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Management and Mitigation Strategies for Harmful Algal Blooms: Current Approaches and Future Prospects

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Abstract This study explores the management and mitigation strategies for harmful algal blooms (HABs), with a focus on analyzing their formation mechanisms, monitoring and early warning technologies, the effectiveness and limitations of various control methods, and the practical application of integrated management measures. It also discusses the current challenges in governance and future development directions. The occurrence of harmful algal blooms is the result of multiple interacting factors, including excessive nutrient inputs, climate change, altered hydrological conditions, and ecosystem imbalance, posing serious threats to aquatic ecosystems, human health, and socioeconomic development. Current response measures primarily fall into three categories: proactive source prevention, direct in-water intervention, and impact mitigation based on monitoring and early warning, encompassing various physical, chemical, and biological methods. Advanced technologies such as satellite remote sensing, unmanned aerial vehicles, and artificial intelligence models have become important tools for monitoring and early warning. In terms of integrated management, watershed-scale nutrient control, ecological restoration measures such as constructed wetlands and ecological floating islands, combined with best management practices (BMPs), have shown promising results. Typical regional cases further validate the importance of cross-sectoral collaboration and comprehensive policies. However, current governance still faces challenges such as high costs, limited technology application, unstable long-term control effects, and increased difficulty due to climate change. Research indicates that a single governance method is insufficient to achieve long-term effective control of harmful algal blooms, highlighting the need for more integrated, adaptive, and ecosystem-based management strategies in the future.

Keywords Harmful algal blooms; Management strategies; Formation mechanism; Monitoring and early warning Comprehensive Management

1 Introduction

Harmful algal blooms (HABs) refer to the phenomenon where tiny algae and cyanobacteria rapidly and massively multiply within a short period of time. These types of algae produce toxins, consume oxygen in the water, and form large amounts of algae bodies, thereby damaging the water environment. Such phenomena not only occur in freshwater areas such as lakes and rivers, but are also common in estuaries and oceans. It has now become a key issue in global water quality and ecological environment (Anabtawi et al., 2024; Brenckman et al., 2025;). Originally, this phenomenon was very rare, but in recent years, with the increase in nutrients such as nitrogen and phosphorus in the water, combined with the effects of climate warming, hydrological changes, and human activities, harmful algal blooms have become more frequent, longer-lasting, and have a wider impact (Chang, 2025). Global studies have shown that since the end of the last century, the frequency and impact of harmful algal blooms have significantly increased, especially in coastal and inland lakes in Asia, Africa, Europe, and North America (Feng et al., 2024).

The greater the quantity of harmful algal blooms, the greater the impact on the ecology, resources, and human health. From an ecological perspective, a large number of algae will block sunlight, affecting the growth of aquatic plants and altering the entire food chain. When the algae die and decompose, they consume a large amount of oxygen, causing water to become oxygen-deficient and leading to the mass death of fish and shrimp, making the living environment in the water worse and worse (Anabtawi et al., 2024; Liu et al., 2025). Many harmful algal blooms contain algae that produce highly toxic biological toxins (such as microcystin, saxitoxin, and short-brown algal toxin, etc.). These toxins accumulate continuously through the food chain, polluting drinking water and seafood, poisoning humans, livestock, pets, and wild animals, and some can cause rapid onset while others accumulate slowly to affect health (Brenckman et al., 2025; Chang, 2025). In terms of economy, harmful algal blooms affect fishing, aquaculture, tourism, and recreational activities, causing annual losses of hundreds of millions of dollars and posing difficulties for the development of "blue economy" in many areas. In terms of water resources, harmful algal blooms make daily water quality testing and risk assessment more difficult, and some lakes and reservoirs cannot be used as drinking water sources normally, increasing the cost of water purification and treatment in water plants (Igwaran et al., 2024).

To address this issue, various management approaches have been adopted, mainly divided into three categories. The first is proactive prevention, such as reducing the inflow of nutrients into water bodies, managing water resources properly, and utilizing land rationally; the second is direct control within the water body, using methods from physics, chemistry, and biology; the third is relying on monitoring and early warning to reduce the harm caused by the rampant growth of algae (Igwaran et al., 2024). Remote sensing, molecular detection, and various sensors are increasingly used in monitoring, and new biological management ideas are gradually being implemented. However, the large-scale promotion of these technologies still faces obstacles and is restricted by policies, management, and social factors; in addition, the impact of climate change makes it even more difficult to predict the governance effects (Lan et al., 2024; Liu et al., 2025; Zahir et al., 2024).

This study will focuses on the control issues of harmful algal blooms in freshwater and marine environments, analyzing the advantages, disadvantages and applicable scenarios of various governance methods. This article integrates the latest global research, sorts out various measures such as source control, water treatment, and hazard mitigation, as well as ongoing research technologies. At the same time, it focuses on the comprehensive governance approach that integrates multiple disciplines and technologies, discusses future development directions, and explores how to establish a more complete monitoring, analysis and policy system to reduce the environmental and social losses caused by algal blooms.

2 Formation Mechanisms of Harmful Algal Blooms

2.1 Excessive nutrients lead to rampant growth of algae

Human activities have led to an increasing accumulation of nutrients in water bodies, which is a significant factor contributing to the rapid proliferation of harmful algae. Especially when the levels of nitrogen and phosphorus are too high, algae will grow in large quantities in various water bodies such as freshwater and estuaries. Nutrients from agricultural fertilization, discharged domestic sewage, surface runoff formed by urban rainfall, and airborne sediment, all of which may cause the continuous accumulation of nutrient salts in water, providing sufficient growth conditions for algae and eliminating the limitation of insufficient nutrients. Such environmental conditions are more favorable for fast-growing algae, such as cyanobacteria and some diatoms (Figure 1) (Brenckman et al., 2025). In studies conducted in many regions around the world, it has been found that the more nutrients there are in water bodies, the more frequently and on a larger scale harmful algae outbreaks occur, and the more significant the impact is. After the large-scale proliferation of algae, it often leads to oxygen deficiency in water bodies, produces odors and releases toxins, thereby damaging water quality and affecting the entire ecosystem. Studies on lakes, rivers, estuaries, and coastal waters have also shown that when the nutrient salt levels in water bodies increase, the number of planktonic organisms usually increases significantly. This further indicates that excessive nutrients are an important cause of algae outbreaks, and therefore, from the perspective of controlling nutrient input, this issue can theoretically be managed and alleviated.

In addition to excessive nutrients, the types and proportions of nutrients, as well as when they enter the water, are also crucial for the outbreak of algae. Many harmful cyanobacteria and flagellate algae have special abilities, such as being able to fix nitrogen from the air, storing excess nutrients, or efficiently utilizing certain forms of nitrogen. These abilities allow them to survive even in cases of nitrogen and phosphorus imbalance and unstable nutrient supply, and sometimes their toxicity becomes stronger. Intermittent nutrient input brought by heavy rain or changes in water flow can cause an algal bloom to occur suddenly if the timing is right (Huang and Liang, 2025). Moreover, phosphorus and other substances released from sediments and dead algae, even if the external nutrient sources are controlled, can allow the algal bloom to persist. This shows that algal blooms caused by eutrophication of water bodies are the result of the combined effect of nutrients introduced from outside and those circulating within the water body. That is to say, to control them, both these types of nutrients need to be controlled, and the long-term nutrient balance between land and water also needs to be managed.

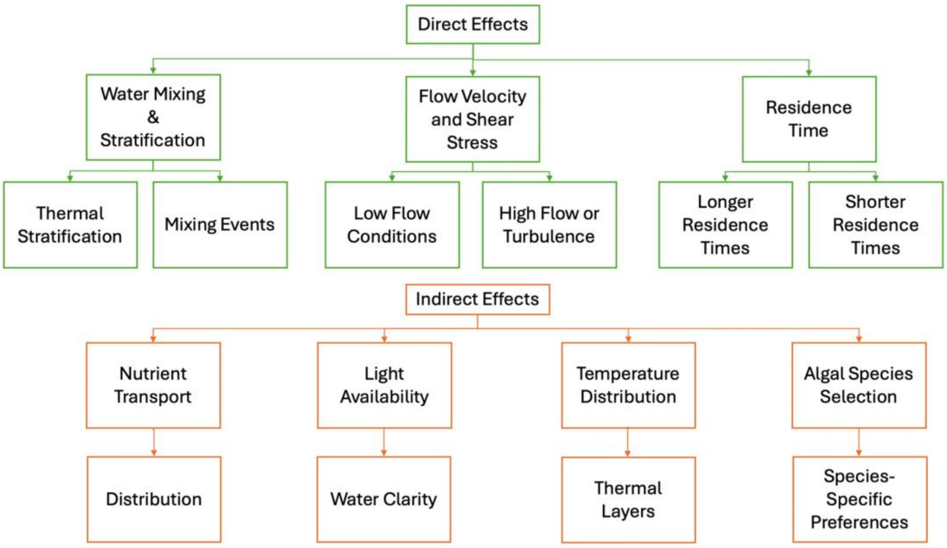


Figure 1 Flow diagram summarizing the mechanisms by which hydrodynamic conditions affect algal blooms in reservoirs, focusing on both direct and indirect effects (Adopted from Brenckman et al., 2025)

2.2 Climate change makes algal blooms more likely to occur

Climate change will cause the water temperature to rise, making the stratification of water layers more stable. At the same time, the flow conditions and the chemical environment of the water body will also change. These changes will provide more favorable conditions for harmful algae to grow, thereby increasing the possibility of algae outbreaks (Feng et al., 2024). When the water surface temperature rises, many cyanobacteria and some toxic marine plankton grow faster, having an easier advantage in competition, and their growth season will also be prolonged. Some species can even expand to regions that were previously colder and difficult to survive, such as higher latitudes or higher altitudes of water bodies. Long-term monitoring data and model studies have shown that in the case of continuous temperature rise and an increase in marine and freshwater heat waves, the range of algae outbreaks in lakes and coastal waters may expand, the duration will be longer, and the toxic risk may also increase (Lan et al., 2024; Wang et al., 2025a). In some bodies of water, the massive proliferation of algae sometimes creates a cycle: when the water surface is covered by a thick layer of algae, it actually absorbs more heat, causing the water temperature to rise even higher. As a result, the algae grow faster (Kuijpers et al., 2025).

Changes in rainfall volume, unstable water salinity, and an increase in extreme weather events all make it easier for algae to undergo large-scale outbreaks. For instance, during heavy rain or storms, more nutrients from the land are washed into lakes or estuaries; while in cases of prolonged drought or slow water flow, the water in lakes and reservoirs cannot flow freely and stays longer. Both of these situations make the already nutrient-rich water bodies more conducive to the rampant growth of algae (Feng et al., 2024; Brenckman et al., 2025). In coastal areas, the increase or decrease of incoming freshwater can affect the salinity of the sea water, and a change in salinity, in turn, can affect the growth of some harmful algae. According to some climate change research predictions, in those areas with relatively low salinity, these algae may grow even more vigorously (Shi et al., 2024). Additionally, ocean acidification, reduced oxygen levels in water, and continuous warming of water temperatures, these factors may also interact with each other to affect the growth of harmful algae, and even cause them to produce more toxins. However, the exact way these factors interact is not yet fully understood. Overall, climate change, the increasing amount of nutrients in water, combined with various human activities, have made the phenomenon of large-scale algae outbreaks increasingly common and severe in many places (Wang et al., 2025).

2.3 The flow conditions have changed, and so has the ecological structure

Fluid dynamic conditions, including water flow velocity, turbulence, water stratification and residence time, have a significant impact on the occurrence and development of red tides by influencing the physical environment for the survival of phytoplankton. Long water residence time and weak scouring effect can lead to continuous accumulation of algae, which is very common in nutrient-rich rivers, reservoirs and large lakes; while strong convection and mixing often dilute or destroy red tides. In artificially controlled rivers and reservoirs, sluices, dams and selective water intake can change water depth, water stratification and hydraulic residence time. Under nutrient-rich conditions, a slow water flow and stratified water body usually form, which is conducive to the dominance of cyanobacteria and increases the risk of red tides. On the contrary, management methods such as enhancing water mixing, increasing scouring or reducing water thermal stability can limit the development of red tides, which also indicates that fluid dynamics is crucial in the formation of red tides.

Changes in the ecological structure and food chains are also intertwined with these flow conditions and further affect whether algal blooms will occur. Changes in water body fertility, artificial alteration of water flow, and excessive fishing can all change the number and species of phytoplankton-eating zooplankton, weakening their ability to control algae. In many water bodies that are rich and stratified, these changes will cause algae to gradually shift from being dominated by diatoms to being dominated by cyanobacteria or flagellates. The latter have advantages in terms of taste, toxicity, or ability to adapt to weak water flow and long-term stillness (Brenckman et al., 2025). Once algal blooms occur, they will in turn change the ecological structure, making the water quality worse, the distribution of light and nutrients changing, and biodiversity decreasing. This, in turn, makes algal blooms more likely to occur again, forming a vicious cycle, and keeping harmful algae in the dominant position. Therefore, the formation of harmful algal blooms is the result of changes in the interaction between the physical environment and the ecosystem. Changes in flow conditions, combined with the reorganization of the biological community in the water body, jointly lead to water bodies becoming more prone to frequent and persistent algal blooms.

3 Monitoring and Early Warning of Harmful Algal Blooms

3.1 Traditional water quality and algal monitoring methods

Conventional HAB monitoring relies on in situ sampling combined with physical, chemical, and biological analyses to quantify algal biomass, species composition, and toxin levels. Routine programs typically measure temperature, nutrients, chlorophyll-a, and other water-quality parameters alongside microscopic identification of phytoplankton and cyanobacteria, often supported by spectrophotometry, chromatography, and biochemical or immunological toxin assays. These approaches remain the regulatory backbone because they provide species-level resolution and direct toxin measurements necessary for public-health decisions and seafood or drinking-water safety compliance. Standardized protocols, such as stepwise workflows integrating physical, chemical, and biological sampling with metabarcoding, improve data comparability across stations and over long time series, supporting robust risk assessment and model calibration (Saleem et al., 2023).

However, traditional monitoring is labor-intensive, costly, and limited in spatial and temporal coverage. Ground sampling and laboratory analyses require skilled personnel and specialized facilities, leading to low sampling frequency relative to the rapid dynamics of blooms (Saleem et al., 2023). These constraints can hinder timely detection of bloom onset or rapid intensification, particularly in large or remote water bodies (Byrd et al., 2025). To address these gaps, newer technologies such as biosensors, automated in situ instruments, and molecular tools (PCR/qPCR, metabarcoding) have been developed to shorten assay times, enable near-real-time detection of target taxa or toxins, and complement classical microscopy-based approaches (Zahir et al., 2024). The future of traditional monitoring lies in its integration with automated, molecular, and observational platforms within multi-scale observing systems.

3.2 Remote sensing and drone-based monitoring technologies

Satellite and airborne remote sensing have transformed HAB monitoring by providing synoptic, repeated observations of bloom extent and intensity over large spatial scales. Optical remote sensing, including multispectral, hyperspectral, and emerging high-performance sensors, retrieves proxies such as chlorophyll-a, phycocyanin, and water color, enabling the detection and mapping of surface blooms in both inland and coastal waters (Figure 2) (Zahir et al., 2024). Meta-analyses of hundreds of studies show rapid growth in remote-sensing-based HAB monitoring, while also highlighting needs for standardized methods, improved atmospheric correction (especially in turbid waters), and harmonized multi-sensor constellations to increase spatial–temporal resolution (Wang et al., 2025). Hyperspectral imaging in particular can discriminate algal groups with high classification accuracy and support robust early-warning applications when coupled with suitable algorithms (Arias et al., 2025; Wang and Qin, 2025).

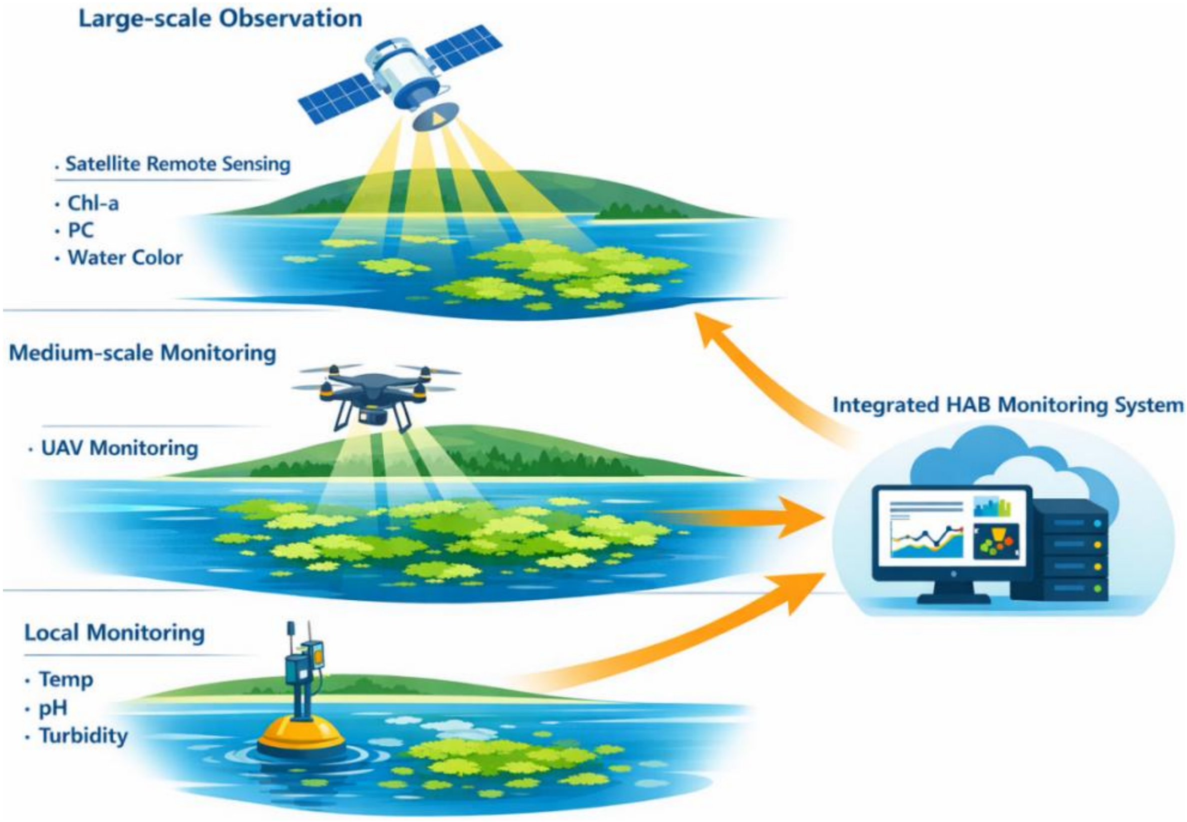


Figure 2 Conceptual framework for harmful algal bloom monitoring (Adopted from Zahir et al., 2024)

Unmanned aerial vehicles (UAVs) provide flexible, high-resolution coverage that bridges scales between in situ sampling and satellites. UAV platforms equipped with RGB, multispectral, hyperspectral, or thermal sensors can rapidly map fine-scale bloom patches, validate satellite products, and guide targeted sampling or public-health interventions (Arias et al., 2025; Wang and Qin, 2025). Recent systems integrate onboard water-quality sensors (e.g., temperature, pH, turbidity) and real-time communications (e.g., LoRaWAN) to deliver immediate data streams for operational decision-making (Hagh et al., 2024). Nonetheless, UAV-based monitoring faces challenges including regulatory constraints, the need for robust calibration and validation, and integration with risk frameworks and other observing platforms (Byrd et al., 2025). The emerging direction is coordinated, multi-platform observation networks that combine satellite, UAV, and in situ data for comprehensive HAB surveillance.

3.3 Prediction and early warning based on models and artificial intelligence

Forecasting and early-warning systems have evolved from empirical statistical models toward sophisticated process-based, data-driven, and hybrid approaches that exploit growing environmental and monitoring datasets.

Numerical and process-based models simulate physical-biogeochemical drivers such as stratification, nutrient dynamics, and algal growth to provide mechanistic insight and scenario testing, whereas data-driven models correlate historical environmental variables and remote-sensing products with bloom metrics for short-term prediction (Lan et al., 2024; Campbell and Vinebrooke, 2025). Ensemble frameworks that stack multiple model types (e.g., tree-based methods, neural networks, Bayesian regression) improve skill in predicting exceedance probabilities of algal densities and toxins, offering probabilistic risk forecasts for management programs (Szewczyk et al., 2025).

Machine-learning and deep-learning techniques, including random forests, gradient boosting (XGBoost, LightGBM), artificial neural networks, CNN-LSTM architectures, Transformers, and other hybrid models, now play a central role in HAB prediction (Szewczyk et al., 2025; Wang et al., 2025). These models effectively capture nonlinear relationships among meteorological, hydrodynamic, nutrient, and remote-sensing inputs, achieving high accuracy for short-term HAB detection and multi-day forecasts and demonstrating operational potential for early-warning systems in both coastal and freshwater systems (Park et al., 2024). Integration of explainable AI (e.g., SHAP values) helps identify key drivers and improve interpretability, while coupling ML with real-time monitoring (sensors, satellites, UAVs) is highlighted as critical for sustained performance and generalizability across diverse bloom scenarios (Zahir et al., 2024).

4 Control and Mitigation Methods for Harmful Algal Blooms

4.1 Physical methods: aeration, mixing, and mechanical removal

These physical methods do not add chemical substances to the water body. Instead, they work by altering the water environment or directly removing algae. For instance, by artificially stirring the water or supplementing oxygen at the bottom, the original stratification structure of the water body can be disrupted, reducing the accumulation of algae on the water surface, while increasing the dissolved oxygen in the water and reducing the possibility of nutrient release from the bottom sediment into the water. In this case, the growth conditions of algae will be restricted, and those algae that do not form algal blooms may have more space to grow. If the oxygenation technology is designed reasonably based on the morphological characteristics of the lake or reservoir and the pollution status, it can increase the oxygen content of the water body within a certain period and reduce the release of phosphorus from the bottom sediment, thereby reducing the number of algae to a certain extent (Brenckman et al., 2025). However, this method requires high costs in construction and operation, and the effects vary greatly in different water bodies. If external inputs of large amounts of nutrients continue, the governance effect is often weakened. Therefore, it is still difficult to promote this method in large lakes or sea areas (Lan et al., 2024).

These physical methods include using dredging tools, filtration equipment, or throw in substances that cause algae to sink to the bottom. These are commonly used in small ponds and aquaculture areas and can quickly reduce the excessive algae in the water (Lan et al., 2024). For example, when dealing with marine red tides, clay or modified clay is often used to cause the algae to aggregate and sink to the bottom. However, it is currently uncertain whether this method will harm underwater organisms (Anderson et al., 2025). There is also a method of thoroughly cleaning the bottom sediment, which can remove nutrient-rich sediment and dormant blue-green algae spores. However, this method is costly and environmentally damaging and cannot be frequently used. In general, physical methods are more suitable for emergency handling in areas with high economic value.

4.2 Chemical methods: using algaecides and oxidants

Chemical methods, especially the use of algicides and oxidants, remain common measures for dealing with excessive algal growth. The main reason is that these methods are more effective and can significantly reduce the algal population within a short period of time, as well as lower the toxins produced by the algae. Through a comprehensive analysis of multiple field test results, it was found that among various chemical agents, only a few, such as copper sulfate, hydrogen peroxide, peroxyl acetate, and carbendazim, can improve water quality by reducing the pigment content of the algae, decreasing the cell count, and removing microcystin toxins. Some oxidants, such as hydrogen peroxide and potassium persulfate, have a good inhibitory or killing effect on blue-green algae like Microcystis in a wide range of pH conditions. If used properly, they have a relatively small impact on the water's acidity and alkalinity, produce little dissolved organic carbon, and can decompose microcystin-LR and chlorophyll a. Moreover, these oxidants also have a strong killing effect on marine flagellates that are harmful to fish, making them a potential alternative to chlorine in ship ballast water treatment and coastal water management.

However, although chemical treatment can take effect quickly, it also brings some environmental and management issues. For instance, copper preparations and some synthetic herbicides may gradually accumulate in sediments or aquatic organisms, thereby posing long-term ecological risks. At the same time, when herbicides or oxidants cause a sudden death of a large number of algae, toxins and organic substances in the cells will rapidly be released into the water, which may increase toxicity in a short period and lead to oxygen deficiency in the water body. Some recent review studies have also pointed out that in practical applications, most chemical treatment measures are difficult to improve water quality in the long term, indicating that relying solely on chemical agents is insufficient to solve the problem of excessive nutrients at the watershed level (Table 1) (Lan et al., 2024). Some recently emerged nano-material oxidants and photocatalysts can improve treatment efficiency and selectivity, but they also raise new issues, such as the fate of nanoparticles in the environment and whether they will be toxic to the ecosystem. The current situation is unclear. Therefore, in practical management, chemical methods are more often used as emergency or short-term control measures. When using these agents, strict control of dosage, enhanced monitoring, and their integration into a prevention-oriented comprehensive management strategy are necessary.

Table 1 Innovative fertilizer technologies for reducing eutrophication (Adopted from Lan et al., 2024)

Fertilizer Technology	Nutrients Provided	Mechanism	Suitable Crops
Slow-Release Fertilizers (SRFs)	Nitrogen, Phosphorus, Potassium	Gradual nutrient release aligned with crop uptake	Cereals, horticultural crops, turfgrass
Controlled-Release Fertilizers (CRFs)	Nitrogen, Phosphorus, Potassium	Coating controls nutrient release over time	Vegetables, fruits, ornamental plants
Nitrification Inhibitors	Nitrogen	Inhibits nitrification, reducing nitrate leaching	Maize, wheat, rice
Urease Inhibitors	Nitrogen (Urea-based)	Prevents rapid urea conversion, reducing ammonia loss	Rice, cereals, pasture
Enhanced Efficiency Fertilizers (EEFs)	Nitrogen, Phosphorus	Combines slow and controlled release with inhibitors	Various crops including cereals, fruits, vegetables
Polymer-Coated Fertilizers	Nitrogen, Potassium	Encapsulated nutrients in a polymer for controlled release	High-value crops like fruits, vegetables, ornamentals
Biochar-Enhanced Fertilizers	Nitrogen, Phosphorus, Potassium, micronutrients	Uses biochar to retain nutrients and reduce leaching	Cereals, legumes, vegetables
Struvite Fertilizers	Phosphorus, Nitrogen, Magnesium	Mineral compound with slow nutrient release	Horticultural crops, cereals

4.3 Biological methods: using microorganisms, filter-feeding organisms and aquatic plants

Biological control methods involve using predator relationships, species competition, or microbial actions to inhibit the growth of harmful algae. This approach is generally considered more environmentally friendly and more in line with natural ecological laws. Microbial control mainly includes the use of bacteria, fungi, or actinomycetes that can kill algae, or the use of some microbial groups to cause the cell lysis of algae, inhibit their growth, or cause the aggregation, sedimentation, and gradual decomposition of algae cells, thus forming a process of "aggregation-lysis-degradation-nutrient regulation". Relevant research and reviews indicate that some strains with algicidal effects, such as certain streptomyces, vibrio, and the algicidal fungus known as D7, not only can reduce the number of algae in water bodies, but can also, to a certain extent, lower the nutrient salt levels in water, thereby simultaneously alleviating the problems of algal blooms and excessive nitrogen and phosphorus (Anabtawi et al., 2024; Pan et al., 2025). Most related studies are still at the stage of laboratory or medium-scale simulation tests, and there is not sufficient evidence to prove that they can improve the long-term water quality of natural bodies. These methods are unstable in natural environments and some microorganisms may even affect non-target organisms. Moreover, due to regulatory requirements and limitations on public acceptance, it is fundamentally difficult to directly introduce foreign microorganisms into natural water bodies (Abate et al., 2024).

Large aquatic plants, as well as filter-feeding organisms (such as mussels, shellfish, zooplankton and certain fish), and some allelochemicals secreted by plants, can also play a role in assisting in the control of algal blooms by altering the food chain, competing for nutrients and sunlight, and releasing inhibitory substances. Through management, by strengthening the population of filter-feeding organisms, the number of cyanobacteria can be reduced, and the algal community can shift towards a less harmful direction; in freshwater environments, restoring seagrass beds, algal fields and emergent plants can provide habitats for natural algal-killing bacteria, making the ecosystem more stable and preventing harmful algae from dominating. Based on plant management strategies, such as adding straw and reed to the water or using purified allelochemicals, they have shown inhibitory effects on algal growth in experimental conditions and small ponds. However, as these methods are used more frequently in practice, their effectiveness becomes less reliable, and they usually cannot be relied upon alone to control algae (Anabtawi et al., 2024). In summary, relying solely on these biological means often does not significantly improve water quality. In other words, biological control should be regarded as part of a long-term comprehensive management approach. At the same time, it is necessary to reduce nutrient input, restore the ecosystem, and carefully consider its benefits and potential problems (Abate et al., 2024).

5 Integrated Management and Practical Applications

5.1 Water pollution control and nutrient management

When dealing with harmful algal blooms, people are increasingly focusing on controlling the nutrient flow throughout the entire river basin. These nutrients come from various sources, such as farmlands, livestock farms, and centralized discharge sources like urban domestic sewage and rainwater (Feng et al., 2024). Global studies have found that nitrogen and phosphorus in rivers flowing into the ocean must be controlled simultaneously; controlling only one of them will still lead to excessive algal growth. The research suggests that nitrogen and phosphorus reduction targets should be set based on the actual conditions of each river basin, while also considering the impact of climate change on water volume, temperature, and extreme weather. This is the fundamental approach for long-term control of algal blooms.

The combination of catchment analysis models and ecological risk assessment tools has now been able to assist in designing and optimizing the best management methods (referred to as BMP). In the Taihu Lake Basin of China, a SWAT - Bayesian Network model shows that reducing fertilizer usage by 40% can maximize the reduction in the probability of harmful algal blooms in the model; at the same time, extensive planting of vegetation filter strips can also bring additional governance effects. Combining these two measures can significantly reduce the risk of harmful algal blooms, even maintaining stability under extreme climates (Liu et al., 2024; Lin et al., 2025). In the Malmaino sea area of Spain, a similar SWAT+-Lagoon modeling study found that the comprehensive application of BMP measures (reducing fertilizer use, planting vegetation filter strips, crop rotation, etc.), can reduce the number of days with harmful algal blooms by 81%, and the chlorophyll a content during the algal bloom period by 50%, with much better effects than single measures (Pacheco et al., 2025). Interviews with water management personnel in the United States also indicate that measures for nutrient management, especially BMP measures in the agricultural sector and urban fertilizer control measures, are the main methods for preventing harmful algal blooms. However, relevant personnel also admit that "under the influence of climate change, harmful algal blooms will not disappear in the short term" (Goodrich et al., 2024).

5.2 Ecological restoration: artificial wetlands and ecological floating islands

Combining ecological restoration projects with the best management methods for river basins can intercept nutrients and rebuild the local food web. Around eutrophic lakes (such as the wetlands along Lake Erie), restoring wetlands can enhance the natural ability to intercept nutrients, buffering the entry of phosphorus and nitrogen before they reach the open waters prone to cyanobacteria blooms. Research summaries on eutrophication and harmful algal blooms indicate that well-planned wetlands, riparian buffer zones, and reconnecting floodplains can reduce the episodic nutrient load brought by heavy rain, which is a key factor in triggering the "extreme situation" of cyanobacteria blooms (Figure 3) (Huang and Han, 2025).

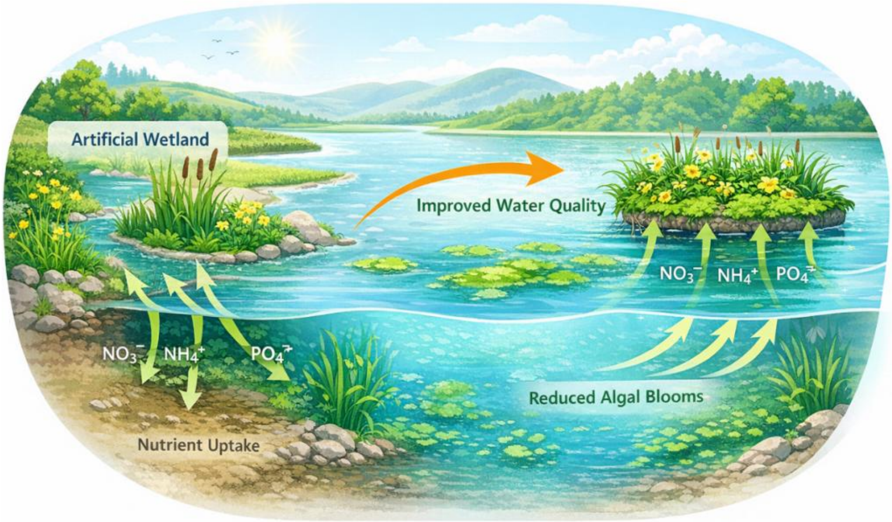


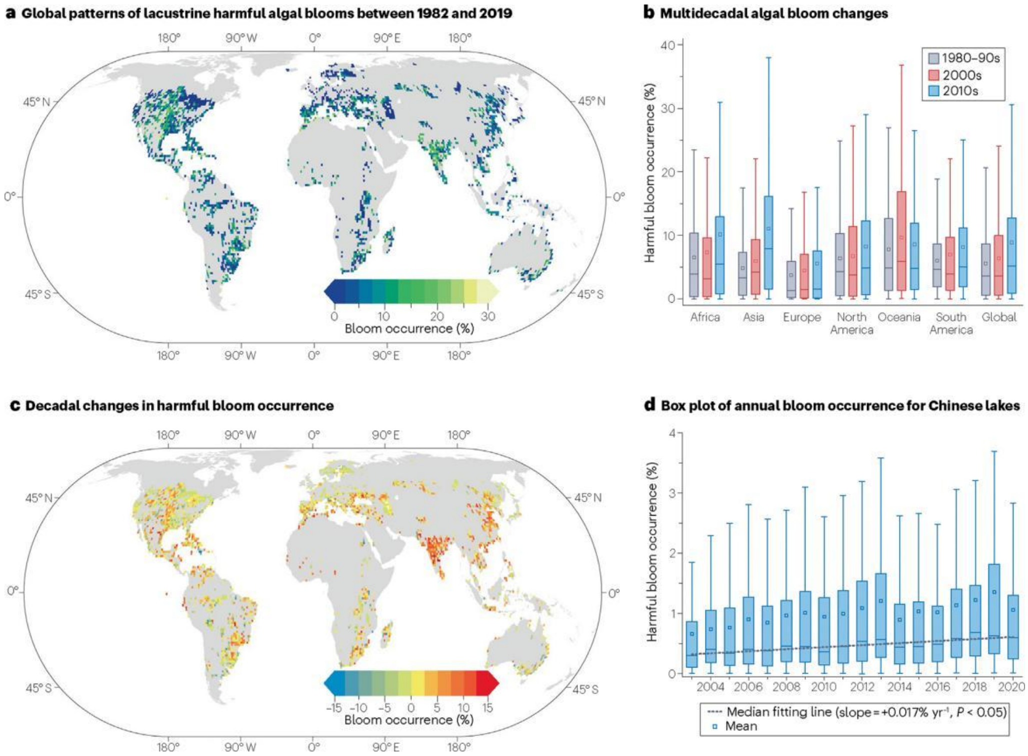
Figure 3 Schematic diagram of ecological restoration mechanism (Adopted from Huang and Han, 2025)

Artificial floating treatment wetlands and ecological floating islands are a type of biological treatment method that can be widely used. They are particularly suitable for application in lakes, especially in small water bodies in cities. In cities such as Baltimore, Boston and Chicago in the United States, the results of long-term pilot projects show that by harvesting the wetland plants grown on these floating islands, approximately 2 grams of phosphorus can be removed per square meter per year. At the same time, the ecological environment around these facilities has also changed, the number and species of large invertebrates, plankton, cyanobacteria and fish in the water have all changed. This indicates that the water quality and ecological environment have indeed improved (Nayak et al., 2025). Although the total amount of nutrients taken away by these floating islands from urban water bodies is not large, they can not only purify the water quality, but also provide habitats for aquatic animals, become an open ecological landscape for the public, and can be used as a test platform to help scientists determine how large the facilities should be built and how they should be designed. It can be said that it brings multiple benefits.

5.3 Typical management cases and regional experience

By comparing cases from different regions, it can be observed that the methods for dealing with algal blooms vary significantly in different areas, but some governance measures are applicable in multiple locations. Researchers analyzed 12 large and medium-sized eutrophic water bodies worldwide and found that most regions would formulate basin management plans based on local water quality standards and carry out governance through means such as regulation, economic measures, risk prevention, and public awareness campaigns. Even if these measures are implemented, algal blooms are difficult to be completely eradicated; they can only reduce the scale of the outbreak but cannot solve the problem at its root. For example, in North America and Europe, early measures relied on controlling nutrient levels to slow down algal blooms, but after the 1990s, due to climate warming and residual nutrients, toxic algal blooms reappeared. This indicates that merely reducing emissions is not sufficient; climate adaptation measures must also be combined (Qiu et al., 2024).

Various on-the-ground projects have also accumulated rich experience. The Domal acid incident caused by the pseudo-Nichols algae in the western United States in 2015 provided an important warning. Washington State, by establishing an early cross-departmental cooperation mechanism, had a higher acceptance rate among the public for fishing bans and risk information. After the Toledo drinking water crisis in Lake Erie in 2014, several international seminars reaffirmed the necessity of reducing emissions, restoring wetlands, and optimizing monitoring systems. The practices in coastal and inland areas have demonstrated that continuously advancing comprehensive projects such as long-term monitoring, model analysis, and watershed governance can more effectively reduce the risk of harmful algal blooms (Figure 4) (Feng et al., 2024).


a Global patterns of lacustrine harmful algal blooms between 1982 and 2019

b Multidecadal algal bloom changes

c Decadal changes in harmful bloom occurrence

d Box plot of annual bloom occurrence for Chinese lakes

Figure 4 Global patterns and trends in harmful bloom occurrences in lakes (Adopted from Feng et al., 2024)

Image caption: a, Global occurrence patterns of harmful lacustrine algal blooms between 1982 and 2019 aggregated into 1° ×1° grid cells and expressed as a percentage of total observational bloom number over the time period. b, Box plots of harmful algal bloom (HAB) occurrence (%) separated by continent and time period; the bottom and top of the boxes are the first and third quartiles, respectively, the bar in the middle shows the median, and the whiskers show the minimum and maximum values. c, Change in harmful bloom occurrence from the 1980-90s to the 2010s expressed as the percentage change in annual bloom frequency in each location. d, Annual HAB occurrence for large, bloom-affected lakes in China, expressed as a percentage of the total number of bloom-containing pixels over the total number of cloud-free MODIS pixels within a year. The data in panels a – c were extracted from Landsat images1, and the data in panel d are from the Moderate-resolution Imaging Spectroradiometer (MODIS)20. Although most global studies show a general increase in HABs in recent decades, the trends vary by region and time period (Adopted from Feng et al., 2024)

6 Key Challenges in the Management of Harmful Algal Blooms

6.1 High management costs and technical limitations

For a long time, controlling the rampant growth of algae has been a challenging issue. It requires significant investment and often yields unsatisfactory results. Many treatment technologies have limited applicability and are difficult to be widely adopted in large lakes and oceans. For instance, physical methods such as manual water mixing and oxygen enhancement can reduce the amount of algae in certain scenarios, but they consume a lot of electricity and have cumbersome equipment, making them unsuitable for long-term use in large water bodies (Lan et al., 2024). Additionally, new technologies like nanomaterials, ultraviolet treatment, etc., can quickly kill algae, but they are costly, subject to policy and safety regulations, and have ecological risks. Therefore, they have not been widely adopted (Wang et al., 2025c).

On the other hand, advanced early warning technologies such as satellite monitoring, automatic sensors, molecular detection, and machine learning are crucial for detecting and resolving algae problems in advance. However, these systems require continuous capital investment and professional maintenance, and they need to be customized based on different water body conditions (Zahir et al., 2024). In practical applications, these technologies face problems such as insufficient funds and decentralized management responsibilities. Currently, they are only widely used in regions with sufficient funds. In areas with high algae risks but scarce resources, the monitoring capabilities are weak, and they are often not detected until the algae outbreak occurs (Feng et al., 2024).

6.2 Instability of long-term control effects

Even if governance measures are implemented, long-term control effects are often unstable. A comprehensive analysis of global on-site governance measures shows that most physical, microbial, and plant-based control methods, when used alone, do not significantly improve water quality; the observed governance benefits mainly come from a few chemical control methods, and their effects usually only last for a short period. The summary of governance strategies for operating reservoirs also indicates that water flow regulation and internal nutrient control can temporarily suppress algal blooms, but as climate and nutrient load conditions change, or residual nutrients in sediments and algae propagules are not treated, the control effects will fail.

The most fundamental way to control the rampant growth of algae is to reduce the nutrients in the water. However, for severely eutrophic water bodies, it takes a long time to restore and the process is unstable, prone to recurrence. Currently, there is no universal method that can completely solve the problem of large-scale and long-term algal blooms. Therefore, the monitoring plan needs to be continuously optimized, and various comprehensive control measures need to be repeatedly evaluated for their effectiveness. For most water body management, the goal is generally to reduce the frequency of algal blooms and mitigate the damage, rather than completely eradicating algae (Anabtawi et al., 2024; Liu et al., 2025).

6.3 Management challenges exacerbated by climate change

Climate change makes the management of algal blooms increasingly challenging, as it turns the management goal into a "moving target", making the already difficult task of reducing emissions even more complicated. The rise in temperature makes water more prone to stratification, and the duration of stratification becomes longer; coupled with changes in hydrological conditions, as well as the increasing occurrence of extreme weather such as ocean heat waves, heavy rains, and droughts, all these create a more favorable environment for harmful algae to grow, prolonging the season and expanding the range of algal blooms. Long-term data shows that although some lakes in North America and Europe have been managed for several decades and have been controlling the input of nutrients, toxic algal blooms have reappeared (Feng et al., 2024), which is the result of the combined effect of climate warming and residual pollution.

Extreme weather events such as ocean heat waves and El Niño have triggered rare large-scale algal blooms, with toxic algae proliferating in the Pacific Ocean and waters in the Southern Hemisphere. This has also sounded the alarm for subsequent algal bloom control efforts. Climate change has significantly reduced the effectiveness of the original emission reduction targets and control methods. Pet et al. pointed out that whether it is nutrient control or water diversion and dilution, all types of control strategies must be re-planned in light of the new water temperature and volume. Emission reduction targets need to be adjusted promptly, and the algal bloom warning line should also take climate factors into account. The combination of climate change and human activities has made the timing and location of algal blooms more difficult to predict, which not only increases the difficulty of prediction but also makes the governance work more cumbersome (Feng et al., 2024; Hwang et al., 2024). If the monitoring network and engineering measures cannot keep up with the pace of climate change, the existing governance methods will soon become ineffective.

7 Future Directions

7.1 Integrated management combining multiple technologies

Future HAB mitigation is expected to rely on integrated, multi-technology portfolios rather than single interventions. Recent reviews stress that physical, chemical, and biological methods each have characteristic limitations, and that combining them can compensate for weaknesses in efficacy, cost, and environmental side-effects (Anabtawi et al., 2024; Lan et al., 2024). Integrated strategies include pairing watershed nutrient controls with in-reservoir hydrodynamic manipulation, selective chemical treatments, and biological controls to deliver both rapid risk reduction and long-term ecosystem recovery. Studies also highlight the potential to couple treatment with biomass harvesting and valorization, turning blooms into resources (e.g., bio-products, materials) and aligning mitigation with circular and low-carbon development goals (Hwang et al., 2024; Liu et al., 2025).

Scaling such integrated approaches requires frameworks that match tool combinations to bloom type, system characteristics, and management objectives. Inland and coastal reviews propose decision schemes in which preventive nutrient and hydrologic measures form the backbone, while more intensive physical, chemical, and biological tools are deployed tactically during high-risk periods (Feng et al., 2024). Future research priorities include rigorous field-scale testing of multi-method packages, better understanding of cumulative ecological impacts, and design of operational guidelines for "integrated management interventions" that explicitly coordinate watershed, in-water, and downstream coastal actions across the aquatic continuum (Anabtawi et al., 2024).

7.2 Intelligent monitoring and precision management

Rapid advances in observation and computation are driving a transition toward intelligent, precision HAB management. Integrated monitoring concepts emphasize combining satellite and drone remote sensing, automated buoys, in situ biosensors, molecular diagnostics, and toxin assays to provide multi-scale, high- frequency data for early warning (Lan et al., 2024; Brenckman et al., 2025). Numerical models and Earth-system frameworks are increasingly merged with machine-learning methods such as random forests, support vector machines, and LSTM networks to improve detection, short-term forecasts, and scenario analysis for management decisions (Esposito et al., 2025; Rathore et al., 2025).

Next-generation systems seek to directly couple these data streams to real-time decision support. AI-assisted integrated governance frameworks link multi-modal monitoring with treatment modules and microalgal resource recovery, aiming to move from "passive emergency response" to active prevention and control (Lin et al., 2025). Digital-twin lake architectures and automated buoy-ML platforms demonstrate how continuous, high-resolution data can drive dynamic, site-specific interventions and automated alerts that signal bloom thresholds relevant for public health and operations (Zahir et al., 2024; Rathore et al., 2025). At larger scales, efforts to build regional and ultimately global HAB observing systems envision standardized, interoperable networks that feed into precision management at local and national levels.

7.3 Ecologically prioritized and sustainable governance approaches

There is a growing emphasis on ecologically prioritized, sustainable governance that addresses root drivers while minimizing collateral damage. Multiple syntheses stress that long- term control must be grounded in nutrient-enrichment management-especially dual nitrogen and phosphorus reductions, improved wastewater and agricultural practices, and hydrologic restoration-integrated with climate-adaptation strategies to confront the "moving targets" created by warming and altered hydrology (Feng et al., 2024; Brenckman et al., 2025). Ecological and nature-based solutions, including wetland nutrient capture, biomanipulation, restoration of macrophytes and seagrasses, and promotion of algicidal and growth-inhibiting bacterial communities, are highlighted as core elements of sustainable HAB prevention (Liu et al., 2025; Hwang et al., 2024).

Governance frameworks are evolving toward cross-sectoral, multi-level arrangements that link water quality, fisheries, public health, and climate objectives. Reviews call for integrated observing networks, open data, and participatory approaches that incorporate local stakeholders, indigenous concepts such as "Sato-Umi," and community co-management to maintain social license for interventions (Hwang et al., 2024). Future directions emphasize embedding HAB policy within broader ecosystem-based and SDG-aligned agendas, strengthening institutional capacity for adaptive management, and ensuring that technological innovation is consistently evaluated against ecological integrity and long-term sustainability criteria (Feng et al., 2024; Brenckman et al., 2025).

8 Concluding Remarks

The research on harmful algal blooms has evolved from focusing only on individual cases in the early stage to a comprehensive research system that includes cause analysis, monitoring, and various governance methods. The technical means involved have also increased. The existing research review summarizes various governance methods such as physical, chemical, and biological ones, and also introduces some emerging technologies, such as nanotechnology, electrocoagulation technology, and ultrasonic technology. The focus of the research is mainly on finding a reasonable balance among the governance effect, economic cost, and environmental impact. The related review also points out that there is currently no single method that can solve all problems or achieve long-term and thorough control of algal blooms. In recent years, with the development of satellite remote sensing, underwater automatic sensors, molecular detection technology, and data models, people's ability to monitor and warn of algal blooms has significantly improved, enabling earlier detection and response to algal blooms in marine and freshwater environments. At the same time, the issue of algal bloom governance has gradually been linked to broader issues such as social development, ecological protection, and policy management. By integrating the results of various studies, it can be seen that although significant progress has been made in scientific understanding and technical reserves, there are still certain deficiencies in long-term governance effects, governance capabilities, and cross-departmental cooperation.

In recent comprehensive studies, "prevention first and comprehensive management" has been regarded as an important approach for controlling algal blooms in the future. For instance, measures such as reducing the discharge of nutrients like nitrogen and phosphorus, improving wastewater treatment and agricultural management methods, and restoring natural water flow have always been considered as important foundations for solving algal bloom problems and key means to reduce the risk of large-scale and long-term algal blooms. However, single governance methods are often limited by factors such as water body size, cost, or ecological impact. Therefore, some studies suggest combining physical, chemical and biological methods, such as using algivorous microorganisms, regulating the food chain structure, or promoting flocculation through nanomaterials, to form more targeted comprehensive management plans. Such plans can not only reduce the risk of algal blooms in the short term but also contribute to the long-term restoration of the water body ecosystem. Moreover, effective prevention also requires the establishment of a complete monitoring network, the formation of unified and standardized monitoring methods, and the establishment of a risk communication mechanism that can promptly convey scientific information to managers and the public, thereby increasing public participation. These practices also indicate that algal bloom control requires interdisciplinary and holistic management from the watershed to the estuary.

In the future, the management of cyanobacterial blooms will rely more on technological upgrades and the optimization of management methods. The new generation of control systems will closely integrate monitoring and management work, integrate various observational data, model algorithms and intelligent tools, build an intelligent monitoring and governance network, and make management more predictive. The current key technical directions are to develop environmental-friendly nanomaterials, promote microbial and ecological restoration methods, and use underwater and hyperspectral observation equipment. Various regions are also improving their management systems, integrating the management of cyanobacterial blooms with major policies such as climate change and public health, and enhancing the adaptability and sustainability of aquatic ecosystems.

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