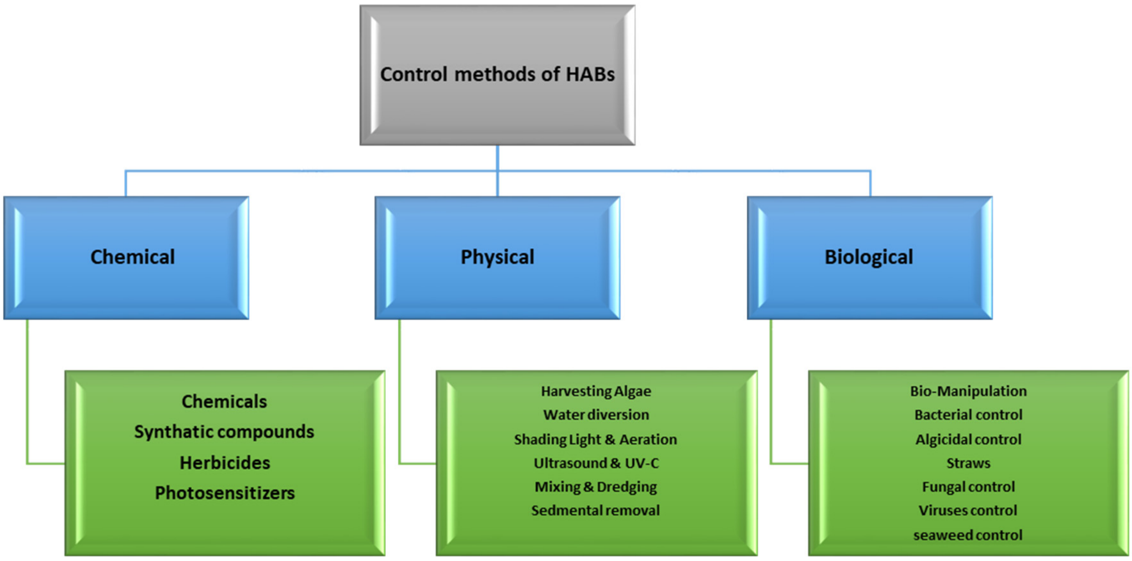

Figure 5. Flowchart of different control methods of HABs.

4. Methods to Control HABs

4.1. Chemical Methods

Chemical methods are a pivotal approach in the battle against HABs, garnering considerable attention for their effectiveness. These strategies primarily involve the application of metals such as copper, iron, and aluminum, recognized for their ability to control algal populations [11]. The core of their efficacy lies in disrupting algal cells, targeting cell membranes, and interfering with essential cellular functions. In addition to these metals, herbicides like atrazine and simazine have been rigorously explored for their capacity to curb algal growth and spread [34]. Photosensitizers, particularly hydrogen peroxide, have also been investigated for their potential to suppress algal proliferation [35].

However, it is crucial to acknowledge and confront the inherent limitations of chemical methods. While offering practical and often cost-effective means to manage HABs, these interventions demand meticulous oversight to mitigate ecological disturbances and related risks [11]. Striking an optimal balance between the advantages of diminishing algal populations and the potential hazards of toxin release is vital, highlighting the necessity for continuous research. Such ongoing investigations are crucial to enhancing our understanding and refining our approaches to addressing the complex challenges posed by HABs [36].

4.2. Physical Methods

Various strategies are classified as physical methods in addressing HABs. These cover techniques include limiting nutrient influx, UV-C exposure, soil condition modifications, hydrodynamic actions, and multiple filtration processes [37]. A practical step in reducing nutrient inputs involves curbing nitrogen and phosphorus levels, as limiting these essential nutrients can hinder the growth of HABs. UV-C exposure offers a method where ultraviolet light disrupts algal cells, rendering them less potent [38,39]. While ultrasonication's large-scale algal control effectiveness remains debated, ultrasound emerges as a promising tool. It is compact, straightforward, and deployable in the field, capable of addressing algae over a considerable area, and its energy demands are moderate. Notably, ultrasonography, unlike chemical methods, is residue-free. Nevertheless, even with supportive evidence for ultrasound's effectiveness in algal control, comprehensive full-scale field tests are scarce, and there are limited data on its commercialization [11]. Soil alteration techniques aim to change the aquatic ecosystem, thus inhibiting algal proliferation. Hydrodynamic processes, in contrast, aim to disperse algal clusters, breaking their unity. Filtration methods work by mechanically extracting algal cells from water. These varied physical tactics provide an environmentally friendly solution with a minimized contamination risk [40]. Dredging proves advantageous in eliminating polluted sediment, yet its expense renders it an impractical approach for managing blooms in most systems [41]. A research review by Faith A. Kibuye et al. summarized that aeration boosted phytoplankton richness, as seen by a more uniform distribution of accessible species, according to long-term monitoring. In addition, there was a shift from cyanophyte dominance to a greater prevalence of cryptophytes [41]. For numerous years, artificial mixing has been employed as a strategy to curb the proliferation of cyanobacteria in eutrophic lakes and reservoirs. This method generally leads to a rise in the oxygen levels within the water [42]. The disruption of the water column and sediment caused by mixing can result in the resuspension of nutrients, leading nutrient-rich pore-water to spread throughout all depths. This nutrient dispersion throughout the water column may enhance algal development, impeding efficient cyanobacterial management [43]. Nonetheless, the limitations of these methods must be acknowledged. Many require significant energy, potentially reducing efficiency and cost-effectiveness, especially in large-scale algal bloom scenarios. The financial implications of their deployment also warrant consideration [43–45].

4.3. Challenges, Monitoring, and Considerations

Though the suggested strategies offer potential remedies for curbing HABs, understanding that each method has intrinsic challenges and constraints is crucial. Chemical techniques, while cost-effective and robust, pose environmental hazards. While eco-friendly, physical processes might demand significant energy and monetary investments. Biological processes, with their ecological advantages, could serve as viable alternatives to these conventional approaches. A detailed juxtaposition of physical, chemical, and natural methods, along with their potential impacts, is provided in Table 1. Moreover, the new analysis focuses on the various tactics nations and commercial companies use to monitor and regulate HABs in coastal waterways [46], which in turn are complementary to appropriate ways to meet the goals of the control methods, as monitoring HABs will allow for the responsible entities to act early and manage cases before they spread widely. Remote biosensors [36], atomic force microscopy [47], matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectrometry (MS), the enzyme-linked immunosorbent test (ELISA) [48], and satellite remote sensing [49] are some examples of these approaches. These techniques have been demonstrated to be helpful in various circumstances.

Table 1. Comparative analysis of methods for combating HABs.

Factors	Chemical	Physical	Biological
Action Mechanism	Utilizing metals like copper, iron, and aluminum disrupts algal cells and interferes with their processes. Employing herbicides (e.g., atrazine, simazine) and photosensitizers (e.g., hydrogen peroxide) against algal growth	Limiting essential nutrients like nitrogen and phosphorus for algal growth. Applying UV-C irradiation and methods like soil modification, hydrodynamic interventions, aeration, dredging, and filtration.	Employing microorganisms (e.g., macrophytes, microalgae, bacteria, viruses) and allelopathic chemicals. Using crop straw (e.g., rice, barley) for HABs control.
Challenges	Risk of environmental toxin release, leading to unintended ecological impacts.	High energy demands, impracticality in large-scale applications, and financial constraints.	Challenges due to complex ecological interactions and potential for unintended outcomes.
References	[50–52]	[25,39,43,53–55]	[43,55–58]

4.4. Biological Management of HABs

Biological techniques are drawing interest due to their environmentally friendly and cost-efficient nature compared to chemical and physical methods. These approaches harness the inherent abilities of diverse microorganisms, such as macrophytes, microalgae, macroalgae, bacteria, viruses, actinomycetes, and pathogens, to regulate HABs. For example, biomanipulation introduces specific biological entities that can outcompete or feed on detrimental algal types [45]. Macrophytes and macroalgae can take up surplus nutrients, thereby curbing algal proliferation. Additionally, several strategies employ bacteria and virus species as tools to destabilize algal communities. Notably, *Streptomyces neyagawaensis emits* particular allelopathic compounds that can stifle the expansion of existing algal cells [59]. Beyond these, recent research has tested crop straws like rice and barley for HABs control [57]. The appeal of biological techniques stems from their eco-compatibility and potential for sustained efficacy. Nevertheless, their use might be constrained by challenges such as grasping intricate ecological dynamics and the possibility of unforeseen repercussions [58]. The present review focuses on the different biotic organisms isolated and used to remove HABs and their mode of action.

4.4.1. Biomanipulation

Biomanipulation is a method of bioengineering aimed at mitigating algal overgrowth by modifying the dynamics within an ecosystem. This technique strategically imposes ecological stress on phytoplankton populations to curb the proliferation of unwanted algal forms [60]. Additionally, it adjusts the predatory impact of fish on zooplankton populations, promoting the prevalence of larger zooplankton species within the ecological hierarchy. Two primary methods are employed to regulate fish populations conducive to biomanipulation: eradicating zooplanktivorous fish species and introducing *Piscivorous* species, such as silver carp, into the aquatic environment [61].

Recent advancements in the field have highlighted the potential of algal phytoremediation systems, such as algal turf scrubbers, to effectively sequester nutrients from eutrophic surface waters. These systems help manage nutrient levels and carbon sequestration, benefiting ecosystem management efforts [62]. Furthermore, studies have pointed out the imbalance in global nutrient cycles, with more excellent phosphorus retention over nitrogen in lakes, which could exacerbate the challenge of controlling algal blooms [63].

The baseline effort for effective fish capture is categorized by a substantial reduction of 75–80% over several years or a consistent removal rate of 200 kg per hectare over three years. A notable study has introduced a mathematical model specifically for temperate, shallow lakes to estimate the necessary annual fish capture using the formula:

Required annual catch (kg per hectare) = $6.9 \times TP^{0.52}$, where TP denotes the total phosphorus concentration in milligrams per liter [64]. The study further suggests that the annual catch requirements for deeper lakes may be less stringent than those for their shallower counterparts. While biomanipulation is considered a viable alternative to nutrient restriction methods, its effectiveness is contingent upon various factors, including the dynamics of fish populations, the resilience of the ecosystem, and effective nutrient management practices. Ensuring the enduring success of biomanipulation demands a holistic approach to ecosystem management that extends beyond mere trophic-level adjustments [61].

Furthermore, research by Gallardo-Rodríguez et al. [40] and colleagues has indicated that the efficacy of biomanipulation is notably enhanced when it is part of a broader strategy that includes comprehensive nutrient reduction. An illustrative case is Lake Vesijärvi in Finland, where implementing nutrient management, coupled with the targeted fishing of *Planktivorous coregonid* fish, led to a marked decrease in phytoplankton biomass, thereby serving the public interest [65]. Acknowledging that biomanipulation is often advocated as a cost-efficient substitute for conventional eutrophication management practices is critical [66]. Nonetheless, various studies have highlighted this approach's intricate and sometimes unpredictable outcomes, with large grazers sometimes only offering a temporary decrease in algal biomass. Recent research underscores the importance of a season-based pollutant management strategy, which is cost-effective in controlling algal blooms in response to future climate changes [67].

Longevity of Biomanipulation

The influence of the persistence of biomanipulation on aquatic ecosystems, particularly its role in mitigating HABs and bolstering water quality, is subject to a complex interplay of factors. The resilience of the ecosystem, the influx of nutrients, the dynamics between predators and prey, and climatic conditions all contribute to the enduring and immediate outcomes of biomanipulation efforts [68]. For the longevity of these effects, proactive measures such as continuous monitoring and the capacity to adapt to changing conditions are critical [43]. Furthermore, adopting sustainability initiatives, like enacting policies to curtail nutrient pollution, is vital for securing the long-term advantages of biomanipulation. In essence, the sustained success of biomanipulation depends on ecological, environmental, and managerial considerations, necessitating a comprehensive approach to ecosystem stewardship [68].

Biomanipulation is predominantly applied in Europe's small and shallow lakes, where it is advised to significantly curtail the population of certain fish species within one to two years to affirm its lasting effect. It promotes the development of juvenile fish capable of evolving into piscivores upon reaching maturity [69]. A study conducted on a 14.8 square kilometer section of a Swedish lake serves as a testament to the impressive results achievable through biomanipulation [67]. Here, Ekvall et al. observed that the extraction of cyprinid fish led to reduced predation on zooplankton communities, which sparked a 55% surge in the population of *Daphnia* sp. [70]. This increase in *Daphnia* numbers subsequently drove a considerable decline in the biomass of toxin-producing cyanobacteria. This marked improvement culminated in repeated treatments initiated a decade following the first biomanipulation effort. Despite this, the impact of the initial biomanipulation began to diminish over five years [71].

Moreover, the long-term impact of biomanipulation has been linked with external phosphorus load. Internal nutrient management has also been shown to sustain the effects of biomanipulation for up to seven years, as delineated by Jůza et al. [72].

Determinants of Biomanipulation Efficacy

The success of biomanipulation as a treatment strategy is governed by an intricate array of factors. Achieving an optimal equilibrium between herbivorous species' feeding rates and cyanobacteria's reproductive rates is essential for effectively mitigating HABs [68]. The objective is for biomanipulation to exert a uniform effect on the diverse characteristics of cyanobacteria [40]. However, should cyanobacteria's reproductive rate surpass herbivores' grazing capabilities, the system may need to be revised. Studies have demonstrated that strategically removing non-predatory fish and introducing *Piscivorous* species can significantly amplify the grazing pressure exerted by zooplankton [73]. This intensification in grazing curtails cyanobacterial proliferation and coincides with a decrease in nutrient recycling, thereby exerting a dual effect on controlling cyanobacterial growth in shallow lakes. De Backer et al. [74] have further corroborated the pivotal role of nutrient management in suppressing cyanobacterial blooms.

Environmental Conditions and Weather

The interplay of climate and weather patterns significantly shapes the efficacy and longevity of biomanipulation strategies. Variations in climate temperatures can profoundly influence the layering of water bodies, which, in turn, dictates the spatial arrangement of plankton and fish populations [75]. In scenarios where warmer temperatures induce extended periods of water stratification, conditions may become more conducive to the proliferation of HABs [76]. Moreover, the patterns of precipitation, ranging from intense rainfall to prolonged droughts, play a critical role in modulating the influx of nutrients into aquatic systems, which can either bolster or undermine biomanipulation efforts [77]. The occurrence of storm events is another vital factor, with the potential to significantly alter water quality and the dynamics of nutrient distribution, thereby affecting the success of biomanipulation interventions.

Additionally, wind patterns are instrumental in mixing aquatic environments, which can lead to shifts in species distribution [78]. The overarching challenge of climate change introduces additional layers of complexity, underscoring the need for biomanipulation strategies that are robust and adaptable. Consequently, integrating climate and weather variables is indispensable for a comprehensive assessment of the enduring impact of biomanipulation techniques [79].

4.4.2. The Role of Submerged Macrophytes in Eutrophication Control

Submerged macrophytes, the foundational autotrophs of lacustrine systems, play a pivotal role in mitigating eutrophication through their interactions with living and non-living elements of shallow aquatic environments [80]. These plants are formidable competitors for nutrients, often outcompeting phytoplankton for these vital resources. Macrophytes are especially crucial in ecosystems burdened with high nutrient loads, as they can effectively regulate nutrient availability [81]. The functions of submerged macrophytes are multifaceted. Primarily, they sequester nutrients from the sediment and the overlying water, thereby imposing a state of nutrient scarcity that can suppress cyanobacterial growth. In addition, macrophytes provide refuge for zooplankton populations, which serve as herbivores that graze on phytoplankton, thereby indirectly curtailing the expansion of cyanobacteria and promoting a zooplankton-dominated system [82]. Lastly, macrophytes synthesize and release allelochemicals—distinctive secondary metabolites with the capacity to inhibit phytoplankton proliferation—thus further restraining the growth of cyanobacteria [82].

The strategic deployment of macrophytes in the management of cyanobacterial populations demands a comprehensive understanding of several factors: the necessity for sufficient coverage of macrophytes, the persistence and efficacy of allelochemicals within the aquatic milieu, and the susceptibility of specific cyanobacterial species to these biochemical inhibitors [83].

Utilization of Natural and Engineered Macrophytes

Aquatic plants that thrive beneath the water's surface, featuring fully submerged foliage and stems, serve as excellent natural macrophytes for extracting excess nutrients from nutrient-rich lakes. Beds of eelgrass, for instance, are not only highly productive but also support a wide array of marine life. They are instrumental in absorbing nutrients from the water, thereby preventing the overgrowth of phytoplankton in eutrophic coastal zones by reducing nutrient availability [84]. Additionally, these plants offer a habitat for a variety of aquatic organisms. Similarly, with its elongated, tape-like leaves, *Vallisneria* excels in nutrient absorption, particularly within freshwater systems [84]. Conversely, *Elodea* species are distinguished by their rapid growth and substantial nutrient uptake capabilities, which benefit nutrient removal [79].

Beyond natural plant solutions, engineered macrophytes also play a role in eutrophication management. Floating treatment wetlands (FTWs) are deployed effectively in highly and moderately nutrient-enriched waters to curb the progression of algal blooms and the associated shifts in water chemistry, such as significant pH level increases [85].

The Impact of Macrophyte Density on Algal Suppression

The presence of macrophyte canopies plays a pivotal role in mitigating eutrophication. Notable declines in the levels of nutrients, water cloudiness, and chlorophyll-a have been documented in areas where *Ceratophyllum demersum* L. establishes a 20–50% coverage [86]. Additional studies have corroborated the beneficial link between the abundance of macrophytes and the clarity of the water body. For example, a macrophyte cover exceeding 25% of a lake's surface is associated with reduced algal biomass [87]. Furthermore, increased macrophyte coverage within lakes correlates with improved conditions, such as greater water transparency [88].

Allelopathic Dynamics in Aquatic Ecosystems

Macrophytes contribute to aquatic ecosystems through allelopathic interactions by sustainably releasing bioactive compounds that suppress phytoplankton biomass. Research by Declerck et al. [80] highlighted that *Elodea nuttallii* exerted a significant allelopathic influence on microalgal populations, with the suppression enduring beyond 50 days. Similarly, Švanys et al. [81] observed that in the Curonian Lagoon *Myriophyllum spicatum*'s presence negatively impacted microalgal growth under nutrient-rich conditions.

Further studies have demonstrated that *Stratiotes aloides* can markedly reduce microalgal proliferation, with in situ experiments showing a 60% decrease in cyanophyte presence and a 73% reduction in overall phytoplankton [82]. A field study in Lake Krumme Laake, Berlin, attributed a decline in microalgal biomass to the allelopathic influence of *Myriophyllum verticillatum*, reinforcing macrophytes' significant role in regulating algal populations.

Zhu et al. [82] conducted an analysis using high-performance liquid chromatography (HPLC) to pinpoint phenolic compounds in macrophytes that were effective against *Chlorella* sp. and *Anabaena* sp., both of which are known contributors to harmful algal blooms.

Notably, many field studies focusing on these allelopathic effects are situated in shaded and still water environments, which are more prone to harmful algal bloom occurrences [88].

4.4.3. Utilizing Straw to Combat Harmful Algal Blooms

The emergence of cyanobacterial blooms poses significant ecological and public health challenges by releasing toxins detrimental to marine life and humans and compromising water quality [70]. The strategic application of organic matter, such as barley and rice straw, has been recognized as an innovative method to manage these cyanobacterial outbreaks. Notably, barley straw has been singled out for its effectiveness in mitigating the growth of cyanobacteria [40].

Mechanism of Action

The proposed mechanism behind barley straw's success in curbing cyanobacterial growth involves the release of allelopathic substances during its aerobic breakdown [84].

Allelopathy describes the biochemical interactions between plant species, where the compounds produced by one can affect the growth of another. In the presence of oxygen, barley straw decomposes to produce chemicals believed to suppress cyanobacteria's expansion [83].

The disintegration of straw in water bodies can increase the oxygen demand. Maintaining oxygen-rich conditions is crucial to ensure the method's efficacy. In scenarios where dissolved oxygen (DO) levels are low, the anti-algal properties of the straw may be compromised. However, ponds with aeration systems have shown more promising results [83]. These aeration systems are vital in preserving oxygen levels to continue the algae-inhibitory effects during straw decomposition [40].

For example, studies targeting the control of *Anabaena flosaquae* have demonstrated that barley straw can significantly curtail algal proliferation. Gallardo-Rodríguez et al. [40] observed a notable reduction in DO levels when straw decayed without sufficient aeration, underscoring the importance of proper oxygenation to balance effective algae management and acceptable oxygen concentrations in water bodies.

Over the last ten years, research by Gallardo-Rodríguez et al. [40] has suggested that compounds such as hydrogen peroxide (H_2O_2) may be produced during the photooxidation of substances like lignin and quinone, which are byproducts of barley straw decomposition, as depicted in Figure 6. The exact processes remain elusive, necessitating further investigation to elucidate the underlying mechanisms fully.

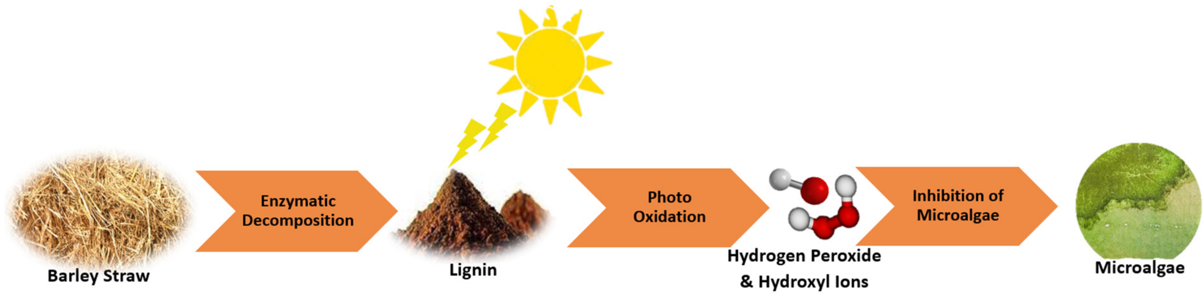

Figure 6. Photooxidation of lignin and inhibition of microalgae.

Barley Straw

In an empirical investigation within the UK, researchers dispersed 50 g per cubic meter of barley straws into a water reservoir to test the straw mechanism theory. The outcome was profound, with a 90% decline in algal presence noted, a stark contrast to prior years without the addition of barley straws [89]. This marked reduction in algal biomass underscores the efficacy of barley straws in curbing cyanobacteria overgrowth.

After the barley straw deployment, water samples were analyzed chemically, revealing a spectrum of organic compounds downstream. Notably, several of these compounds are recognized for their lethal effects on algae [90]. The detection of these substances post-straw decomposition offers a plausible rationale for the reduction in algal numbers. Further research indicated that an extract of barley could thwart the growth of *Microcystis aeruginosa*, evidenced by the chlorophyll-a concentration decreasing by a factor of ten relative to the control, hinting at the decomposed barley straw extract's capacity to restrain algal proliferation [91].

An additional study lent credence to these observations. Here, 25 g per cubic meter of barley straws were introduced to a reservoir. Within a mere 12 days, algal cell counts plummeted by 90% [91]. The study also documented the swift emergence of phenolic compounds, notorious for their algicidal properties. This emergence of bioactive compounds adds weight to the theory that allelopathic interactions are instrumental in modulating cyanobacterial communities [92].

The exploration of chopped wheat straw's effect on algal bloom dynamics within aquatic ecosystems was the focus of research by Mariraj Mohan [93]. In a departure from anticipated outcomes, introducing chopped wheat straw did not suppress algal blooms. On the contrary, its presence was associated with an uptick in HABs proliferation. This was quantified by measuring chlorophyll-a levels, a reliable measure of algal biomass. Chlorophyll levels were recorded at 400 micrograms per liter in environments devoid of wheat straw. However, these levels surged to 520 mg/L following the introduction of wheat straw [93].

Additionally, a separate investigation reported that straw bales placed in a loch had no observable effect on algal concentrations throughout the study. Despite initial assumptions that straw bales might help curb algal blooms, the evidence suggested that their deployment did not lead to a marked decrease in algal presence [94].

Rice Straw and Ragi Straw

Mariraj Mohan's research has shed light on the suppressive effects of rice and ragi straw on algal proliferation in water bodies [88]. These straws, through the collective action of their inherent compounds, have shown a notable capacity to impede algae growth. In particular, rice straw, when decomposed at a 2 g/L concentration, was markedly effective, reducing chlorophyll levels in treatment tanks to about 29.32 mg/m^3 over ten weeks—a stark contrast to the 46.73 mg/m^3 observed in control tanks. This finding suggests that the breakdown of these straws releases substances that prevent algae from spreading rather than removing existing colonies [93].

Further exploration into the effects of rice straw extracts on aquatic microorganisms revealed exciting dynamics. Over a two-week study, *Chlorella* sp. and *Anabaena* sp., harvested from the Abbassa fishpond, responded differently to the straw extracts. The extracts significantly curtailed *Anabaena*'s growth, with the most profound inhibition—over 95%—occurring at extract concentrations of 1, 5, and 10 mg/L. Intriguingly, these same extracts seemed to promote the growth of *Chlorella*, highlighting a selective inhibitory effect [95]. A detailed description of straw utilization is provided in Table 2.

Table 2. Straw utilization against HABs.

Type of Straw	Type of Action	Description	Reference
Barley Straw	Cyanobacteria Growth Inhibition	Barley straw is recognized for its ability to control cyanobacterial growth by releasing allelopathic substances during aerobic decomposition, which hinders cyanobacteria.	[40]
Rice Straw	Cyanobacteria Growth Inhibition	Extracts from rice straw significantly inhibit cyanobacteria (*Anabaena* sp.) growth, depending on extract concentration, while promoting microalgae growth (*Chlorella* sp.) in a concentration-dependent manner.	[57]
Barley Straw	Hydrogen Peroxide Emission	The decomposition of barley straw may emit hydrogen peroxide (H_2O_2) through the photooxidation of lignin and quinone, though further study is needed to understand this mechanism.	[68]
Barley Straw	Oxygenation Necessity	Effective algae control using barley straw requires sufficient oxygenation, as oxygen consumption increases during the straw's decomposition process in water.	[83]

Table 2. *Cont.*

Type of Straw	Type of Action	Description	Reference
Barley Straw	Release of Phenolic Compounds	Decomposing barley straws emit phenolic compounds, which are toxic to algae, supporting the theory that allelopathic interactions affect cyanobacterial populations.	[83]
Barley Straw	Algal Biomass Reduction	Deploying barley straws in reservoirs has been observed to significantly lower algal counts, likely due to the production of organic compounds with potential algal toxicity during decomposition.	[89]
Wheat Straw	Increase in Algal Biomass	Introducing chopped wheat straw unexpectedly increased HABs growth, with a notable rise in chlorophyll-a levels.	[91]
Rice Straw	Algae Growth Inhibition	Rice and ragi straws show inhibitory effects on algae due to the combined action of various compounds released during decomposition.	[92]

4.4.4. Bacterial Use for Controlling HABs

Bacteria exhibit an array of dynamic defenses against HABs. They initiate their countermeasures by swiftly diminishing algal cell populations through the intriguing process of alga-bacterium bioflocculation. This natural phenomenon involves the aggregation of algal cells, precipitating a marked decrease in their numbers [96]. Additionally, these microorganisms serve as natural overseers, adeptly curbing the rampant spread of deleterious algae. By deploying algicidal bacteria, they leverage a lysis mechanism to dismantle their algal counterparts, methodically mitigating potential harm. In a final display of their ecological prowess, bacteria form synergistic clusters known as microbial aggregates, culminating in developing periphytons and biofilms [96]. This collective strategy underscores their collaborative strength and critical role in preserving the delicate balance of aquatic habitats and protecting them from the destabilizing effects of HABs [97].

Bioflocculation

Bacterial bioflocculation is a pivotal method for eradicating algal blooms, relying on the collective settling of algal cells. This process is orchestrated by bacteria, which compel algal cells to emit specific extracellular polymeric substances (EPS). These substances significantly boost the clumping of algal cells, causing them to settle, a process illustrated in Figure 7.

This natural occurrence of bacterial-induced algal clumping is prevalent in aquatic ecosystems, with bacterial species like *Porphyrobacter* playing a critical role in this aggregation [37]. Consequently, using bacterial bioflocculants has become a focal point in managing HABs.

Bioflocculants, instrumental in HABs mitigation, comprise bacterial secretions such as polysaccharides, proteins, and lipids [98]. Nevertheless, deploying these bioflocculants from pure bacterial cultures is primarily experimental and restricted to laboratories, pilot plants, or localized in situ applications [83].

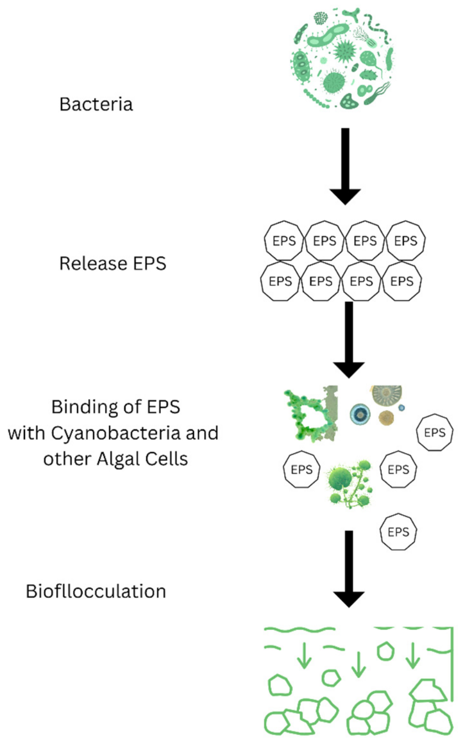

Figure 7. Schematic diagram of bio-flocculation of algae by bacterial EPS release.

Inhibition of Harmful Algal Growth

In aquatic ecosystems, the interplay between bacteria and algae is a delicate balance of survival, often hinging on the suppression of HABs [96]. In their quest for dominance, Algicidal bacteria secrete various allelochemicals that give them an edge over algal species. In nutrient-rich, eutrophic lakes, specific bacterial strains stand out for their ability to curb the proliferation of cyanobacteria. Notably, the *Bacillus fluxes strain SSZ01* has been identified for its secretion of harmine and norharmane, compounds known for their potent effects against cyanobacteria [97]. Furthermore, a raw bacterial extract containing β-carbolines has been shown to antagonize cyanobacteria by interfering with their cell division [99]. These insights underscore the significant potential of bacteria as a strategic tool for the targeted inhibition and management of HABs.

Algicidal bacteria utilize direct and indirect tactics to eradicate HABs, showcasing their capacity to control these detrimental occurrences [100]. These microorganisms directly engage in physical interactions with algae, leading to their destruction. A notable instance is the *Myxobacteria*, the first identified algicidal bacteria, which can decisively eliminate unicellular Cladophora through direct contact [101]. Similarly, the *Streptococcus thermophilus strain LY03* employs chemotaxis to move toward algal cells and then secretes chitinase enzymes that break down the algal cell walls, causing the cells to lyse and die [102].

Indirectly, bacteria secrete various algicidal substances ranging from peptides, proteins, alkaloids, amino acids, antibiotics, pigments, and fatty acids [98]—*Bacillus* sp. *SY-1*, for example, produces Bacillamide, a polypeptide that specifically targets the algal species *Cochlodinium polykrikoides* [103]. Other noteworthy compounds include phenazine from *Pseudomonas aeruginosa strain O-2-2*, *deinoxanthin from Deinococcus xianganeasis Y35*, *prodigiosin from Hahella KA22*, *and palmitoleic* acid from *Vibrio* sp. *BS02*, all of which have been shown to inhibit various algae, highlighting their potential in HABs management [104]. Moreover, *Bacillus* bacteria emit Mycosubtilins that disrupt the cytoplasmic membrane of algae, increasing ion permeability and causing the rupture of dinoflagellates [105].

Field studies, however, indicate that bacteria's algicidal effects can vary significantly from those observed in controlled laboratory experiments. A 2013 study pointed out bacterial cell concentrations ranging from 3.7×10^3 to 1.3×10^6 per ml are necessary to achieve algicidal activity in natural settings [105]. Additionally, the increased presence of these bacteria during the declining phases of algal blooms suggests their role in the natural attenuation of HABs [106–108].

Actinomycetes for Inhibiting HABs

The actinomycete *Streptomyces neyagawaensis* has emerged as a promising agent in the fight against algal blooms. This bacterium is adept at synthesizing allelopathic substances with algicidal effects capable of curbing the expansion of various algae, notably those detrimental to aquatic ecosystems [108].

Intrigued by its potential, researchers have embarked on investigative studies to gauge the effects of *S. neyagawaensis* on predominant algal species in the Paltang, Juam, Daechung Reservoirs, and the Naktong River [109]. The outcomes of these studies were quite revealing, showing that *S. neyagawaensis* selectively targets specific algal species within a genus, effectively inhibiting the growth of *A. flosaquae* and *A. cylindrical* while leaving *A. macrospora* and *A. affinis* unaffected. Additionally, the bacterium's impact differed even among strains of the same species, highlighting its selective and nuanced approach to algal control [98]. The utilization of bacteria against HABs is summarized in Table 3.

Table 3. Bacteria utilization against HABs.

Bacteria	Type of Action	Description	References
Bacillus amyloliquefaciens	Bio-flocculation	Creates bioflocculants that help cluster and remove algal cells, playing a role in controlling HABs.	[37]
Streptomyces neyagawaensis	Algicidal	Generates allelopathic substances that suppress the growth of various algae, including harmful species, affecting specific species and strains.	[57]
Streptomyces sp.	Anti-algal	Produces metabolites that suppress algal growth, showing effectiveness against harmful algal blooms.	[94]
Myxobacteria	Algicidal	Eliminates algae through direct contact, effectively removing them through close interaction.	[101]
Streptococcus thermophilus	Algicidal	Demonstrates chemotaxis towards algal cells and produces enzymes that break down algal cell walls, leading to cell destruction.	[102]
Pseudomonas aeruginosa	Algicidal	EIt emits compounds that directly disrupt algal cells, ending harmful algal blooms.	[103]
Bacillus Fluxus	Algicidal	Releases harmine and norharmane, which are highly toxic to cyanobacteria and help inhibit the growth of HABs.	[110]
Citrobacter sp. *AzoR-1*	Algicidal	PIt produces a bio-flucculant that clusters *M. aeruginosa* cells via interparticle bridging and biosorption, aiding HABs control.	[111]

4.4.5. Fungi for Algal Control

Algicidal fungi are pivotal in managing algal populations within aquatic ecosystems, thanks to their ability to suppress algal growth. The primary mode of their algicidal action involves the release of bioactive substances that either impede or destroy algae [112]. These fungi-induced allelochemicals can provoke oxidative stress in microalgae, interrupting their growth and disrupting cellular functions [113]. In particular, active metabolites can impair chlorophyll, a vital pigment for photosynthesis, in species such as *Heterosigma akashiwo*, potentially inhibiting the photosynthetic process [114].

A variety of algicidal fungi have been recognized, including *Trametes versicolor F21a*, *Bjerkandera adusta* T1, *Lopharia spadicea*, *Phanerochaete chrysosporium*, *Trichoderma citrinoviride*, and Irpex lacteus T2b. These fungi are known for their production of enzymes and secondary metabolites that can compromise algal cell integrity, obstruct photosynthesis, or trigger oxidative stress [105–117].

Observations indicate an uptick in algicidal fungi during the decline of algal blooms, suggesting their instrumental role in curbing and potentially reversing harmful algal bloom events by directly targeting overabundant algal growth [118].

Research has detailed the complex interactions between cyanobacterial cells and fungal mycelia, where cyanobacteria, both alive and dead, initially adhere to fungal mycelia before being overwhelmed by the mycelial network [119]. Specifically, the mycelia of *P. chrysosporium* are known to severely damage cyanobacterial cell membranes, with chlorophyll being a molecule particularly vulnerable to this assault [120].

An investigation by Gao et al. [78] into the algicidal mechanisms of *Trametes versicolor F21a*, using proteomic analysis, identified several biological processes, including glucan 1,4-α-glucosidase and hydrolase activities, as critical in the eradication of cyanobacterial cells. Additionally, this study implicated various metabolic pathways, such as glycolysis/gluconeogenesis and amino acid synthesis, in the algicidal process [74].

In a comprehensive study, the algicidal capabilities of four *Aspergillus* fungi species were explored, leading to the identification of eleven potent metabolites, notably five anthraquinones, four steroids, and two terpenoids, with anthraquinones being particularly effective against a range of algae [117].

White-rot fungi (WRF) are adept at degrading diverse organic pollutants, including chlorophenols, polycyclic aromatic hydrocarbons, and pesticides, significantly enhancing water quality [113]. This ability underscores the potential of WRF as an effective agent in combating excessive algal growth [118]. The degradation prowess of WRF is primarily due to their secretion of extracellular enzymes such as lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase, which have a broad range of substrate affinities [119].

Fungi-Based Pelletization

Fungal pelletization emerges as an effective strategy to mitigate algal overabundance. This intricate process entails the symbiotic interaction between fungal and algal cells, leading to the formation and subsequent sedimentation of fungus–alga pellets [120]. Initiated by the swelling of spores and their germination, the process progresses with the expansive growth and branching of fungal hyphae [37]. These hyphae engage with algal cells, culminating in the creation of pellets. The pelletization process is subject to variations influenced by pH levels, salinity, and the rheological properties of the medium [121]. The resulting fungus–alga pellets exhibit diverse morphologies, from spherical to ellipsoidal, entwined with hyphae, and range in size from the microscopic scale to several millimeters [122]. In time, the fungal cells self-digest, leading to the breakdown of the pellets, thus synchronizing their life cycle with that of the fungi.

This innovative fungal pelletization technique is applied in the realms of wastewater treatment and the harvesting of microalgal biomass [123]. A prime example is the utilization of *Cunninghamella echinulata NRRL 3655* fungal cells to efficiently collect *Chlorella vulgaris UTEX 259* microalgal cells, forming fungus–alga pellets measuring 2 to 10 mm in diameter [124]. Furthermore, fungal bioflocculants, instrumental in microbial aggregation, significantly enhance fungal flocculation processes [37]. These bioflocculants, secreted by various filamentous fungi, are primarily composed of polysaccharides and proteins and have been effectively used in wastewater treatment and microalgal biomass harvesting [124]. Nonetheless, the full potential of these bioflocculants in managing HABs is yet to be realized, as challenges such as adjusting the pH of the bioflocculants and accommodating varying water conditions and species specificity remain to be addressed for practical HABs management [125].

4.4.6. Seaweeds for HABs Control

Seaweed, often called "macro-algae", is essential in counteracting eutrophication by effectively absorbing surplus nutrients from bodies of water. This nutrient absorption is coupled with photosynthesis, where seaweed utilizes these nutrients and enriches the water with oxygen, a beneficial byproduct. Seaweed is a natural barrier against HABs by taking up excess nitrogen and phosphorus, thus maintaining water clarity, supporting marine life, and fostering ecological balance [125].

Additionally, certain cultivated seaweeds demonstrate exceptional productivity and can assimilate nitrogen, phosphorus, and even carbon dioxide [126]. The cultivation of seaweed on a large scale is being explored, with considerations of practicality, scientific and technological hurdles, ecological preservation, and financial feasibility [127]. In China, for instance, *Laminaria japonica Aresch* is extensively cultivated. It has been instrumental in mitigating the adverse effects associated with scallop aquaculture. Studies have pinpointed *Gracilaria lemaneiformis* and *Porphyra haitanensis* as effective for managing eutrophication along China's southeastern to southern coasts [128].

Moreover, coastal waters are facing an increased rate of oxygen depletion, mainly due to eutrophication [129]. Research by Gao et al. [130] underscores the importance of seaweed cultivation in boosting oxygen levels in seawater, with an impressive annual oxygen output of 2,532,221 tonnes. Seaweed varieties like *Porphyra yezoensis* have been noted for their potential to diminish phosphorus and nitrogen concentrations, achieving reductions of 0.049 and 0.008 tons per hectare annually, respectively [131]. Additionally, Xiao et al. [132] have documented the successful nutrient removal from Chinese coastal waters using seaweed, which has led to better aquaculture outcomes by improving water quality and curbing algal blooms. Thus, introducing seaweeds to limit the nutrients available to microalgae emerges as a viable strategy for controlling algal blooms [133].

4.4.7. Viruses for HABs Control

Cyanophages, a specialized category of viruses, target cyanobacteria, distinguishing them from conventional bacteriophages. These viruses are characterized by their capacity to infect a wide array of cyanobacterial genera and their dependency on light for specific stages of their developmental cycle [133]. The genetic impact of cyanophages on their host cells is a focal point of interest, as some harbor genes that are integral to photosynthesis, potentially altering the photosynthetic efficiency of the cyanobacteria they infect [134]. Cyanophage research has concentrated on saline and freshwater aquatic environments [131]. A notable study has indicated genetic similarities between cyanophages in marine and freshwater systems [135]. Cyanophages such as Ma-LMM01, Ma-LBP, and VLP are known to specifically attack cyanobacteria that produce the toxin microcystin [136].

In the realm of combating HABs in aquatic ecosystems, antiviral treatments targeting algae have been deployed [137]. Cyanophage research is burgeoning, with discoveries continually advancing the field. Cyanophages like SM-1, SM-2, Ma-LBP, and those belonging to the *Myoviridae* family are known for their targeted action against *M. aeruginosa* [138]. The *Siphoviridae* viral family has been identified as an effective agent against *Cylindrospermopsis raciborskii*, initiating lytic cycles that could be a biological control for HABs [138]. Early 21st-century research has shown that the Cyanostyloviridae genus and S-PM2 are effective against *Lyngbya majuscule*, while other studies have reported cyanophages combating *Synechococcus* sp. [139]. SAM-1, in particular, has demonstrated a broader host range through specific species interactions [46].

A notable cyanophage, Ma-LEP, exemplifies cyanophages' diversity and functional range. It is essential to recognize that certain phages, initially considered specific to *M. aeruginosa*, were susceptible to *Synechococcus* strains, highlighting a misclassification in identifying their cyanobacterial targets [140]. When naturally occurring viral communities were introduced into aquatic habitats, there was a dramatic 95% reduction in the host population within six days [141]. However, the population recovered within three weeks, possibly due to resistance development or ecological balance restoration [142].

The presence of cyanophages has been inversely related to cyanobacteria populations, suggesting that strategic, intermittent cyanophage introductions could temporarily suppress algal blooms under optimal conditions [143]. Moreover, cyanophages can modulate the metabolites produced by cyanobacteria, which may result in less detrimental blooms [142].

Conversely, the application of cyanophages for cyanobacterial management is challenging. Introducing cyanophages can lead to phage-resistant cyanobacterial strains. Additionally, the toxins released during the breakdown of blooms present another layer of complexity [143]. This could require the periodic introduction of new phages to combat recurring blooms. Furthermore, the toxins may be broken down by native microbial communities in the environment [111]. The sensitivity of bacteria to cyanophages varies, ranging from 0.1 to 32% as observed in the Lowland Dam Reservoir [133]. In some cases, cyanobacteria infected by phages have shown reduced photosynthesis and CO_2-fixation capabilities [144].

4.4.8. Use of Biological Approaches at Lake

Biological strategies for lake restoration are emerging as a viable alternative to traditional physical and chemical methods. While effective in the short term, these conventional approaches, particularly for smaller bodies of water, do not tackle the fundamental problem of eutrophication and are often costly and partially effective. Chemical treatments, lacking a comprehensive treatment system, are prone to creating secondary pollutants and leaving behind residues and, thus, are typically reserved for urgent scenarios [145].

On the other hand, biological techniques provide a sustainable, economically viable option, albeit with a more extended timeframe required to see full results. For example, biomanipulation was employed as the exclusive treatment in Dongen, temporarily improving water quality. Conversely, no improvement was observed in Eindhoven, indicating that persistent phosphorus release from sediments may obstruct recovery efforts there [146].

Moreover, the combined use of bacteria, fungi, and viruses has shown promise in eradicating HABs, as depicted in Figure 8. This synergistic approach was exemplified when restoring the Xuxi River in Wuxi City, China, using bacterial and biological control methods. However, this treatment coincided with a significant increase in algal populations, underscoring the complexities of water pollution management [147].

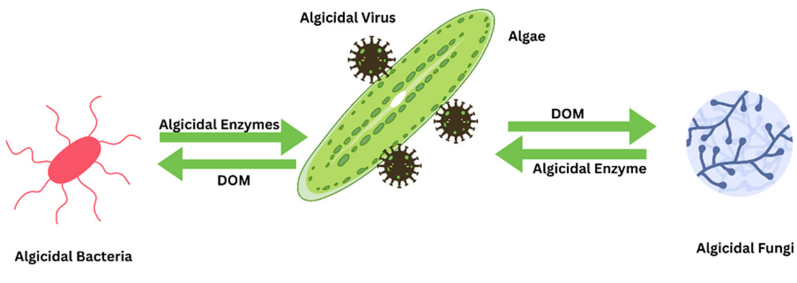

Figure 8. Synergetic effect of algicidal bacteria, fungi, and viruses against HABs.

The application of this technology was tested in urban rivers like Xuxi and Gankeng to address water pollution. The effectiveness of BT was gauged by monitoring essential water quality parameters such as temperature, chemical oxygen demand (COD), and dissolved oxygen (DO) before and after the intervention [148].

Separately, the deployment of quagga mussels has been studied for their potential to combat algae, especially cyanobacteria, in urban ponds. The results indicated that quagga mussels could significantly reduce phytoplankton biomass, suggesting their utility in controlling algal blooms in urban water bodies [136].

Additionally, using aquatic plants for nutrient absorption present an environmentally friendly and cost-efficient method to counteract eutrophication. An assessment of six macrophyte species under various nitrogen and phosphorus concentrations showed notable nutrient reductions in a pond setting [149]. Moreover, ecological floating beds were found to remove nitrogen and phosphorus from nutrient-rich waters quickly. However, restoring microbial eukaryotic communities did not keep pace with the nutrient removal, likely due to the stabilizing effects of priority and rhizospheric micro-environments.

In a series of in situ experiments over three years on Lake Donghu in China, biomanipulation was tested for its effectiveness in reducing blooms. These studies revealed that an increase in filter-feeding fish populations, such as silver and bighead carp, was instrumental in clearing water blooms from the lake, as documented by Yu et al. [149].

4.5. Future Prospect

This research lays the groundwork for future exploration and practical application by evaluating the strengths and weaknesses of diverse chemical, physical, and biological methods for managing HABs. A critical future direction is the amalgamation of these approaches. Researchers and environmental organizations can craft specialized strategies to tackle specific bloom scenarios and ecological conditions by integrating chemical, physical, and biological methods. Such a comprehensive approach promises enhanced efficiency and effectiveness in controlling HABs. This study emphasizes the importance of understanding each control method's long-term impacts, ecological threats, and potential unintended consequences. This insight is critical for guiding decision making and refining approaches to lessen adverse environmental effects.

Conducting field tests and validating these methods in real-world scenarios will be essential to future research. Field testing is necessary to confirm these strategies' real-world efficacy and feasibility, thus narrowing the gap between theoretical research and practical implementation. International cooperation is essential in tackling the global challenge of HABs.

Additionally, the future of HABs management is intrinsically linked to technological advancements. Innovations could result in more accurate and targeted chemical treatments, more energy-efficient physical methods, and sophisticated biological control agents, thereby boosting the effectiveness and sustainability of HABs management strategies; future strategies must be flexible to adapt to evolving environmental conditions. As the demand for scientific research into HABs remains high, further practical application of emerging technologies are essential for effective HABs control.

4.6. Conclusions

Effectively addressing HABs necessitates a thorough and diverse approach involving various biological methods. This analysis underscores the absence of a universal solution, highlighting that each method has strengths and limitations. Successful mitigation in aquatic settings hinges on carefully assessing factors such as the water body's specific characteristics and the algal bloom's severity.

Biomanipulation, proven effective in extensive ecosystems, raises uncertainty about its suitability for smaller water bodies with no immediate results. Algicidal bacteria may benefit smaller systems, provided a comprehensive understanding and safe deployment are ensured. However, these methods do not guarantee complete HABs eradication, requiring ongoing applications. Phage therapy utilizing algicidal viruses presents a targeted and promising solution, albeit with the challenge of identifying suitable phages, especially in regions with prevalent algal species.

While not extensively researched, fungal interventions for HABs control exhibit potential in controlled settings or as part of a holistic HABs management plan. Determining viable HABs eradication methods for lakes and ponds depends on meticulously analyzing local conditions and algal types. Complemented by thorough monitoring, a synergistic application of these strategies often proves to be the most effective course of action.

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