Harmful Algal Blooms in a Changing Climate: Triggers, Detection, and Management

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Abstract
Harmful algal blooms (HABs) have emerged as one of the most challenging ecological and environmental problems affecting freshwater, coastal, and marine ecosystems worldwide. These events occur when certain species of algae or cyanobacteria experience rapid population growth and produce harmful effects through toxin production, oxygen depletion, habitat alteration, or disruption of aquatic food webs. In recent decades, the frequency, geographical distribution, and intensity of HAB events have increased in many regions due to the combined influence of climate change, nutrient enrichment, hydrological alterations, and increasing anthropogenic pressure. Rising water temperatures, altered precipitation patterns, ocean warming, and extreme climatic events are creating conditions that favor bloom formation and persistence.

Climate change does not act as a single trigger but interacts with nutrient availability, water circulation, and biological processes to influence HAB development. Warmer conditions may enhance the growth of toxin-producing cyanobacteria and harmful marine phytoplankton, while increased nutrient loading from agricultural runoff and wastewater discharge provides the resources required for excessive biomass accumulation. Recent advances in detection technologies, including molecular tools, satellite remote sensing, automated sensors, and artificial intelligence-based prediction models, have improved the ability to monitor and forecast HAB events. However, challenges remain in developing reliable early warning systems, especially in regions with limited monitoring capacity.

This review discusses the major environmental drivers of HABs under changing climatic conditions, summarizes current detection approaches, and evaluates management strategies for reducing their ecological and socioeconomic impacts. Particular attention is given to recent scientific advances and integrated approaches combining environmental monitoring, nutrient management, and predictive modelling. Understanding the complex relationship between climate change and HAB dynamics is essential for protecting aquatic ecosystems, fisheries, public health, and water resources in the future.

Keywords: Harmful algal blooms; Climate change; Cyanobacteria; Phytoplankton; Remote sensing; Aquatic ecosystems; Environmental monitoring; Toxins

1. Introduction

Aquatic ecosystems are increasingly experiencing ecological disturbances caused by harmful algal blooms (HABs), which represent periods of excessive growth of algae or cyanobacteria capable of producing negative environmental, economic, and public health consequences. Although algal blooms are naturally occurring phenomena and some blooms contribute positively to aquatic productivity, harmful blooms differ because they can produce toxic compounds, reduce dissolved oxygen levels, block sunlight penetration, and disrupt aquatic food chains. These impacts can affect drinking water supplies, fisheries, tourism, and ecosystem stability (Wurtsbaugh et al., 2019).

Historically, HAB events were often considered localized ecological problems associated mainly with nutrient pollution and eutrophication. However, recent observations indicate that HABs are becoming increasingly widespread and complex due to the interaction between human activities and global climate change. Rising temperatures, changing rainfall patterns, increased frequency of extreme weather events, and alterations in ocean chemistry are modifying aquatic environments in ways that favor many bloom-forming species. Recent global assessments suggest that climate change is reshaping HAB dynamics by influencing species distribution, bloom timing, toxin production, and ecosystem vulnerability (Gobler, 2020).

Freshwater systems are particularly vulnerable to harmful cyanobacterial blooms because many cyanobacteria have physiological advantages under warmer and nutrient-rich conditions. Species such as Microcystis, Dolichospermum (formerly Anabaena), and Aphanizomenon can form extensive surface blooms and produce toxins including microcystins, cylindrospermopsin, and saxitoxins. These compounds pose risks to aquatic organisms and humans through contaminated drinking water and recreational exposure (Huisman et al., 2018). Recent reviews have highlighted that inland HAB occurrences have increased globally due to a combination of nutrient enrichment, urbanization, and warming temperatures.

Marine HABs also represent a growing concern because toxin-producing dinoflagellates, diatoms, and other phytoplankton species can accumulate in seafood organisms and cause illnesses such as paralytic shellfish poisoning, diarrhetic shellfish poisoning, and amnesic shellfish poisoning. Climate-driven changes in ocean temperature, currents, and nutrient availability are altering marine HAB patterns and expanding the geographical range of some harmful species (Wells et al., 2020).

The management of HABs has become increasingly challenging because climate change introduces additional uncertainty into bloom prediction and control. Traditional monitoring approaches based on microscopic identification and laboratory toxin analysis remain important but are often limited by sampling frequency and geographical coverage. Therefore, modern HAB management increasingly relies on advanced approaches, including satellite observation, molecular detection, automated monitoring systems, and artificial intelligence-based forecasting models (Davidson et al., 2021).

This narrative review examines how climate change influences HAB development, discusses major environmental triggers, summarizes current detection methods, and evaluates management approaches aimed at reducing the impacts of these events. By integrating recent scientific findings, this review highlights the need for multidisciplinary strategies to address HAB challenges in a rapidly changing climate.

2. Harmful Algal Blooms: Ecological Importance and Global Expansion

Harmful algal blooms represent a diverse group of ecological events involving different organisms across freshwater, estuarine, and marine environments. The term “harmful” does not refer only to toxin production; blooms may also become harmful through excessive biomass accumulation, oxygen depletion, shading of aquatic plants, and disruption of ecological interactions.

The ecological consequences of HABs can be severe. Dense blooms reduce light availability for submerged vegetation, alter nutrient cycling, and create hypoxic or anoxic conditions when organic matter decomposes. Fish mortality events associated with oxygen depletion have been reported in both freshwater lakes and coastal regions. In addition, toxin-producing species can affect organisms across multiple trophic levels, from zooplankton and fish to birds and marine mammals.

Among freshwater systems, cyanobacteria are among the most concerning HAB-forming organisms because of their ability to tolerate environmental stress and regulate buoyancy, allowing them to dominate surface waters during favorable conditions. Warmer temperatures provide a competitive advantage to many cyanobacteria compared with other phytoplankton groups. Research indicates that climate warming is likely to increase the occurrence of cyanobacterial blooms in many freshwater systems, particularly where nutrient pollution remains high (Paerl & Huisman, 2009; Jöhnk et al., 2008).

Marine HABs are also expanding in distribution. Species associated with harmful events have been detected in regions where they were previously uncommon, partly due to changing ocean temperatures and altered circulation patterns. Recent studies indicate that warming oceans may facilitate the movement of some HAB species toward higher latitudes, creating new ecological challenges for fisheries and coastal communities (Gobler, 2020).

The economic impacts of HABs are substantial. Fisheries closures, reduced tourism activity, increased water treatment costs, and losses in aquaculture production create significant financial burdens. Shellfish industries are particularly vulnerable because filter-feeding organisms accumulate algal toxins even when the water appears visually normal. Therefore, effective monitoring and early detection remain essential components of aquatic resource management.

Table 1. Major Environmental Drivers Associated with Harmful Algal Bloom Formation

Harmful algal group	Representative species	Major toxin(s)	Primary impacts	Typical habitat
Cyanobacteria	Microcystis aeruginosa	Microcystins	Liver toxicity, drinking water contamination	Freshwater
Cyanobacteria	Dolichospermum spp.	Anatoxin-a, Saxitoxins	Neurotoxicity, fish mortality	Freshwater
Dinoflagellates	Alexandrium spp.	Saxitoxins	Paralytic shellfish poisoning	Marine
Dinoflagellates	Karenia brevis	Brevetoxins	Fish kills, respiratory irritation	Marine
Dinoflagellates	Dinophysis spp.	Okadaic acid	Diarrhetic shellfish poisoning	Marine
Diatoms	Pseudo-nitzschia spp.	Domoic acid	Amnesic shellfish poisoning	Marine
Raphidophytes	Heterosigma akashiwo	Reactive oxygen species	Massive fish kills	Coastal marine

2. Climate Change and Environmental Triggers of Harmful Algal Blooms

Harmful algal blooms (HABs) arise from a complex interplay of physical, chemical, and biological processes rather than from a single environmental factor. While nutrient enrichment has historically been regarded as the dominant driver of bloom formation, recent evidence demonstrates that climate change is increasingly modifying these processes by altering temperature regimes, hydrological cycles, ocean circulation, and biogeochemical dynamics. These climatic changes not only increase the frequency of bloom events but also extend bloom duration, expand their geographical distribution, and enhance toxin production in several harmful algal species (Gobler, 2020; Wells et al., 2020).

2.1 Rising Water Temperature

Among the various climatic drivers, increasing water temperature is considered one of the most influential factors promoting HAB development. Most bloom-forming cyanobacteria and dinoflagellates exhibit optimal growth at temperatures higher than those preferred by many competing phytoplankton species. Consequently, global warming increasingly favors harmful taxa over non-toxic phytoplankton communities.

Higher temperatures accelerate cellular metabolism, photosynthesis, and nutrient uptake, enabling harmful algae to complete their life cycles more rapidly. Cyanobacteria such as Microcystis aeruginosa, Dolichospermum spp., and Planktothrix agardhii often dominate freshwater ecosystems during prolonged warm periods, whereas marine dinoflagellates including Alexandrium, Karenia, and Dinophysis species benefit from warmer coastal waters (Paerl et al., 2018).

Marine heatwaves, whose frequency has increased considerably during the past two decades, have been linked to unprecedented HAB events worldwide. For example, the extensive northeast Pacific marine heatwave between 2014 and 2016 created favorable environmental conditions for one of the largest recorded blooms of the diatom Pseudo-nitzschia, resulting in elevated domoic acid concentrations and widespread fisheries closures along the western coast of North America (McCabe et al., 2016). Similar observations have been reported in European, Australian, and Asian coastal waters, suggesting that marine warming is becoming a global catalyst for HAB expansion.

Temperature also influences toxin biosynthesis. Several experimental studies have demonstrated increased production of microcystins, saxitoxins, and brevetoxins under elevated temperatures, although species-specific responses remain variable (Gobler, 2020). Consequently, warmer waters may increase not only bloom biomass but also bloom toxicity, thereby amplifying ecological and public health risks.

2.2 Nutrient Enrichment and Eutrophication

Although climate change creates favorable environmental conditions, excessive nutrient loading remains the fundamental prerequisite for most HAB events. Nitrogen (N) and phosphorus (P) originating from agricultural runoff, untreated municipal wastewater, industrial discharges, and urban stormwater stimulate primary productivity, often leading to eutrophication in freshwater and coastal ecosystems.

The interaction between eutrophication and climate change has become increasingly important. Rising temperatures accelerate nutrient recycling within sediments, while more frequent heavy rainfall events transport greater quantities of dissolved nutrients into rivers, lakes, and estuaries. Conversely, drought conditions reduce river discharge, increasing nutrient residence time and allowing bloom-forming species to proliferate under stagnant conditions (Paerl & Otten, 2016).

Recent studies suggest that changing nitrogen-to-phosphorus (N:P) ratios may also influence community composition. Certain cyanobacteria capable of atmospheric nitrogen fixation gain a competitive advantage under phosphorus-rich but nitrogen-limited conditions, whereas other harmful algae thrive when nitrogen availability increases. Consequently, both nutrient concentration and nutrient stoichiometry influence bloom initiation, species succession, and toxin production.

Importantly, nutrient reduction alone may not completely eliminate HABs under future climate scenarios because warmer waters continue to provide physiological advantages to bloom-forming taxa. This highlights the need for integrated watershed management strategies that simultaneously address eutrophication and climate adaptation.

2.3 Hydrological Changes and Extreme Weather Events

Climate change has intensified the global hydrological cycle, producing more frequent floods, prolonged droughts, hurricanes, and intense precipitation events. These hydrological extremes strongly influence HAB dynamics by modifying nutrient transport, water residence time, salinity, and ecosystem stability.

Heavy rainfall rapidly transports sediments, fertilizers, livestock waste, and organic matter into receiving water bodies. The resulting nutrient pulses frequently trigger bloom initiation shortly after storm events. In contrast, prolonged droughts reduce river flow and increase water residence time, creating stable conditions that facilitate cyanobacterial dominance in reservoirs and lakes.

Storm-driven mixing may initially disrupt existing blooms but often redistributes nutrients throughout the water column, promoting subsequent bloom development once calm conditions return. Coastal hurricanes also modify estuarine salinity and circulation patterns, altering the distribution of bloom-forming species and occasionally introducing offshore populations into nearshore environments.

Marine heatwaves combined with altered precipitation regimes have increasingly produced compound climatic events in which multiple environmental stressors occur simultaneously. These compound events are now recognized as important drivers of large-scale HAB outbreaks under projected climate change scenarios.

2.4 Ocean Acidification and Elevated Carbon Dioxide

Increasing atmospheric carbon dioxide concentrations are causing progressive ocean acidification while simultaneously increasing dissolved inorganic carbon available for photosynthesis. Many bloom-forming algae possess carbon concentrating mechanisms that enable efficient utilization of elevated CO_2 concentrations, potentially providing competitive advantages under future climate conditions.

Experimental investigations indicate that increased CO_2 availability can enhance growth rates in several cyanobacterial and dinoflagellate species while altering cellular toxin production. However, responses remain highly species-specific because physiological adaptation varies considerably among phytoplankton taxa.

Ocean acidification also influences nutrient chemistry, trace metal availability, and microbial interactions, indirectly affecting bloom dynamics. Although acidification alone rarely initiates HABs, it interacts synergistically with warming, eutrophication, and stratification to increase bloom probability in vulnerable ecosystems (Wells et al., 2020).

2.5 Water Column Stratification

Thermal stratification has become increasingly common in both freshwater and marine ecosystems due to rising surface temperatures. Strong stratification reduces vertical mixing between surface and deeper waters, producing stable environmental conditions that favor buoyant cyanobacteria and motile dinoflagellates.

Many harmful cyanobacteria regulate their buoyancy through intracellular gas vesicles, allowing them to remain near the illuminated surface where photosynthesis is maximized. Dinoflagellates similarly exploit stable water columns through vertical migration, accessing nutrients at depth while maintaining favorable light conditions near the surface.

Extended stratification additionally promotes oxygen depletion within bottom waters. Resulting hypoxia accelerates phosphorus release from sediments, creating positive feedback mechanisms that further stimulate bloom persistence.

2.6 Biological Interactions

Beyond physical and chemical drivers, biological interactions substantially influence HAB dynamics. Competition among phytoplankton species, grazing by zooplankton, viral infections, bacterial symbioses, and allelopathic interactions collectively determine whether bloom-forming species become dominant.

Climate change may alter food web structure by reducing populations of grazers capable of controlling phytoplankton biomass. Simultaneously, changing microbial communities influence nutrient cycling, toxin degradation, and bloom longevity. Increasing evidence indicates that bacterial communities associated with harmful algae contribute to nutrient acquisition and toxin synthesis, highlighting the importance of considering HABs as complex microbial ecosystems rather than isolated algal events.

The combined influence of climatic drivers, eutrophication, and ecological interactions demonstrates that HAB development is governed by multiple reinforcing mechanisms rather than a single environmental trigger. Consequently, predictive models increasingly incorporate physical, chemical, and biological variables simultaneously to improve forecasting accuracy.

Table 2. Climate-Related Drivers Promoting Harmful Algal Blooms

Climate driver	Mechanism	Effect on HABs
Rising water temperature	Accelerated metabolism and reproduction	Faster bloom initiation and longer bloom duration
Marine heatwaves	Elevated sea surface temperature	Large-scale bloom expansion
Thermal stratification	Stable water column	Enhanced cyanobacterial and dinoflagellate dominance
Heavy rainfall	Increased nutrient runoff	Bloom initiation following nutrient pulses
Drought	Longer water residence time	Persistent blooms in lakes and reservoirs
Ocean acidification	Increased dissolved CO_2	Enhanced growth in some harmful taxa
Sea-level rise	Altered estuarine salinity	Changes in species distribution
Extreme storms	Nutrient redistribution	Bloom disruption followed by rapid resurgence

3. Detection and Monitoring Technologies for Harmful Algal Blooms

The increasing frequency and spatial expansion of harmful algal blooms (HABs) have intensified the demand for rapid, accurate, and cost-effective monitoring systems. Traditional monitoring approaches based solely on field sampling and microscopic identification remain valuable but are often labor-intensive, time-consuming, and inadequate for providing early warning over large spatial scales. Consequently, significant advances have been made during the past decade in integrating remote sensing, molecular biology, autonomous monitoring platforms, and artificial intelligence (AI) into HAB surveillance programs. These technologies enable continuous environmental monitoring, facilitate early bloom detection, and improve forecasting accuracy, thereby supporting timely management interventions.

3.1 Conventional Monitoring Methods

Routine monitoring of HABs has traditionally relied on water sampling followed by microscopic examination of phytoplankton communities. Identification is primarily based on cellular morphology, pigmentation, and taxonomic characteristics. Measurements of chlorophyll-a, nutrient concentrations, dissolved oxygen, pH, turbidity, and temperature are commonly incorporated to evaluate bloom development and environmental conditions.

Although microscopy remains the benchmark for species identification, it has several limitations. Accurate identification requires highly trained taxonomists, sample processing is time-intensive, and morphologically similar species are often difficult to distinguish. Furthermore, microscopic methods may underestimate low-abundance toxic species that can rapidly proliferate under favorable environmental conditions. These limitations have encouraged the development of complementary molecular and remote sensing techniques.

3.2 Remote Sensing Technologies

Satellite remote sensing has become one of the most effective tools for monitoring HABs across large aquatic environments. Earth-observation satellites equipped with multispectral and hyperspectral sensors can detect changes in water color, chlorophyll-a concentration, suspended particles, and cyanobacterial pigments such as phycocyanin and phycoerythrin.

Satellite platforms including Sentinel-2, Sentinel-3, Landsat-8/9, MODIS (Moderate Resolution Imaging Spectroradiometer), and VIIRS (Visible Infrared Imaging Radiometer Suite) now provide frequent observations of coastal waters, reservoirs, estuaries, and large lakes. These datasets enable researchers to identify bloom initiation, estimate bloom extent, monitor seasonal variability, and assess long-term ecological trends.

One of the greatest advantages of satellite monitoring is its ability to cover extensive geographical regions at relatively low operational cost. Continuous observations also facilitate the development of predictive models by integrating historical bloom records with environmental variables. However, cloud cover, atmospheric interference, limited penetration into deeper waters, and difficulty distinguishing between algal species remain important constraints. Consequently, remote sensing is most effective when integrated with field observations and laboratory analyses.

3.3 Molecular Techniques and Environmental DNA (eDNA)

Molecular biology has revolutionized HAB detection by enabling rapid identification of harmful species before visible blooms develop. Polymerase chain reaction (PCR), quantitative PCR (qPCR), digital PCR, fluorescence in situ hybridization (FISH), and next-generation sequencing (NGS) have substantially improved taxonomic resolution compared with traditional microscopy.

Environmental DNA (eDNA) has emerged as one of the most promising monitoring approaches. Organisms continuously release genetic material into surrounding water through cellular debris, mucus, feces, and extracellular DNA. By collecting water samples and sequencing environmental DNA, researchers can identify harmful algal species without directly isolating intact cells.

Metabarcoding further expands this capability by simultaneously identifying hundreds of phytoplankton taxa from a single sample. These methods enable early detection of invasive or toxin-producing species even when present at very low abundances. Early identification is particularly valuable because management measures are generally more effective before blooms reach their peak intensity.

Despite their sensitivity, molecular methods require standardized laboratory procedures, high-quality reference databases, and specialized technical expertise. Environmental factors influencing DNA degradation may also affect detection accuracy, highlighting the importance of integrating molecular analyses with ecological monitoring.

3.4 Biosensors and Autonomous Monitoring Systems

Recent technological advances have facilitated the deployment of autonomous monitoring systems capable of collecting environmental data continuously with minimal human intervention. Instrumented buoys, underwater gliders, autonomous surface vehicles, and sensor-equipped drones now provide near real-time information on water quality and bloom dynamics.

Modern biosensors can rapidly detect chlorophyll-a, phycocyanin, dissolved oxygen, pH, conductivity, nutrient concentrations, and in some cases specific cyanobacterial toxins such as microcystins. Portable immunosensors and electrochemical biosensors are increasingly used for rapid field assessment because they require limited sample preparation while providing results within minutes.

The integration of Internet of Things (IoT) technologies has further enhanced monitoring efficiency. Sensor networks transmit real-time environmental data directly to centralized databases, enabling automated alert systems that notify environmental agencies when bloom thresholds are exceeded. Such systems are particularly valuable for drinking water reservoirs, aquaculture facilities, and recreational waters where timely intervention is essential.

3.5 Artificial Intelligence and Predictive Modelling

Artificial intelligence has become an increasingly powerful tool for predicting HAB occurrence under changing environmental conditions. Machine learning algorithms can analyze complex relationships among meteorological, hydrological, chemical, and biological variables that traditional statistical models often fail to capture.

Algorithms including Random Forest, Support Vector Machines, Artificial Neural Networks, Gradient Boosting, and Deep Learning have demonstrated high predictive performance for forecasting bloom initiation, duration, and intensity. These models integrate multiple environmental variables, including water temperature, nutrient concentrations, rainfall, wind speed, solar radiation, river discharge, and historical bloom records.

Recent studies have further combined satellite imagery with machine learning to generate automated bloom detection systems capable of classifying HAB events with high accuracy. Such integrated approaches are increasingly supporting environmental decision-making by providing early warning systems for water resource managers and public health authorities.

Despite these advances, predictive accuracy remains dependent on data quality and availability. Many models perform well within individual ecosystems but exhibit reduced transferability to geographically distinct regions because bloom dynamics differ among aquatic environments. Continued development of standardized datasets and hybrid modelling approaches is therefore expected to improve forecasting reliability under future climate scenarios.

Table 3. Comparison of Common Detection Technologies for Harmful Algal Blooms

Detection method	**Principle**	**Major advantages**	**Limitations**	**Typical applications**
Light microscopy	Morphological identification	Taxonomically reliable; widely accepted	Time-consuming; requires expertise	Routine monitoring
Chlorophyll-a analysis	Pigment quantification	Simple and inexpensive	Non-specific for harmful species	Water quality assessment
Satellite remote sensing	Spectral reflectance	Large spatial coverage; continuous monitoring	Cloud interference; limited species identification	Coastal and inland water surveillance
Environmental DNA (eDNA)	Detection of genetic material	Highly sensitive; early detection	Laboratory intensive; requires reference databases	Species identification
qPCR	Amplification of target genes	High specificity and sensitivity	Species-specific primers required	Detection of toxin-producing species
Biosensors	Chemical or immunological detection	Rapid, portable, real-time analysis	Limited range of detectable toxins	Drinking water monitoring
Autonomous buoys	Continuous environmental sensing	Real-time data acquisition	High installation and maintenance costs	Long-term ecosystem monitoring
AI and Machine Learning	Data-driven prediction	High forecasting capability	Requires large datasets and validation	Early warning systems

4. Management and Mitigation Strategies

Given the multifactorial nature of harmful algal blooms, no single management strategy can effectively prevent bloom formation under all environmental conditions. Instead, successful mitigation requires integrated approaches that address both the underlying causes of eutrophication and the climatic factors that promote bloom persistence. Contemporary management therefore combines watershed-scale nutrient reduction, ecological restoration, physical and chemical interventions, biological control, and advanced monitoring systems within adaptive management frameworks.

4.1 Nutrient Load Reduction

Reducing external nutrient inputs remains the most sustainable long-term strategy for minimizing HAB occurrence. Agricultural best management practices—including precision fertilizer application, vegetated buffer strips, constructed wetlands, and controlled drainage systems—can substantially decrease nitrogen and phosphorus runoff into receiving water bodies. Upgrading wastewater treatment facilities to include advanced nutrient removal technologies further limits anthropogenic nutrient enrichment.

Integrated watershed management is particularly important because nutrient sources often originate far upstream of affected lakes, reservoirs, or coastal ecosystems. Consequently, effective HAB mitigation requires coordinated land-use planning involving agricultural, industrial, and municipal stakeholders.

4.2 Physical and Chemical Control Methods

Several physical techniques have been employed to suppress HAB development in localized water bodies. Artificial mixing and aeration disrupt thermal stratification, reducing the competitive advantage of buoyant cyanobacteria. Flushing reservoirs with increased water exchange may also reduce bloom residence time where hydrological conditions permit.

Chemical treatments, particularly hydrogen peroxide and modified clay formulations, have shown promise for rapidly reducing bloom biomass. Hydrogen peroxide selectively damages cyanobacterial cells while exerting comparatively limited impacts on many non-target organisms when applied appropriately. Modified clays have been widely investigated in coastal environments because they aggregate algal cells, promoting sedimentation and bloom removal.

However, chemical interventions should be considered short-term emergency responses rather than permanent solutions because repeated applications may produce unintended ecological consequences and do not address the environmental conditions that initiate blooms.

4.3 Biological Control and Nature-Based Solutions

Biological control strategies are receiving increasing attention as environmentally sustainable alternatives to chemical treatments. Certain bacteria, viruses, fungi, and zooplankton naturally suppress harmful algal populations through predation, parasitism, or allelopathic interactions. Although several promising laboratory studies have been reported, large-scale field applications remain limited due to ecological uncertainties and regulatory concerns.

Nature-based solutions—including wetland restoration, riparian vegetation establishment, and conservation of aquatic biodiversity—can improve ecosystem resilience by enhancing nutrient retention, increasing ecological stability, and supporting balanced food webs. These ecosystem-based approaches align closely with climate adaptation strategies and offer long-term environmental benefits beyond HAB control alone.

4.4 Integrated Early Warning Systems

Modern HAB management increasingly emphasizes prevention rather than reactive intervention. Integrated early warning systems combine satellite observations, autonomous sensor networks, meteorological forecasts, hydrodynamic models, and machine learning algorithms to predict bloom development before harmful concentrations are reached.

These forecasting systems enable environmental authorities to issue timely public advisories, optimize drinking water treatment processes, regulate shellfish harvesting, and implement targeted mitigation measures. As climate variability continues to increase, predictive management supported by continuous environmental monitoring is expected to become the cornerstone of future HAB mitigation programs.

5. Future Research Directions

Despite substantial progress in understanding the ecology of harmful algal blooms (HABs), several scientific and management challenges remain unresolved. One of the most pressing research priorities is improving the ability to predict bloom occurrence under increasingly complex climate scenarios. Current forecasting models often rely on historical environmental datasets and may not fully capture the interactions among rising temperatures, altered precipitation patterns, nutrient dynamics, and biological feedback mechanisms. Developing integrated predictive frameworks that combine hydrodynamic modelling, remote sensing, machine learning, and ecological process-based models will likely improve forecasting accuracy and support more effective early warning systems.

Another important research gap concerns the physiological responses of HAB-forming species to multiple simultaneous environmental stressors. Most experimental studies have investigated the effects of individual variables such as temperature, nutrient availability, or carbon dioxide concentration in isolation. However, natural ecosystems experience multiple interacting stressors that can influence bloom development in unpredictable ways. Future investigations should therefore adopt multifactorial experimental designs that better reflect real-world environmental conditions and improve understanding of synergistic effects on bloom initiation, persistence, and toxin production.

The application of molecular technologies also presents promising opportunities for advancing HAB research. Environmental DNA (eDNA), metagenomics, transcriptomics, proteomics, and metabolomics have begun to reveal the complex microbial interactions associated with bloom formation. Expanding these approaches could improve species identification, facilitate early detection of emerging harmful taxa, and provide valuable insights into the genetic mechanisms regulating toxin biosynthesis and environmental adaptation.

Climate change is expected to alter the geographical distribution of many harmful algal species, including their expansion into regions previously considered environmentally unsuitable. Long-term ecological monitoring programs are therefore essential for identifying emerging hotspots, evaluating changes in bloom phenology, and assessing ecosystem resilience under changing climatic conditions. Greater international collaboration and standardized monitoring protocols would further enhance data comparability and improve global assessments of HAB trends.

Finally, future management strategies should move beyond reactive bloom control toward ecosystem-based prevention. Reducing nutrient inputs, restoring wetlands, protecting riparian vegetation, improving watershed management, and integrating climate adaptation policies into aquatic resource management offer more sustainable long-term solutions than repeated chemical interventions. Successful HAB mitigation will ultimately depend on interdisciplinary collaboration among ecologists, climatologists, microbiologists, environmental engineers, public health professionals, policymakers, and local stakeholders.

6. Conclusion

Harmful algal blooms have evolved from localized environmental disturbances into one of the most significant global challenges affecting freshwater, estuarine, and marine ecosystems. The evidence reviewed in this paper demonstrates that climate change is substantially altering the environmental conditions that regulate bloom dynamics, while anthropogenic nutrient enrichment continues to provide the resources necessary for bloom proliferation. Rising temperatures, intensified thermal stratification, altered hydrological cycles, ocean acidification, and increasing frequency of extreme weather events collectively create conditions that favor the expansion of toxin-producing algae across diverse aquatic environments.

Recent technological advances have transformed HAB monitoring through the integration of satellite remote sensing, environmental DNA, molecular diagnostics, autonomous sensor platforms, and artificial intelligence-based predictive modelling. These innovations have improved early detection capabilities and offer considerable potential for developing proactive management strategies. Nevertheless, no single monitoring technique provides complete coverage of the diverse environmental and biological factors governing HAB development. Consequently, integrated monitoring systems that combine conventional field observations with advanced technological approaches are likely to provide the greatest reliability.

Similarly, effective mitigation cannot rely solely on localized bloom suppression. Sustainable management requires comprehensive watershed-scale nutrient reduction, ecosystem restoration, adaptive monitoring, and climate-resilient environmental policies. As climate change continues to intensify, preventive management approaches supported by interdisciplinary research and international cooperation will become increasingly important for protecting aquatic ecosystems, safeguarding public health, and maintaining global food and water security.

Future research should prioritize understanding the cumulative impacts of multiple climate stressors, improving predictive modelling under rapidly changing environmental conditions, and developing scalable ecosystem-based management strategies. Continued investment in innovative monitoring technologies and integrated environmental management will be essential for reducing the ecological and socioeconomic consequences of harmful algal blooms in the decades ahead.

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