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Review Article

Harmful Algal Blooms: Causes, Ecological and Human Health Impacts, Detection Technologies, Prevention Strategies, and Future Perspective

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Abstract

Harmful algal blooms (HABs) have become an increasingly significant global environmental issue due to their growing frequency, intensity, and geographical distribution in freshwater, estuarine, and marine ecosystems. Anthropogenic nutrient enrichment, climate change, rising water temperatures, and hydrological alterations have accelerated bloom formation, resulting in severe ecological degradation, biodiversity loss, economic damage, and public health risks. Many bloom-forming cyanobacteria and microalgae produce potent cyanotoxins and phycotoxins, including microcystins, anatoxins, cylindrospermopsins, saxitoxins, brevetoxins, and domoic acid, which contaminate drinking water, threaten aquatic organisms, and cause serious human illnesses through recreational exposure and seafood consumption. This review provides a comprehensive overview of harmful algal blooms, including their classification, environmental drivers, bloom formation mechanisms, toxin production, and ecological, economic, and health impacts. Recent advances in HAB detection and monitoring, such as molecular diagnostics, environmental DNA (eDNA), biosensors, satellite remote sensing, unmanned aerial vehicles (UAVs), artificial intelligence (AI), and machine learning are critically discussed for their role in improving early warning and bloom prediction. The review also evaluates current prevention and control strategies, including nutrient management, watershed protection, physical and chemical interventions, biological control, microbial bioremediation, and integrated ecosystem-based management approaches. Furthermore, future perspectives emphasize the integration of AI-driven forecasting, Internet of Things (IoT)-based monitoring systems, climate-resilient water management, and interdisciplinary collaboration to strengthen HAB surveillance and sustainable mitigation. By integrating recent technological developments with environmentally sustainable management strategies, this review provides a valuable resource for researchers, environmental managers, policymakers, and water resource professionals working toward the protection of aquatic ecosystems and long-term water security.

Keywords: Harmful Algal Blooms; Cyanobacteria; Eutrophication; Cyanotoxins; Environmental DNA (eDNA); Remote Sensing; Artificial Intelligence; Biosensors; Sustainable Management; Water Quality

Abbreviations

HAB: Harmful Algal Bloom; HABs: Harmful Algal Blooms; AI: Artificial Intelligence; ML: Machine Learning; PCR: Polymerase Chain Reaction; qPCR: Quantitative Polymerase Chain Reaction; eDNA: Environmental DNA; UAV: Unmanned Aerial Vehicle; WHO: World Health Organization; PSP: Paralytic Shellfish Poisoning; NSP: Neurotoxic Shellfish Poisoning; DSP: Diarrhetic Shellfish Poisoning; ASP: Amnesic Shellfish Poisoning.

Introduction

Algae are photosynthetic microorganisms that play a fundamental role in maintaining the productivity and ecological balance of freshwater and marine ecosystems. As primary producers, they contribute significantly to global carbon fixation, oxygen evolution, nutrient cycling, and the maintenance of aquatic food webs. Under natural environmental conditions, algal populations remain in dynamic equilibrium and provide essential ecosystem services that support biodiversity and water quality. However, under favourable environmental conditions, including excessive nutrient availability, elevated water temperature, prolonged sunlight exposure, and stable hydrological conditions, algal populations may proliferate rapidly, resulting in the formation of algal blooms. Although algal blooms are natural ecological events, reported increases in their frequency, intensity, persistence, and geographical distribution in some regions have become major environmental concerns worldwide [4,26].

During recent decades, harmful algal blooms (HABs) have emerged as one of the most significant threats to freshwater, estuarine, and marine ecosystems. In many regions, changes in HAB occurrence, intensity, duration, and geographic distribution have been associated with anthropogenic activities. such as rapid urbanization, agricultural intensification, industrialization, aquaculture expansion, and climate change. Excessive inputs of nitrogen and phosphorus from agricultural runoff, untreated domestic sewage, industrial effluents, livestock farming, and urban stormwater accelerate eutrophication, thereby creating favourable conditions for excessive algal growth. Furthermore, climate-related factors, including rising water temperatures, altered precipitation patterns, prolonged droughts, increased atmospheric carbon dioxide concentrations, and extreme weather events, further enhance bloom development by promoting the growth and persistence of bloom-forming species [1,14,19,20].

It is important to distinguish among the terms algal bloom, cyanobacterial bloom, nuisance bloom, and harmful algal bloom (HAB). An algal bloom broadly refers to a rapid and excessive increase in the biomass or abundance of algae in an aquatic environment, whereas a cyanobacterial bloom specifically refers to the proliferation of cyanobacteria, which are often referred to as blue-green algae. A nuisance bloom is characterized primarily by its adverse effects on water quality, ecosystem functioning, aesthetics, or recreational activities and does not necessarily involve toxin production. In contrast, a harmful algal bloom (HAB) refers to a bloom that causes or has the potential to cause adverse ecological, environmental, or human-health effects. Importantly, HABs are not restricted to toxin-producing blooms. High algal or cyanobacterial biomass can cause harm through oxygen depletion, reduced light penetration, habitat alteration, and other ecological effects even in the absence of known toxins. Where toxins are produced, their occurrence and concentrations may vary depending on the species or strain and environmental conditions such as nutrient availability, temperature, light, and other physicochemical factors. Thus, toxin production should be considered one mechanism of HAB-associated harm rather than a prerequisite for defining a bloom as harmful [5,6].

Recent studies indicate that HABs occur across a wide range of freshwater, estuarine, and marine environments, while trends in their frequency, intensity, duration, and geographic distribution vary among regions and ecosystems, affecting lakes, rivers, reservoirs, estuaries, and coastal waters across all continents. Freshwater HABs are predominantly caused by cyanobacteria, whereas marine blooms are primarily associated with dinoflagellates, diatoms, haptophytes, and other phytoplankton groups. Many bloom-forming organisms produce potent cyanotoxins and phycotoxins, including microcystins, anatoxins, cylindrospermopsins, saxitoxins, brevetoxins, and domoic acid. These toxins contaminate drinking water supplies, accumulate within aquatic food webs, and pose serious risks to aquatic organisms, livestock, wildlife, and human health through contaminated water, seafood consumption, recreational activities, and aerosol exposure. Consequently, HABs have become an important global concern for environmental protection, water resource management, food security, and public health [3,11,12].

Beyond their ecological consequences, harmful algal blooms impose substantial socioeconomic burdens worldwide. Bloom events reduce fisheries and aquaculture productivity, increase operational costs for drinking water treatment, adversely affect tourism and recreational activities, and require extensive investments in environmental monitoring, risk assessment, and mitigation programs. The projected increase in HAB occurrence under future climate change scenarios highlights the urgent need for sustainable management strategies capable of minimizing their environmental, economic, and societal impacts [1,4].

Significant advances have been achieved in understanding the ecology, monitoring, and management of harmful algal blooms. Conventional monitoring methods based on microscopic identification and physicochemical water quality analysis have been complemented by advanced technologies such as molecular diagnostics, environmental DNA (eDNA), metagenomics, biosensors, satellite remote sensing, unmanned aerial vehicles (UAVs), artificial intelligence (AI), and machine learning. These emerging technologies have considerably improved the early detection, prediction, and real-time monitoring of bloom events while supporting more effective environmental management. In addition, environmentally sustainable approaches, including biological control, microbial bioremediation, nutrient management, constructed wetlands, and integrated watershed management, have gained increasing attention as alternatives to conventional chemical control methods [20,28,29].

Although numerous review articles have examined individual aspects of harmful algal blooms, including eutrophication, toxin production, bloom ecology, and monitoring technologies, relatively few have integrated recent technological innovations with sustainable prevention and management strategies. Rapid developments in artificial intelligence, remote sensing, environmental DNA-based monitoring, microbial biotechnology, and climate-resilient water management have created the need for an updated and comprehensive synthesis that bridges these multidisciplinary advances.

Therefore, this review provides a comprehensive overview of harmful algal blooms by examining their causes, classification, bloom formation mechanisms, toxin production, ecological, economic, and public health impacts, recent advances in detection and monitoring technologies, prevention and control strategies, and future research perspectives. Unlike previous reviews that primarily focused on bloom ecology or toxin production, the present review integrates emerging monitoring technologies, artificial intelligence-based prediction systems, biological control approaches, and sustainable management strategies to provide a multidisciplinary perspective on HAB mitigation. The information presented herein is expected to serve as a valuable resource for researchers, environmental scientists, water resource managers, policymakers, and public health professionals involved in the monitoring, prevention, and sustainable management of harmful algal blooms.

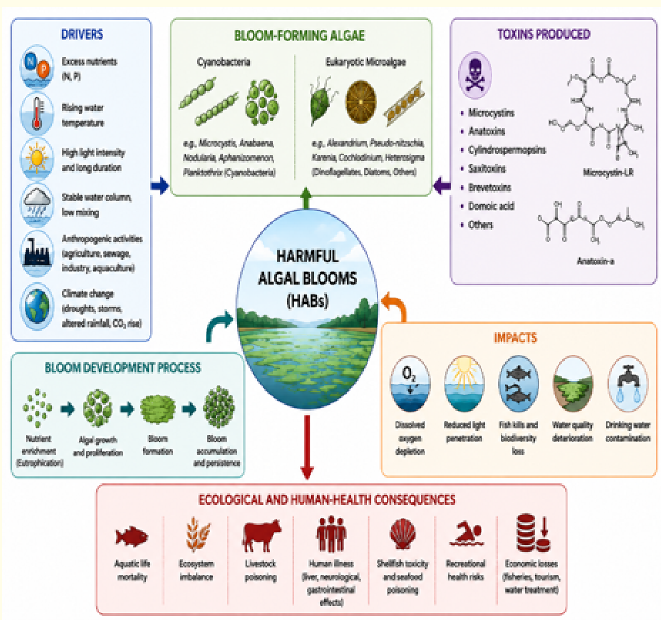

Figure 1: Schematic representation of harmful algal bloom (HAB) formation showing major drivers, bloom-forming organisms, bloom development process, toxins produced, impacts, and ecological and human-health consequences. Source: Author-generated.

Global Distribution and Trends of HABs

Recent studies indicate that harmful algal blooms (HABs) occur across a wide range of freshwater, estuarine, and marine environments, while trends in their frequency, intensity, duration, and geographic distribution vary among regions and ecosystems, affecting lakes, rivers, reservoirs, estuaries, and coastal waters across all continents. Freshwater HABs are predominantly caused by cyanobacteria, whereas marine blooms are primarily associated with dinoflagellates, diatoms, haptophytes, and other phytoplankton groups. Many bloom-forming organisms produce potent cyanotoxins and phycotoxins, including microcystins, anatoxins, cylindrospermopsins, saxitoxins, brevetoxins, and domoic acid. These toxins contaminate drinking water supplies, accumulate within aquatic food webs, and pose serious risks to aquatic organisms, livestock, wildlife, and human health through contaminated water, seafood consumption, recreational activities, and aerosol exposure. Consequently, HABs have become an important global concern for environmental protection, water resource management, food security, and public health [3,4,11,12,15].

Literature search and review methodology

The literature searches primarily considered peer-reviewed studies published between 2000 and 2025, together with selected earlier landmark studies that provided important historical or foundational information. Studies were included when they addressed HAB occurrence, causative organisms, toxin production, environmental drivers, ecological or human-health impacts, detection and monitoring approaches, or prevention and management strategies. Review articles, research articles, authoritative reports, and relevant guidance documents were also considered where appropriate [4,11,15].

Studies were excluded when they were unrelated to HABs or cyanobacterial blooms, duplicate records, or lacked sufficient information relevant to the objectives of this review. Retrieved literature was screened based on title, abstract, and relevance, followed by full-text assessment where necessary. The selected literature was synthesized thematically to compare HAB detection methods, environmental drivers, impacts, and management strategies [1,20,29].

Biology of algae and harmful algal blooms

Algae are a diverse group of photosynthetic organisms that inhabit a wide range of aquatic and terrestrial environments. They play a fundamental role in global primary production and contribute substantially to oxygen production through photosynthesis. Marine phytoplankton and other oceanic photosynthetic microorganisms account for a substantial proportion of global oxygen production; therefore, this contribution should not be attributed to algae alone. Algae utilize sunlight, carbon dioxide, and inorganic nutrients to produce organic matter, thereby regulating carbon cycling, nutrient dynamics, and ecosystem productivity. Algae utilize sunlight, carbon dioxide, and inorganic nutrients to produce organic matter, thereby regulating carbon cycling, nutrient dynamics, and ecosystem productivity. Depending on their morphology and cellular organization, algae range from microscopic unicellular species to large multicellular seaweeds, occupying freshwater, marine, estuarine, and moist terrestrial habitats [4,26].

Algae exhibit remarkable taxonomic and physiological diversity and are classified into several major groups based on pigmentation, storage products, cell wall composition, and evolutionary relationships. The principal groups include Cyanobacteria (blue-green algae), Chlorophyta (green algae), Bacillariophyta (diatoms), Dinophyta (dinoflagellates), Rhodophyta (red algae), and Phaeophyceae (brown algae). Each group possesses distinct ecological characteristics, environmental preferences, and physiological adaptations that enable survival under diverse environmental conditions. While many algal species are beneficial and essential for ecosystem functioning, certain taxa can proliferate excessively under favourable environmental conditions and form algal blooms [26].

An algal bloom is defined as the rapid increase in the abundance or biomass of algae within an aquatic ecosystem. Bloom formation generally occurs when environmental conditions, including nutrient availability, water temperature, solar radiation, hydrological stability, and water residence time, become favourable for rapid cellular proliferation. Most algal blooms are natural ecological events and may not adversely affect ecosystem health. However, excessive bloom development can reduce water transparency, alter nutrient cycling, decrease dissolved oxygen concentrations, and disrupt aquatic ecosystem functioning [26,27].

A subset of algal blooms is classified as harmful algal blooms (HABs), which occur when bloom-forming algae produce toxic metabolites or accumulate sufficient biomass to cause ecological, economic, or public health impacts. Freshwater HABs are predominantly associated with cyanobacteria, whereas marine HABs are commonly caused by dinoflagellates, diatoms, haptophytes, raphidophytes, and other phytoplankton species.

Harmful algal blooms have been reported across a wide range of freshwater, estuarine, and marine environments, with changes in bloom frequency, intensity, duration, and geographical distribution varying among regions, ecosystems, and taxa.Their occurrence is associated with deterioration of water quality, oxygen depletion, biodiversity loss, fish mortality, contamination of drinking water resources, seafood poisoning, and significant economic losses affecting fisheries, aquaculture, tourism, and water treatment industries [11,15]. The development of harmful algal blooms is governed by complex interactions among physical, chemical, and biological factors. Nutrient enrichment, particularly excessive nitrogen and phosphorus inputs, remains the principal driver of bloom initiation, while elevated temperatures, altered precipitation patterns, thermal stratification, increased atmospheric carbon dioxide concentrations, and extreme climatic events further promote bloom persistence and geographical expansion. In addition, species-specific physiological characteristics, including buoyancy regulation, nitrogen fixation, efficient nutrient uptake, and toxin production, enhance the competitive advantage of bloom-forming organisms under changing environmental conditions [15,19,20].

Understanding the biology, diversity, ecological roles, and bloom-forming mechanisms of algae is essential for predicting bloom occurrence, assessing ecological risks, and developing effective monitoring and management strategies. Therefore, the following sections discuss the classification of algae, the different types of algal blooms, major bloom-forming organisms, and the environmental factors that regulate harmful algal bloom development [26,27].

Algal Group	Cell Type	Pigments	Habitat	Representative Genera	HAB-Associated Toxins/Effects
Cyanobacteria (Blue-green algae)	Prokaryotic	Chlorophyll-a, Phycocyanin	Freshwater, Brackish	*Microcystis, Dolichospermum, Planktothrix, Oscillatoria*	Microcystins, cylindrospermopsin, anatoxin-a, saxitoxins
Bacillariophyta (Diatoms)	Eukaryotic	Chlorophyll-a, c, Fucoxanthin	Marine, Freshwater	*Pseudo-nitzschia*, *Skeletonema*	Domoic acid
Dinophyta (Dinoflagellates)	Eukaryotic	Chlorophyll-a, c, Peridinin	Marine	*Alexandrium*, *Karenia*, *Dinophysis*	Saxitoxins, brevetoxins, okadaic acid
Haptophyta	Eukaryotic	Chlorophyll-a, c	Marine	*Phaeocystis*	Ecological effects; toxin production is species-dependent

Table 1: Classification and Characteristics of Major Algal Groups Associated with Harmful Algal.

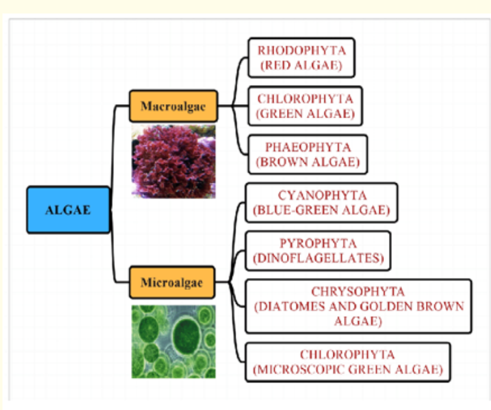

Figure 2: Classification of major algal groups associated with harmful algal blooms (HABs).
Source: Author-generated.

Definition of algal bloom

An algal bloom is defined as the rapid increase in the abundance, density, or biomass of algae or cyanobacteria within an aquatic ecosystem over a relatively short period. Bloom formation is a natural ecological phenomenon that occurs in freshwater, estuarine, and marine environments when environmental conditions become favourable for accelerated algal growth. These conditions typically include high nutrient availability, elevated water temperature, adequate sunlight, stable hydrological conditions, and sufficient residence time, all of which stimulate rapid photosynthesis and cell division [3,7,8].

Under normal conditions, algal populations remain in ecological balance and contribute positively to aquatic ecosystem functioning by supporting primary productivity, oxygen generation, and nutrient cycling. However, when environmental conditions promote excessive growth, algal populations can increase exponentially and dominate the phytoplankton community, resulting in visible discoloration of the water surface. Depending on the dominant species, blooms may appear green, blue-green, brown, red, or golden and may persist from several days to several months [5,6].

Not all algal blooms are harmful. Many blooms are temporary natural events that play an important role in aquatic food webs without causing adverse ecological effects. In contrast, harmful algal blooms (HABs) occur when bloom-forming algae produce toxic secondary metabolites or accumulate sufficient biomass to disrupt ecosystem functioning. Harmful blooms reduce light penetration, alter nutrient cycling, decrease dissolved oxygen concentrations through biomass decomposition, and may cause fish mortality, biodiversity loss, and deterioration of water quality. In addition, toxin-producing species release cyanotoxins or phycotoxins that threaten aquatic organisms, livestock, wildlife, and human health through contaminated drinking water, seafood consumption, recreational exposure, and inhalation of aerosolized toxins [14,20].

It is important to distinguish among algal blooms, cyanobacterial blooms, nuisance blooms, and harmful algal blooms (HABs). An algal bloom is a broad term describing an unusually high increase in algal abundance or biomass, whereas a cyanobacterial bloom specifically refers to the proliferation of cyanobacteria within an aquatic environment. A nuisance bloom refers to a bloom that adversely affects water quality, ecosystem functioning, aesthetics, or recreational activities, but it does not necessarily involve toxin production. In contrast, a harmful algal bloom (HAB) is defined by its potential to cause ecological, environmental, economic, or public health harm. Importantly, toxin production is not a prerequisite for a bloom to be classified as harmful, because high biomass alone can cause reduced light penetration, oxygen depletion, habitat alteration, and other ecological disturbances. When toxins are produced, their occurrence and concentration may vary among species or strains and under different environmental conditions. Therefore, toxin-mediated effects represent one mechanism of HAB-associated harm, whereas biomass-related ecological effects represent another [20,29].

The occurrence of algal blooms is regulated by the interaction of physical, chemical, and biological factors. Excessive nitrogen and phosphorus loading from agricultural runoff, domestic wastewater, industrial effluents, and urban stormwater remains the principal driver of bloom development. Climate-related factors, including rising water temperatures, thermal stratification, elevated atmospheric carbon dioxide concentrations, altered precipitation patterns, and extreme weather events, further promote bloom initiation and persistence. Biological characteristics such as buoyancy regulation, efficient nutrient uptake, nitrogen fixation, and rapid reproductive capacity also enhance the competitive advantage of bloom-forming species.

Because algal blooms vary considerably in their composition, ecological effects, and toxicity, understanding their formation, classification, and environmental drivers is essential for effective monitoring, early warning, risk assessment, and sustainable management of aquatic ecosystems. The following sections discuss the historical development of harmful algal bloom research and the major algal groups responsible for bloom formation [11,12].

Historical background of harmful algal blooms

Harmful algal blooms (HABs) have been recognized for centuries, although their ecological significance and impacts on human health have become fully appreciated only during the last few decades. Historical records indicate that unusual water discoloration, massive fish mortality, and seafood poisoning events were documented as early as ancient civilizations. Early observations of "red tides" in coastal waters were primarily based on visible changes in water colour and unexplained mortality of marine organisms. At that time, the biological causes of these phenomena remained largely unknown due to limited scientific knowledge and the absence of advanced analytical techniques [1,25].

The scientific investigation of harmful algal blooms began during the late nineteenth and early twentieth centuries with the development of light microscopy, which enabled researchers to identify bloom-forming algae and cyanobacteria. During this period, several marine dinoflagellates were recognized as the causative agents of recurrent red tide events, while freshwater cyanobacteria were increasingly associated with deteriorating water quality in lakes and reservoirs. These discoveries established the foundation for modern HAB research and highlighted the ecological importance of bloom-forming microorganisms [13,19,29].

During the second half of the twentieth century, rapid industrialization, urban expansion, intensive agriculture, and increasing nutrient discharge into aquatic ecosystems contributed to a marked increase in the occurrence of harmful algal blooms worldwide. Excessive inputs of nitrogen and phosphorus accelerated eutrophication, promoting the proliferation of bloom-forming species in freshwater and coastal environments. At the same time, advances in analytical chemistry led to the identification of several cyanotoxins and marine phycotoxins, including microcystins, saxitoxins, brevetoxins, anatoxins, cylindrospermopsins, domoic acid, and okadaic acid. These discoveries demonstrated that HABs represent not only ecological disturbances but also serious threats to public health, fisheries, aquaculture, and drinking water safety [28,30,38].

In recent decades, the frequency, duration, and geographical distribution of harmful algal blooms have increased substantially across both freshwater and marine ecosystems. Climate change, characterized by rising water temperatures, altered precipitation patterns, thermal stratification, elevated atmospheric carbon dioxide concentrations, and more frequent extreme weather events, has further intensified bloom development and expanded the distribution of bloom-forming species into previously unaffected regions. Consequently, HABs are now recognized as one of the most significant global environmental challenges affecting aquatic ecosystems [20,29].

Modern HAB research has progressed rapidly with the integration of molecular biology, environmental DNA (eDNA), genomics, remote sensing, biosensors, artificial intelligence (AI), and machine learning technologies. These approaches have significantly improved the detection, monitoring, forecasting, and management of bloom events. International organizations, including the World Health Organization (WHO), the Intergovernmental Oceanographic Commission (IOC), and the United Nations Environment Programme (UNEP), have also promoted global monitoring programs, risk assessment frameworks, and management strategies to reduce the environmental and public health impacts of harmful algal blooms.

Today, harmful algal blooms are recognized as complex ecological phenomena resulting from interactions among nutrient enrichment, climate change, hydrological conditions, and species-specific biological characteristics. Continued research and international collaboration remain essential for improving bloom prediction, developing sustainable mitigation strategies, and protecting aquatic ecosystems under changing environmental conditions [26].

Classification of algae and types of algal blooms

Algae comprise a highly diverse group of photosynthetic organisms that differ in morphology, pigmentation, cellular organization, habitat, and ecological function. They are widely distributed in freshwater, marine, estuarine, and terrestrial environments, where they serve as primary producers and play essential roles in carbon fixation, oxygen production, nutrient cycling, and the maintenance of aquatic food webs. Based on their evolutionary relationships, photosynthetic pigments, storage products, and cellular characteristics, algae are classified into several major taxonomic groups, including Cyanobacteria (blue-green algae), Chlorophyta (green algae), Bacillariophyta (diatoms), Dinophyta (dinoflagellates), Rhodophyta (red algae), and Phaeophyceae (brown algae). Each group exhibits distinct physiological adaptations and ecological characteristics that influence its distribution, growth, and bloom-forming potential [26].

Among these groups, cyanobacteria are the dominant bloom-forming organisms in freshwater ecosystems. They possess several adaptive characteristics, including gas vesicles for buoyancy regulation, efficient nutrient uptake systems, atmospheric nitrogen fixation in selected genera, and tolerance to high temperatures and fluctuating environmental conditions.

These adaptations enable cyanobacteria such as *Microcystis*, *Dolichospermum*, *Aphanizomenon*, and *Oscillatoria* to outcompete other phytoplankton under eutrophic conditions and frequently form dense harmful blooms [11,12].

Green algae (Chlorophyta) constitute one of the largest and most diverse algal groups and occur predominantly in freshwater habitats, although numerous marine species are also known. They are generally considered beneficial primary producers and contribute significantly to aquatic productivity. Under nutrient-rich conditions, however, some chlorophytes, including *Chlorella*, *Scenedesmus*, and *Cladophora*, may develop nuisance blooms that interfere with recreational activities and water quality, although they rarely produce potent toxins [11,12].

Diatoms (Bacillariophyta) are unicellular algae characterized by siliceous cell walls known as frustules. They contribute substantially to global primary productivity and play an important role in marine and freshwater food webs. While most diatom blooms are ecologically beneficial, certain species, particularly those belonging to the genus *Pseudo-nitzschia*, produce domoic acid, a neurotoxin responsible for Amnesic Shellfish Poisoning (ASP). Consequently, some diatom blooms are classified as harmful algal blooms [26].

Dinoflagellates (Dinophyta) are predominantly marine phytoplankton possessing two flagella that facilitate motility within the water column. Numerous dinoflagellate species, including *Alexandrium*, *Karenia*, *Dinophysis*, and *Prorocentrum*, are responsible for harmful marine blooms commonly referred to as "red tides." These organisms produce a variety of potent phycotoxins, including saxitoxins, brevetoxins, and okadaic acid, which accumulate in shellfish and marine food webs, posing significant risks to aquatic ecosystems, fisheries, and human health [11,27].

Red algae (Rhodophyta) are multicellular marine algae distinguished by the pigment phycoerythrin, which enables efficient photosynthesis under low-light conditions. They are widely utilized in food, pharmaceutical, and biotechnology industries because of their ability to produce commercially valuable compounds such as agar and carrageenan. Brown algae (Phaeophyceae), including kelps and seaweeds, dominate many temperate marine coastal ecosystems and contribute substantially to coastal productivity and habitat formation. Unlike cyanobacteria and dinoflagellates, red and brown algae rarely form harmful planktonic blooms but are ecologically important components of marine ecosystems [14,19].

Algal blooms can be broadly categorized into non-harmful and harmful blooms. Non-harmful blooms occur naturally and contribute to aquatic primary productivity without causing significant ecological disturbances. In contrast, harmful algal blooms (HABs) develop when bloom-forming algae either produce toxic secondary metabolites or accumulate excessive biomass that disrupts ecosystem functioning. HABs occur in freshwater, estuarine, and marine environments and are increasingly recognized as one of the most serious environmental problems affecting aquatic ecosystems worldwide [3,8].

Freshwater harmful algal blooms are primarily caused by cyanobacteria, whereas marine harmful algal blooms are mainly associated with dinoflagellates, diatoms, haptophytes, and raphidophytes. The occurrence of HABs is closely linked to excessive nutrient enrichment, eutrophication, elevated water temperatures, climate change, altered hydrological conditions, and increased atmospheric carbon dioxide concentrations. These environmental factors promote rapid cellular proliferation, bloom persistence, and toxin production [29].

The harmful effects of HABs arise through two principal mechanisms. First, several bloom-forming species synthesize cyanotoxins or phycotoxins, including microcystins, anatoxins, cylindrospermopsins, saxitoxins, brevetoxins, domoic acid, and okadaic acid, which contaminate drinking water, seafood, and aquatic food webs, posing significant risks to wildlife, livestock, and human health. Second, dense bloom biomass reduces water transparency, suppresses submerged aquatic vegetation, alters nutrient cycling, and consumes dissolved oxygen during decomposition, frequently resulting in hypoxia, fish mortality, biodiversity loss, and deterioration of overall ecosystem health.

Understanding the classification of algae together with the diversity of bloom types is fundamental for identifying bloom-forming species, assessing ecological risks, improving monitoring programs, and developing sustainable management strategies. The increasing frequency and geographical expansion of harmful algal blooms under changing climatic conditions further emphasize the importance of understanding the biological characteristics and ecological behaviour of major algal groups before examining the mechanisms responsible for bloom formation [20,29].

Causes and mechanisms of harmful algal bloom formation

Harmful algal blooms (HABs) develop through complex interactions among physical, chemical, biological, and anthropogenic factors. Although algal blooms are natural ecological events, their increasing frequency, intensity, duration, and geographical distribution are primarily associated with human-induced environmental changes. Excessive nutrient loading, climate change, altered hydrological conditions, and species-specific physiological adaptations collectively create favourable conditions for rapid proliferation of bloom-forming algae and cyanobacteria. These interacting factors regulate bloom initiation, growth, persistence, toxin production, and ecological impacts, making HABs one of the most significant environmental challenges affecting aquatic ecosystems worldwide [13,19,21,29].

Nutrient enrichment, commonly known as eutrophication, is an important driver of harmful algal bloom formation in many aquatic systems, although the relative importance of nitrogen and phosphorus varies among ecosystems, bloom-forming taxa, and environmental conditions. Excessive inputs of nitrogen (N) and phosphorus (P) stimulate rapid algal growth by providing essential nutrients required for photosynthesis, protein synthesis, and cellular metabolism. Major sources of nutrient pollution include agricultural runoff containing fertilizers and animal manure, untreated domestic sewage, industrial effluents, aquaculture activities, livestock farming, and urban stormwater runoff. Continuous nutrient loading disrupts the natural ecological balance of aquatic ecosystems and promotes the dominance of opportunistic bloom-forming species. In freshwater ecosystems, cyanobacteria frequently become dominant because several genera possess specialized physiological adaptations such as atmospheric nitrogen fixation, buoyancy regulation through gas vesicles, efficient nutrient uptake systems, and tolerance to nutrient fluctuations [15,19,26].

Climate change has further intensified the occurrence and expansion of harmful algal blooms worldwide. Rising global temperatures increase water temperature, accelerate algal metabolic activity, and prolong the growing season of bloom-forming species. Thermal stratification reduces vertical mixing of water, allowing buoyant cyanobacteria to remain near the surface where light availability is greatest. Changes in precipitation patterns, including heavy rainfall and flooding, increase nutrient transport from agricultural and urban landscapes into rivers, lakes, and reservoirs, whereas prolonged droughts reduce water flow and increase nutrient concentrations. Elevated atmospheric carbon dioxide levels enhance photosynthetic efficiency in several algal groups, while extreme weather events such as storms and hurricanes redistribute nutrients and modify aquatic habitats, creating favourable conditions for bloom initiation and persistence. Consequently, climate change acts synergistically with eutrophication to increase bloom frequency, duration, toxicity, and geographical distribution [15,20].

In addition to nutrient enrichment and climate change, several environmental factors regulate the development of harmful algal blooms. Water temperature strongly influences algal metabolism, with most bloom-forming cyanobacteria exhibiting optimal growth between 25°C and 30°C. Solar radiation and photoperiod determine photosynthetic activity and biomass accumulation, while water transparency controls light penetration within the water column. Hydrological conditions, including low water flow, prolonged residence time, thermal stratification, and reduced turbulence, facilitate bloom establishment by preventing dilution and allowing algal cells to accumulate at the water surface. Other physicochemical parameters, including pH, dissolved oxygen, salinity, conductivity, and micronutrient availability, also influence species composition and bloom dynamics. Biological interactions such as grazing pressure, microbial competition, allelopathy, and viral infections further regulate bloom development by affecting population growth and community structure [3,8,24].

The mechanism of harmful algal bloom formation involves a sequence of interconnected ecological processes. Initially, excessive nutrient inputs increase primary productivity and stimulate rapid algal cell division. Under favourable environmental conditions, bloom-forming species proliferate exponentially and gradually dominate the phytoplankton community due to their superior physiological adaptations. Cyanobacteria, for example, regulate buoyancy through intracellular gas vesicles, enabling them to migrate vertically within the water column to optimize light and nutrient acquisition. Nitrogen-fixing genera such as *Dolichospermum* and *Aphanizomenon* maintain growth even under nitrogen-limited conditions by utilizing atmospheric nitrogen.

As biomass accumulates, dense surface scums reduce light penetration, suppress submerged aquatic vegetation, and alter aquatic ecosystem structure. During bloom senescence, microbial decomposition consumes dissolved oxygen, leading to hypoxic or anoxic conditions that frequently cause fish mortality, biodiversity loss, and degradation of water quality [20,29].

Many bloom-forming species simultaneously synthesize toxic secondary metabolites, including microcystins, anatoxins, cylindrospermopsins, saxitoxins, brevetoxins, domoic acid, and okadaic acid. These toxins contaminate drinking water supplies, accumulate within aquatic food webs, and threaten aquatic organisms, livestock, wildlife, and human health through recreational exposure and seafood consumption. The severity of harmful algal blooms therefore depends not only on bloom biomass but also on species composition, toxin production, environmental conditions, and exposure pathways.

Overall, harmful algal bloom formation is governed by the combined influence of nutrient enrichment, climate change, environmental variables, and species-specific biological characteristics. Understanding these interacting mechanisms is essential for improving bloom prediction, developing effective monitoring programs, and implementing sustainable prevention and management strategies to protect aquatic ecosystems and public health.

Factor	Effect on HAB Development	Major Consequences
Nitrogen enrichment	Stimulates algal growth	Eutrophication
Phosphorus enrichment	Increases bloom intensity	Dense algal blooms
Elevated temperature	Accelerates cell division	Longer bloom duration
High light intensity	Enhances photosynthesis	Increased biomass
Water column stratification	Favors buoyant cyanobacteria	Surface bloom formation
Low water flow	Promotes cell accumulation	Persistent blooms
Climate change	Alters rainfall and temperature	Increased bloom frequency
Agricultural runoff	Nutrient loading	Water quality deterioration
Industrial and domestic wastewater	Excess nutrient input	Rapid bloom initiation

Table 2: Environmental Factors Influencing Harmful Algal Bloom Formation.

Harmful algal blooms

Harmful algal blooms (HABs) occur in freshwater, estuarine, and marine environments and are characterized by the excessive proliferation of bloom-forming algae or cyanobacteria. Their ecological and public-health significance varies according to the dominant organisms, bloom biomass, toxin-producing capacity, and environmental conditions. Freshwater HABs are predominantly associated with cyanobacteria, whereas marine HABs commonly involve dinoflagellates, diatoms, haptophytes, raphidophytes, and other phytoplankton groups. Although the organisms and environmental characteristics differ among habitats, HAB events can affect water quality, aquatic ecosystems, fisheries, and public health. Understanding these habitat-specific characteristics is important for appropriate monitoring, risk assessment, and management [4,11,15].

however, the dominant bloom-forming organisms differ according to habitat characteristics. Freshwater HABs are predominantly caused by toxin-producing cyanobacteria, whereas marine HABs are mainly associated with dinoflagellates, diatoms, haptophytes, raphidophytes, and several other phytoplankton groups. Despite differences in species composition, both freshwater and marine HABs produce similar ecological, economic, and public health consequences. Understanding their characteristics is essential for effective monitoring, prediction, and management [13,15].

Freshwater harmful algal blooms

Freshwater harmful algal blooms (HABs) are predominantly associated with cyanobacteria and occur in lakes, reservoirs, rivers, and other inland water bodies. Their development is

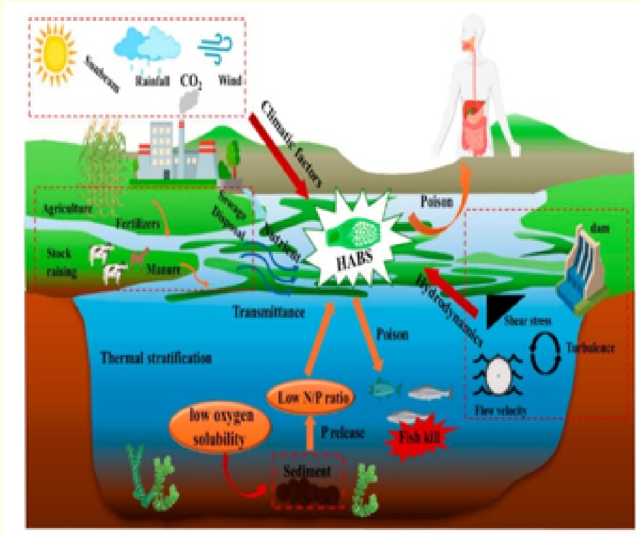

Figure 3: Major environmental factors and interactions involved in harmful algal bloom (HAB) formation. Arrows indicate the direction of influence. Source: Author-generated.

favored by nutrient-enriched conditions and suitable physical characteristics of the water body, particularly stable water columns and extended water residence times. Common bloom-forming genera include *Microcystis*, *Dolichospermum* (formerly *Anabaena*), *Aphanizomenon*, *Oscillatoria*, *Planktothrix*, *Cylindrospermopsis*, and *Lyngbya*. Several of these taxa can produce cyanotoxins, including microcystins, cylindrospermopsin, anatoxin-a, and saxitoxins, creating concerns for drinking-water safety, aquatic organisms, and recreational water use. The ecological significance of freshwater HABs is therefore determined not only by biomass accumulation but also by the taxonomic composition of the bloom, toxin-producing potential, and duration of exposure [7,15].

Freshwater cyanobacteria produce a wide variety of cyanotoxins, including microcystins, anatoxins, cylindrospermopsins, saxitoxins, and lipopolysaccharides. These toxins affect different organs and physiological systems in humans and animals. Microcystins primarily damage the liver, anatoxins act as neurotoxins affecting the nervous system, cylindrospermopsins exhibit hepatotoxic and cytotoxic effects, while saxitoxins interfere with nerve impulse transmission and may cause paralysis. Human exposure occurs through consumption of contaminated drinking water, recreational activities, inhalation of aerosols, and consumption of contaminated fish or shellfish [3,8,30].

The ecological impacts of freshwater HABs are equally significant. Dense cyanobacterial blooms reduce water transparency, limiting light penetration and inhibiting the growth of submerged aquatic vegetation. During bloom decomposition, microbial respiration consumes dissolved oxygen, producing hypoxic or anoxic conditions that frequently result in fish kills, biodiversity loss, habitat degradation, and alteration of aquatic food webs. Persistent blooms also interfere with drinking water production by causing unpleasant taste and odour, clogging filtration systems, and increasing treatment costs [4].

Several cyanobacterial genera are frequently responsible for freshwater harmful algal blooms. Among them, *Microcystis aeruginosa* is widely studied because of its global distribution and ability to produce microcystins. Other important bloom-forming genera include *Dolichospermum* (formerly *Anabaena* in older literature), *Aphanizomenon*, *Oscillatoria*, *Planktothrix*, *Cylindrospermopsis*, and *Lyngbya* [15].

Marine harmful algal blooms

Marine harmful algal blooms occur in coastal waters, estuaries, lagoons, and open oceans and are mainly caused by dinoflagellates, diatoms, haptophytes, raphidophytes, and several other phytoplankton groups. These blooms are commonly referred to

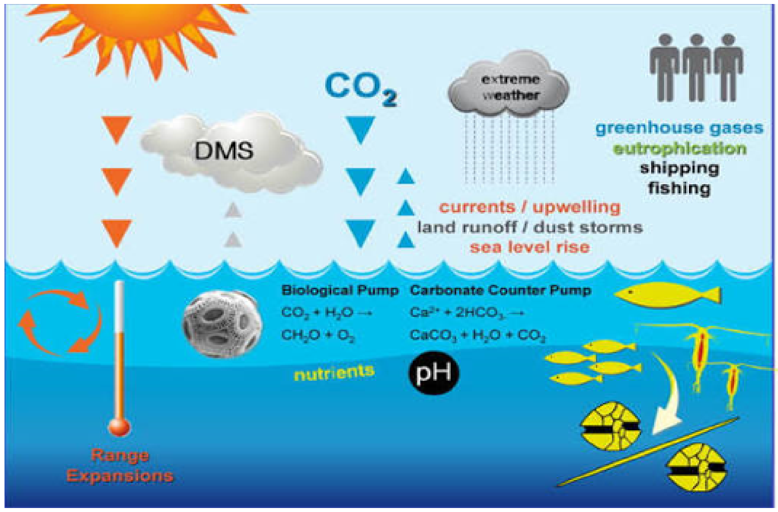

Figure 4: Major environmental, ecological, health, and socioeconomic impacts of harmful algal blooms (HABs). Source: Author-generated.

as red tides, although the colour of bloom events varies depending on the dominant species, pigment composition, and bloom density. Marine HABs have become increasingly frequent worldwide because of Marine HAB development is influenced by interacting physical, chemical, and biological conditions, including nutrient availability, temperature, water-column dynamics, and ocean circulation on marine ecosystems [7,15].

Dinoflagellates represent the most important group of marine bloom-forming organisms. Species belonging to the genera *Alexandrium*, *Karenia*, *Dinophysis*, *Prorocentrum*, *Gymnodinium*, and *Noctiluca* are responsible for recurrent harmful bloom events in many coastal regions. These organisms produce several potent marine toxins, including saxitoxins, brevetoxins, okadaic acid, yessotoxins, and azaspiracids. Marine diatoms, particularly species of *Pseudo-nitzschia*, produce domoic acid, the causative agent of Amnesic Shellfish Poisoning (ASP). Haptophytes such as *Prymnesium parvum* and raphidophytes such as *Heterosigma akashiwo* are also known to cause severe fish mortality in aquaculture systems [11,24].

Marine phycotoxins accumulate within shellfish and other marine organisms without causing obvious symptoms in the host. However, consumption of contaminated seafood by humans may result in several forms of shellfish poisoning, including Paralytic Shellfish Poisoning (PSP), Neurotoxic Shellfish Poisoning (NSP), Diarrhetic Shellfish Poisoning (DSP), and Amnesic Shellfish Poisoning (ASP). Clinical manifestations include nausea, vomiting, diarrhoea, neurological impairment, respiratory distress, paralysis, and, in severe cases, death. Consequently, routine monitoring of shellfish harvesting areas and seafood safety has become an essential component of coastal public health management [3,7].

Apart from toxin production, marine HABs cause substantial ecological disturbances through excessive biomass accumulation. Dense blooms reduce water clarity, alter nutrient cycling, and decrease dissolved oxygen concentrations following decomposition. Fish mortality may result from hypoxia, gill irritation, or exposure to algal toxins, while marine mammals, seabirds, sea turtles, and other wildlife are frequently affected through food-web contamination. Coral reef ecosystems may also experience reduced resilience due to repeated bloom events and deteriorating water quality [4].

Marine harmful algal blooms also generate considerable socioeconomic losses. Commercial fisheries and aquaculture industries experience substantial economic damage due to fish mortality, shellfish harvesting closures, reduced seafood exports, and increased monitoring costs. Coastal tourism is negatively affected by beach closures, water discoloration, unpleasant odours, and concerns regarding human health. Governments and environmental agencies invest significant resources in bloom surveillance, toxin monitoring, forecasting systems, and emergency response programs to reduce the impacts of marine HABs [1,29].

Although freshwater and marine harmful algal blooms differ in their dominant species and environmental characteristics, both are increasing in frequency and geographical distribution under changing climatic conditions. Their continued expansion highlights the importance of integrated monitoring programs, early-warning systems, nutrient management strategies, and sustainable environmental policies to minimize ecological degradation and protect public health [28,29].

Environmental, human health, and economic impacts of harmful algal blooms

The increasing occurrence of harmful algal blooms (HABs) has become a major global environmental concern because of their widespread impacts on aquatic ecosystems, human health, and economic activities. HABs affect both freshwater and marine environments through excessive biomass accumulation and the production of harmful cyanotoxins and phycotoxins. Their impacts extend beyond ecological degradation and include significant financial losses to fisheries, aquaculture, tourism, drinking water treatment, and healthcare systems. The severity of these impacts depends on bloom duration, species composition, toxin production, environmental conditions, and the degree of human exposure [1,3,4].

Environmental impacts

Harmful algal blooms significantly alter the physical, chemical, and biological characteristics of aquatic ecosystems. One of the most immediate environmental effects is the formation of dense surface blooms that reduce water transparency and limit sunlight penetration into the water column. Reduced light availability inhibits the growth of submerged aquatic vegetation, decreases photosynthetic activity, and alters the structure of aquatic habitats. The decline of aquatic plants also affects organisms that depend on these habitats for shelter, feeding, and reproduction [4].

HAB-associated toxin	Major producer(s)	Typical exposure route	Major human health effects	Main health concern	Analytical methods	Guideline/monitoring framework
Microcystins	*Microcystis, Dolichospermum, Planktothrix*	Contaminated drinking water, recreational water, contaminated food	Hepatotoxicity; acute exposure may cause liver injury	Drinking-water safety and recreational exposure	ELISA, HPLC, LC–MS/MS	Drinking-water safety and cyanotoxin monitoring
Cylindrospermopsin	*Cylindrospermopsis/Raphidiopsis, Aphanizomenon*	Drinking water, recreational water	Hepatotoxic and cytotoxic effects; possible renal and systemic effects	Chronic and acute water exposure	ELISA, HPLC, LC–MS/MS	Drinking-water and cyanotoxin monitoring
Anatoxin-a	*Dolichospermum, Aphanizomenon, Oscillatoria/Planktothrix*	Ingestion or accidental exposure to contaminated water	Neurotoxicity; neurological symptoms and respiratory impairment in severe exposure	Acute neurological toxicity	LC–MS/MS, HPLC, targeted analytical assays	Cyanotoxin monitoring and recreational-water risk assessment
Saxitoxins	*Alexandrium, Gymnodinium, Pyrodinium; some cyanobacteria*	Consumption of contaminated shellfish or seafood; contaminated water	Neurological symptoms ranging from tingling and weakness to paralysis	Paralytic shellfish poisoning	HPLC, LC–MS/MS, receptor-binding/functional assays	Shellfish-toxin monitoring and food-safety surveillance

Brevetoxins	*Karenia*	Contaminated shellfish; inhalation of marine aerosols; recreational exposure	Neurotoxic effects; respiratory irritation from aerosol exposure	Neurotoxic shellfish poisoning and respiratory exposure	LC–MS/MS, HPLC, immunoassays	Shellfish-toxin monitoring and coastal public-health surveillance
Okadaic acid	*Dinophysis, Prorocentrum*	Consumption of contaminated shellfish	Gastrointestinal illness, particularly acute diarrhoeal symptoms	Diarrhetic shellfish poisoning	LC–MS/MS, HPLC	Shellfish-toxin monitoring and food-safety surveillance
Domoic acid	*Pseudo-nitzschia*	Consumption of contaminated shellfish/seafood	Gastrointestinal and neurological effects; severe cases may involve memory impairment and seizures	Amnesic shellfish poisoning	HPLC, LC–MS/MS	Shellfish-toxin monitoring and food-safety surveillance
Azaspiracids	*Azadinium, Amphidoma*	Consumption of contaminated shellfish	Gastrointestinal illness	Emerging shellfish-toxin risk	LC–MS/MS, HPLC	Shellfish-toxin monitoring and food-safety surveillance

Table 3: Major HAB-Associated Toxins and Human Health Risk.

Another major environmental consequence is oxygen depletion. During bloom senescence, large quantities of algal biomass are decomposed by microorganisms, which consume dissolved oxygen through respiration. This process frequently creates hypoxic or anoxic conditions that cause mass mortality of fish, benthic organisms, and aquatic invertebrates. Repeated oxygen depletion can permanently alter aquatic community structure and reduce biodiversity [4].

Harmful algal blooms also disrupt aquatic food webs. Toxin-producing algae reduce the abundance of zooplankton grazers, allowing bloom-forming species to dominate phytoplankton communities. These ecological changes influence nutrient cycling, predator–prey interactions, and energy transfer within aquatic ecosystems. Furthermore, toxins released into the water accumulate in aquatic organisms and move through the food chain, affecting fish, amphibians, birds, marine mammals, and other wildlife. Frequent bloom events ultimately reduce ecosystem resilience and impair essential ecosystem services such as fisheries, water purification, and biodiversity conservation [4,24].

Human health impacts

Harmful algal blooms represent an important public health concern because many bloom-forming cyanobacteria and marine phytoplankton produce toxins that can affect humans through multiple exposure pathways. Human exposure occurs primarily through consumption of contaminated drinking water, recreational activities, seafood consumption, and inhalation of aerosolized toxins. The severity of health effects depends on the toxin type, concentration, duration of exposure, and individual susceptibility [3,7,30].

Freshwater cyanobacteria commonly produce microcystins, anatoxins, cylindrospermopsins, and saxitoxins. Microcystins primarily affect the liver and are associated with hepatotoxicity, while anatoxins and saxitoxins interfere with the nervous system and may cause muscle paralysis or respiratory failure. Cylindrospermopsins exhibit both hepatotoxic and cytotoxic properties and may damage multiple organs following prolonged exposure [7,8].

Marine harmful algal blooms produce phycotoxins such as brevetoxins, domoic acid, okadaic acid, and saxitoxins. These toxins accumulate within shellfish and other seafood without causing visible symptoms in the organisms themselves. Consumption of contaminated seafood may lead to Paralytic Shellfish Poisoning (PSP), Neurotoxic Shellfish Poisoning (NSP), Diarrhetic Shellfish Poisoning (DSP), and Amnesic Shellfish Poisoning (ASP). Clinical symptoms include nausea, vomiting, diarrhoea, abdominal pain, dizziness, skin irritation, respiratory distress, neurological disorders, memory loss, and, in severe cases, paralysis or death [3,24].

People working in fisheries, aquaculture, water treatment facilities, and coastal industries are particularly vulnerable because of repeated occupational exposure. Therefore, continuous monitoring of drinking water sources, routine seafood safety surveillance, public awareness programs, and effective early-warning systems are essential for reducing health risks associated with harmful algal blooms [3,30].

Economic impacts

Harmful algal blooms generate substantial economic losses worldwide by affecting fisheries, aquaculture, tourism, drinking water treatment, environmental monitoring, and public health. Commercial fisheries experience reduced productivity because of fish mortality, shellfish harvesting closures, and contamination of seafood products. Aquaculture industries often suffer severe financial losses due to disease outbreaks, reduced growth rates, and mortality of cultured fish and shellfish [1,29].

Tourism is also significantly affected by harmful algal blooms. Beach closures, unpleasant odors, water discoloration, fish kills, and public concerns regarding water safety reduce recreational activities and decrease tourism revenue. Coastal communities that depend on tourism frequently experience long-term economic consequences following severe bloom events [1,29].

Water treatment facilities incur additional costs associated with toxin monitoring, laboratory analysis, activated carbon filtration, ozonation, membrane filtration, and other advanced treatment technologies required to ensure safe drinking water. Governments and environmental agencies also invest considerable financial resources in bloom surveillance, forecasting programs, environmental restoration, scientific research, and emergency response measures [1,30].

Indirect economic losses include increased healthcare expenditures, reduced property values near affected water bodies, loss of recreational opportunities, and long-term degradation of ecosystem services. As climate change is expected to increase the frequency and intensity of harmful algal blooms, implementing preventive nutrient management strategies, continuous monitoring systems, and sustainable watershed management practices is likely to be more cost-effective than responding to large-scale bloom events after they occur.

Overall, the environmental, public health, and economic impacts of harmful algal blooms demonstrate the urgent need for integrated management strategies that combine scientific monitoring, environmental protection, public awareness, and effective policy implementation to safeguard aquatic ecosystems and ensure sustainable water resource management [4,29].

Detection and monitoring technologies

Early detection and continuous monitoring of harmful algal blooms (HABs) are essential for minimizing their environmental, public health, and economic impacts. Accurate monitoring enables timely implementation of mitigation measures, protection of drinking water resources, and effective management of freshwater and marine ecosystems. Conventional monitoring methods, including microscopic identification and physicochemical analysis, have long been used for bloom surveillance. However, recent advances in molecular biology, biosensor technology, environmental DNA (eDNA), remote sensing, and artificial intelligence (AI) have significantly improved the speed, sensitivity, and accuracy of HAB detection. Integrating these complementary technologies provides comprehensive monitoring systems capable of supporting early-warning programs and sustainable bloom management [28,29].

No single detection method is sufficient for comprehensive HAB surveillance. Microscopy and pigment-based measurements are useful for routine biomass assessment but provide limited information on toxin production, whereas molecular approaches offer greater taxonomic or functional specificity but may not directly indicate active toxin accumulation. Remote sensing provides broad spatial coverage but is primarily applicable to surface-associated blooms, while analytical techniques such as HPLC and LC–MS provide stronger toxin-specific confirmation but require specialized laboratory facilities. Consequently, integrated monitoring that combines rapid field-based screening with targeted molecular and chemical confirmation is likely to provide more reliable early-warning and risk-assessment capability [29,32].

Detection/ Monitoring Method	Primary Target	Typical Sample/Platform	Main Advantages	Key Limitations	Operational/ Field Applicability
Microscopy	Algal/cyanobacterial cells and morphology	Water samples	Direct observation; taxonomic information; relatively simple	Requires trained personnel; low sensitivity for some taxa; time-consuming	Routine laboratory and field microscopy
Pigment/ Chlorophyll-a analysis	Overall algal biomass	Water samples	Rapid estimation of algal biomass; useful for routine monitoring	Does not reliably identify harmful taxa or specific toxins	Routine water-quality monitoring
Flow cytometry	Cell abundance, size and fluorescence characteristics	Water samples	Rapid, quantitative cell analysis; useful for high-throughput monitoring	Instrument cost; specialist operation; limited taxonomic specificity without additional markers	Advanced laboratory monitoring
PCR/qPCR	Taxon-specific or toxin-associated genes	Water samples/filtered biomass	High specificity; can detect target organisms or functional genes	Requires molecular facilities; DNA detection does not necessarily indicate active toxin production	Laboratory and targeted monitoring
eDNA/Metabarcoding	DNA from multiple organisms	Water samples	Broad biodiversity assessment; useful for detecting low-abundance taxa	Interpretation and standardization challenges; DNA persistence may complicate temporal interpretation	Research and advanced surveillance
Remote sensing	Surface bloom biomass and spatial distribution	Satellite/aerial imagery	Large spatial coverage; repeated monitoring; useful for bloom mapping	Cloud cover, spatial resolution and water-optical conditions can affect performance; subsurface blooms may be missed	Large lakes, reservoirs and coastal waters
Biosensors	Specific cells, toxins or biomarkers	Water samples/portable platforms	Potential for rapid and on-site detection	Sensor specificity, calibration, matrix effects and long-term stability can limit application	Emerging field and near-real-time monitoring
HPLC/LC-MS-based toxin analysis	Specific cyanotoxins and phycotoxins	Water, algae, shellfish/seafood extracts	High analytical specificity; useful for toxin confirmation and quantification	Expensive instrumentation; laboratory expertise and sample preparation required	Reference laboratory and confirmatory analysis

Table 4: Comparison of HAB Detection and Monitoring Technologies.

Conventional monitoring techniques

Conventional monitoring remains the cornerstone of harmful algal bloom surveillance and is routinely employed by environmental agencies, research institutions, and water quality laboratories. These methods include field sampling, microscopic examination of phytoplankton communities, chlorophyll-*a* estimation, pigment analysis, and measurement of physicochemical parameters such as water temperature, pH, dissolved oxygen, conductivity, turbidity, salinity, and nutrient concentrations [29,37].

Microscopic identification enables direct observation and taxonomic classification of bloom-forming algae based on their morphology. Although microscopy is considered the standard method for species identification, it requires experienced taxonomists and considerable processing time. Chlorophyll-*a* and phycocyanin measurements are widely used as indicators of algal biomass but cannot distinguish harmful species from non-toxic algae. Consequently, conventional methods are often combined with advanced analytical techniques to improve monitoring accuracy and enable reliable bloom assessment [37,29].

Molecular and biosensor-based detection technologies

The development of molecular biology has transformed the detection and identification of harmful algal bloom species. Molecular techniques such as Polymerase Chain Reaction (PCR), quantitative PCR (qPCR), reverse transcription PCR (RT-PCR), DNA sequencing, fluorescence in situ hybridization (FISH), and metagenomic analysis provide rapid, highly sensitive, and species-specific identification of bloom-forming microorganisms. These techniques can detect toxin-producing species before visible blooms develop, thereby improving early-warning capabilities [29].

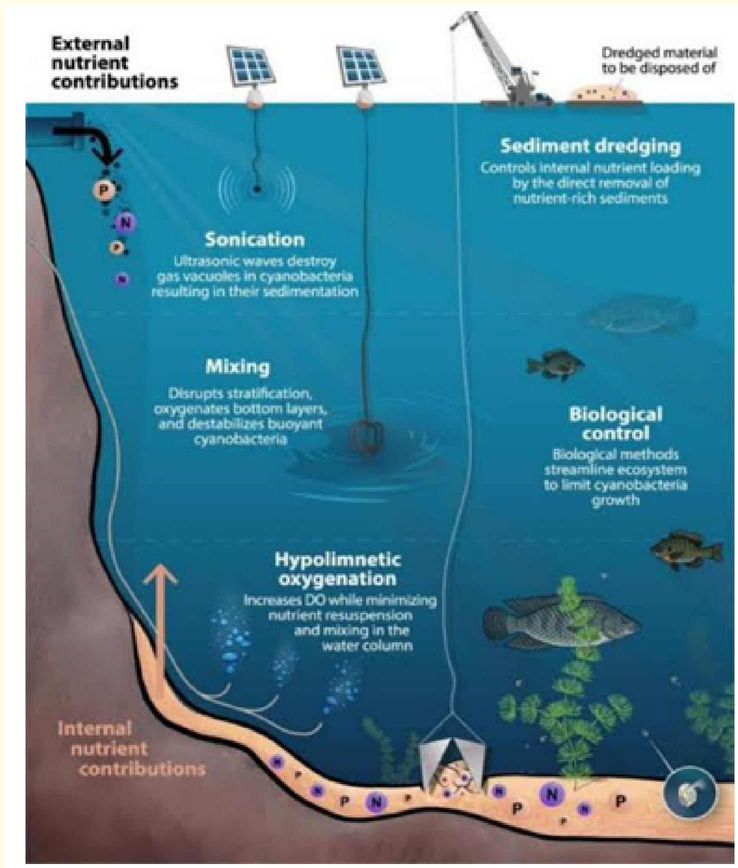

Figure 5: Nutrient management and watershed protection strategies for the prevention of harmful algal blooms. Source: Author-generated.

Environmental DNA (eDNA) has emerged as a powerful non-invasive monitoring tool for aquatic ecosystems. Organisms continuously release DNA into surrounding water through cells, mucus, and other biological materials. Analysis of eDNA enables the detection of bloom-forming algae without the need for direct organism isolation. Compared with conventional microscopy, eDNA offers higher sensitivity, improved detection of rare species, and more comprehensive biodiversity assessment [29].

Biosensor technology has further strengthened HAB monitoring by enabling rapid and portable detection of algal toxins. Modern biosensors employ antibodies, enzymes, nucleic acids, aptamers, or nanomaterials to detect toxins such as microcystins, saxitoxins, cylindrospermopsins, brevetoxins, and domoic acid. Electrochemical, optical, fluorescence, and immunosensor-based platforms provide highly sensitive real-time toxin measurements and are increasingly being incorporated into routine water quality monitoring programs [29].

Remote sensing and artificial intelligence

Remote sensing has become an indispensable tool for large-scale monitoring of harmful algal blooms in lakes, reservoirs, estuaries, and coastal waters. Satellite platforms, aerial imaging systems, hyperspectral sensors, and unmanned aerial vehicles (UAVs) enable continuous observation of bloom dynamics over extensive geographic regions. These technologies detect variations in chlorophyll-*a*, phycocyanin, water colour, suspended particles, and surface bloom distribution, allowing rapid assessment of bloom intensity and spatial extent while reducing the need for extensive field sampling [32,38].

Artificial intelligence (AI) and machine learning (ML) have recently emerged as powerful tools for bloom prediction and decision support. AI algorithms integrate environmental variables such as nutrient concentrations, water temperature, solar radiation, rainfall, wind speed, hydrological conditions, and historical bloom records to forecast bloom occurrence and severity. Machine learning approaches including Artificial Neural Networks (ANN), Random Forest (RF), Support Vector Machines (SVM), Gradient Boosting, and Deep Learning models have demonstrated high predictive accuracy for early bloom forecasting. When combined with satellite imagery and real-time sensor networks, AI-based systems provide efficient early-warning platforms capable of supporting rapid management decisions and reducing ecological and economic losses [29,38].

Advantages, limitations, and future perspectives

Each monitoring technology offers unique advantages while presenting certain limitations. Conventional microscopic techniques are inexpensive, standardized, and widely accepted but require skilled personnel and are relatively time-consuming. Molecular methods and eDNA provide highly sensitive and species-specific detection but require sophisticated laboratory facilities and specialized expertise. Biosensors enable rapid on-site toxin detection, although their long-term stability, calibration, and operational costs remain important considerations. Remote sensing facilitates continuous monitoring over large geographic areas but may be affected by cloud cover, atmospheric interference, and water depth. Similarly, AI-based prediction models provide highly accurate bloom forecasting but depend on the availability of high-quality environmental datasets and continuous model validation [29,38].

Future HAB monitoring is expected to integrate conventional monitoring, molecular diagnostics, eDNA, biosensors, satellite observations, Internet of Things (IoT)-based water quality sensors, cloud computing, and artificial intelligence into unified real-time monitoring platforms. Such integrated systems will improve prediction accuracy, reduce monitoring costs, strengthen early-warning capabilities, and support evidence-based management of freshwater and marine ecosystems. Continued technological innovation, standardized monitoring protocols, interdisciplinary collaboration, and international data sharing will be essential for improving global HAB surveillance and ensuring sustainable water resource management under changing environmental conditions.

Because no single detection method can simultaneously provide high taxonomic specificity, rapid response, continuous monitoring, and broad spatial coverage, different approaches are suited to different operational requirements. A comparative summary of major HAB detection and monitoring approaches is presented in Table 4 [29].

Prevention and control strategies for harmful algal blooms

The increasing occurrence of harmful algal blooms (HABs) has highlighted the need for effective prevention and control strategies to protect aquatic ecosystems, public health, and water resources. Traditional approaches based solely on chemical treatment are often associated with high costs, limited long-term effectiveness,

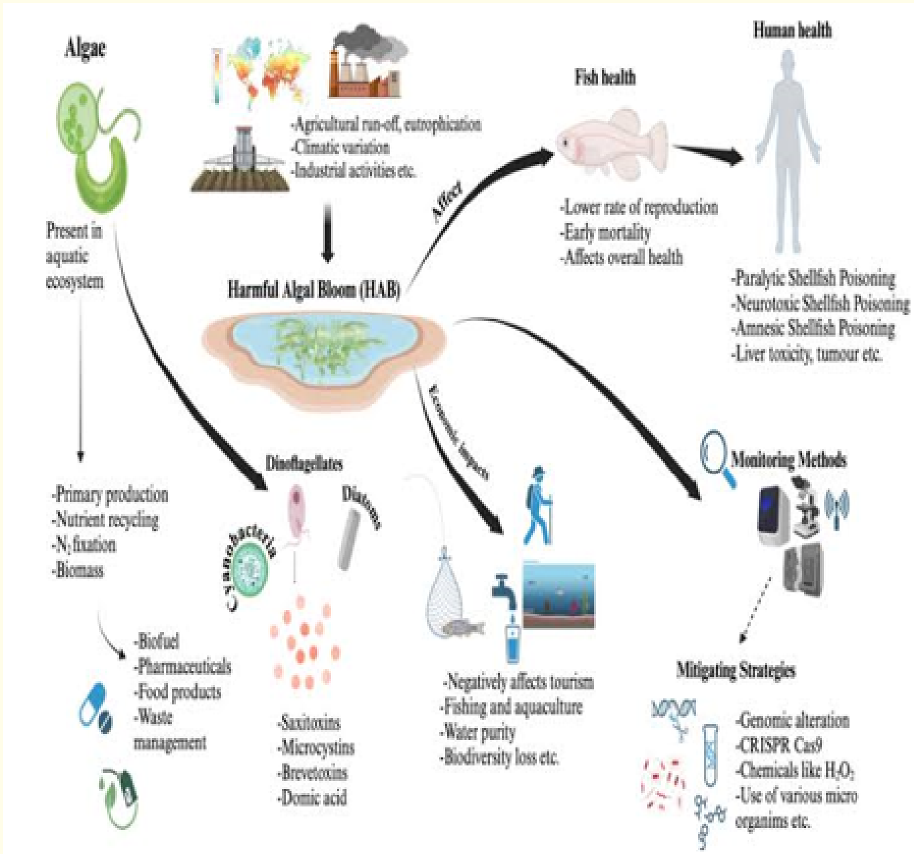

Figure 6: Conventional monitoring approaches for harmful algal bloom (HAB) detection.
Source: Author-generated.

and undesirable ecological consequences. Therefore, modern HAB management emphasizes integrated strategies that combine nutrient reduction, physical and chemical control, biological approaches, and sustainable watershed management. The selection of an appropriate control method depends on bloom severity, ecosystem characteristics, dominant algal species, environmental conditions, and socioeconomic considerations. An integrated management framework is widely recognized as the most effective approach for preventing bloom formation and minimizing their impacts [2,20].

HAB management can be broadly classified into three complementary levels: prevention, in-water mitigation, and emergency response. Prevention primarily aims to reduce the environmental conditions that favour bloom initiation, particularly through external nutrient-load reduction and watershed management. In-water mitigation is applied after bloom development and includes physical, chemical, and biological interventions to reduce bloom biomass or toxin exposure. Emergency response is required during severe or toxic bloom events and focuses on rapid risk assessment, public-health protection, drinking-water safety, and restriction of exposure. The selection of an intervention should consider bloom severity, dominant taxa, toxin status, water-body characteristics, treatment efficacy, potential toxin release, non-target effects, regulatory requirements, cost, and field-scale feasibility [2,20].

Nutrient management and watershed protection

Excessive nitrogen and phosphorus loading is an important driver of harmful algal bloom development in many aquatic systems, although the relative importance of individual nutrients varies among ecosystems, bloom-forming taxa, and environmental conditions. Nutrient management therefore remains an important long-term prevention strategy, particularly when implemented at the watershed scale. Reducing nutrient inputs from agricultural runoff, domestic sewage, industrial wastewater, livestock farming, and aquaculture can significantly decrease eutrophication and limit bloom development. Sustainable agricultural practices, including precision fertilizer application, buffer strips, conservation tillage, and controlled irrigation, reduce nutrient losses from farmland [1,14].

Improved wastewater treatment technologies capable of removing nitrogen and phosphorus before discharge into natural water bodies are equally important. Constructed wetlands, riparian vegetation, stormwater management systems, and watershed restoration programs further reduce nutrient transport into lakes, rivers, reservoirs, and coastal waters. Integrated watershed management, involving governments, industries, farmers, and local communities, provides a sustainable framework for maintaining water quality and reducing the long-term risk of HAB formation [20,22].

Nutrient reduction is primarily a long-term preventive strategy rather than an immediate response to an established bloom. Its effectiveness depends on sustained reductions in nitrogen and phosphorus loading and appropriate watershed-scale implementation. Therefore, nutrient management is most suitable for reducing long-term bloom risk, whereas additional interventions may be required during active bloom events [20].

Nutrient management is primarily a preventive rather than an immediate bloom-control strategy. Its effectiveness depends on the nutrient regime, hydrology, sediment nutrient release, and dominant bloom-forming taxa of the affected water body. Therefore, reducing both nitrogen and phosphorus inputs should not be considered universally equivalent across systems, and nutrient-management plans should be based on site-specific nutrient limitation and loading characteristics. Although watershed interventions can provide durable benefits, their effects may require prolonged implementation and may be limited where internal nutrient loading remains substantial [22,35].

Physical and chemical control methods

Several physical methods have been developed to suppress harmful algal blooms without substantially altering water chemistry. Mechanical harvesting removes dense surface scums and floating biomass from affected water bodies, while artificial mixing and aeration reduce thermal stratification and improve dissolved oxygen concentrations. Water circulation systems and ultrasonic treatment have also been investigated to inhibit cyanobacterial growth and reduce bloom persistence [2,22].

Physical interventions can provide relatively rapid reduction of surface biomass or improvement of water-column conditions, but their effectiveness is strongly dependent on bloom density, water-body characteristics, and the spatial distribution of biomass. Mechanical harvesting is most suitable for concentrated surface accumulations but may be difficult to apply at large spatial scales. Mixing and aeration can reduce stratification and improve oxygen conditions, although they may require continuous energy input and may not directly remove cyanobacterial biomass or toxins. Ultrasonic treatment and circulation-based approaches have shown potential in some systems, but their effectiveness can vary with species, water depth, treatment intensity, and operational conditions. Therefore, field-scale validation remains necessary before broad application [2,20].

Chemical control methods primarily involve the application of algicides such as copper sulfate, hydrogen peroxide, potassium permanganate, and modified clay formulations. These treatments can rapidly reduce bloom biomass; however, excessive application may damage non-target aquatic organisms and cause the release of intracellular toxins following cell lysis. Consequently, chemical methods are generally recommended only for emergency situations and should be applied under strict environmental guidelines [2,22].

The effectiveness of physical and chemical interventions is strongly dependent on bloom density, water-body characteristics, treatment conditions, and the target organism. Physical methods may provide rapid reduction of surface biomass but can be limited by high energy requirements, incomplete removal, and difficulties in treating large or deep-water bodies. Chemical algicides can provide rapid bloom suppression; however, treatment-induced cell lysis may increase the release of intracellular toxins into the surrounding water. Potential non-target effects on aquatic organisms and uncertainty regarding repeated application also require careful consideration. Therefore, chemical interventions should be selected on the basis of site-specific risk assessment, regulatory requirements, and evidence of field-scale effectiveness rather than solely on short-term biomass reduction [2,20].

Chemical treatments can act rapidly, but their application requires careful consideration of dose, bloom composition, water chemistry, and treatment timing. Cell-lytic algicides may cause rapid biomass decline while simultaneously increasing extracellular toxin concentrations through cell disruption. Non-target effects on aquatic organisms and possible effects on ecosystem structure further limit their routine use. Modified clays and other flocculation-based treatments may reduce suspended bloom biomass, but their performance depends on particle characteristics, water depth, mixing conditions, and sediment interactions. Consequently, chemical and physical controls are generally more appropriate for targeted or emergency situations than as stand-alone long-term prevention measures [2,20].

The practical use of physical and chemical control methods should therefore be based on site-specific risk assessment and field-scale validation. Treatment selection should consider expected bloom reduction, potential toxin release, effects on non-target organisms, regulatory requirements, treatment cost, and the feasibility of repeated application. These methods are generally more appropriate for targeted or emergency situations than as stand-alone long-term strategies for HAB prevention [2,22].

Biological control and bioremediation

Biological control has emerged as an environmentally friendly alternative to conventional chemical treatments. This approach utilizes naturally occurring microorganisms, aquatic plants, algae, viruses, fungi, and zooplankton to suppress bloom- forming species. Various bacterial species are capable of degrading cyanotoxins or inhibiting cyanobacterial growth through the production of algicidal compounds. Likewise, certain fungi and viruses specifically infect bloom-forming algae and contribute to bloom decline under natural conditions [2,16,20].

Microbial bioremediation using beneficial bacteria has gained increasing attention because of its ability to improve water quality while simultaneously reducing nutrient concentrations. Floating treatment wetlands, aquatic macrophytes, and biofilm-based systems also enhance nutrient removal and restore ecological balance. Although many biological control methods remain under investigation, they represent promising sustainable alternatives for long-term HAB management with minimal ecological disturbance [16,20].

Despite their potential sustainability advantages, biological control approaches require careful evaluation before field-scale application. Their effectiveness may be species- and strain-specific and can vary with temperature, nutrient availability, microbial community composition, and bloom stage. Algicidal microorganisms or agents that cause cell lysis may also increase extracellular toxin concentrations, creating a potential short-term water-quality risk even when bloom biomass declines. In addition, unintended effects on non-target phytoplankton and aquatic microbial communities, environmental persistence, ecological safety, and regulatory acceptance remain important considerations. Consequently, most biological approaches require further controlled field validation before routine large-scale deployment. An additional consideration is the possibility that rapid cell disruption may release intracellular cyanotoxins; therefore, biomass reduction should not be evaluated solely on the basis of visible bloom decline [2,16].

The effectiveness of HAB control strategies is strongly context dependent. Nutrient reduction offers the greatest potential for long-term prevention but generally requires sustained watershed-scale intervention, whereas physical and chemical treatments can provide more rapid responses but may have operational, ecological, or toxin-release limitations. Biological approaches may offer more targeted alternatives, but their consistency under field conditions and potential non-target effects require further validation. Therefore, prevention and control should be viewed as complementary rather than mutually exclusive strategies, with method selection guided by bloom characteristics, ecosystem conditions, treatment objectives, and available evidence [2,16,20].

Future perspectives and research directions

Future management of harmful algal blooms (HABs) will require a shift from reactive bloom control toward integrated prediction, early warning, and ecosystem-based management. Although existing monitoring and control approaches have improved HAB detection and mitigation, their effectiveness can vary according to bloom-forming taxa, environmental conditions, water-body characteristics, and available infrastructure. Future research should therefore focus on developing management frameworks that combine environmental monitoring, biological indicators, toxin assessment, and predictive modelling to support timely decision-making [28,29].

Climate change is expected to remain an important factor influencing HAB occurrence, duration, and geographic distribution through changes in temperature, precipitation, hydrological regimes, and nutrient dynamics. Future studies should investigate how these interacting factors influence bloom initiation, persistence, toxicity, and seasonal dynamics across freshwater and marine ecosystems. Long-term datasets and standardized monitoring programs will be particularly important for distinguishing climate-driven changes from local nutrient and land-use effects [13,19,29].

Advances in remote sensing, automated sensors, molecular approaches, and analytical technologies provide opportunities for more rapid and comprehensive HAB surveillance. Rather than relying on a single detection technology, future monitoring systems should integrate complementary approaches to obtain information on bloom biomass, taxonomic composition, environmental conditions, and toxin occurrence. Such integration could improve early-warning capacity and help identify blooms that pose greater ecological or human-health risks [29,38].

Artificial intelligence and machine-learning approaches may further support HAB forecasting by integrating large datasets containing environmental, biological, meteorological, and historical bloom information. However, future applications should emphasize model validation across different ecosystems, transparency of predictive outputs, data quality, and standardized performance evaluation. Predictive models should ultimately be linked with practical management thresholds so that forecasts can support timely and evidence-based interventions [29,38].

Future HAB control should also prioritize environmentally sustainable and site-specific strategies. Nutrient reduction remains essential for long-term prevention, whereas physical, chemical, and biological approaches may provide targeted responses during established blooms. Research should therefore evaluate combinations of prevention and control measures while considering treatment efficiency, toxin release, non-target effects, ecological recovery, cost, and feasibility under field conditions. Greater emphasis should also be placed on validating promising laboratory-scale technologies at realistic field scales [2,20].

An important future priority is the development of standardized protocols for HAB monitoring, toxin assessment, treatment evaluation, and ecological risk assessment. Consistent methodologies would improve comparison among studies and facilitate the development of reliable evidence-based management guidelines. Greater collaboration among researchers, water-resource managers, public-health authorities, and environmental agencies will also be necessary to translate scientific findings into effective HAB management practices [2,29].

Overall, future HAB research should move toward integrated, predictive, and ecosystem-based management that combines improved surveillance with sustainable prevention and control. The development of reliable early-warning systems, validated predictive models, standardized monitoring approaches, and environmentally responsible intervention strategies will be critical for reducing the ecological and human-health consequences associated with HABs [28,29].

Conclusion

Harmful algal blooms (HABs) are complex ecological events arising from interactions among nutrient enrichment, climatic variability, hydrological conditions, and biological processes. Their impacts extend beyond changes in algal biomass to include oxygen depletion, ecological disruption, toxin contamination, human-health risks, and economic losses. The review highlights that HAB occurrence and severity cannot be attributed to a single environmental driver; rather, bloom development and persistence depend on the interaction of multiple physicochemical and biological factors.

Effective HAB management therefore requires an integrated approach that links prevention, monitoring, risk assessment, and targeted intervention. Nutrient-load reduction remains fundamental for limiting bloom development, while physical, chemical, and biological approaches may provide complementary options for managing established blooms. However, the effectiveness and environmental suitability of these interventions vary among ecosystems and bloom types, emphasizing the need for site-specific evaluation rather than reliance on a universal control strategy.

Advances in molecular diagnostics, remote sensing, biosensors, automated monitoring, and predictive modelling are improving the ability to detect and characterize HABs at earlier stages. Nevertheless, technological development alone is insufficient. Reliable HAB management requires standardized monitoring protocols, validated analytical methods, long-term environmental datasets, and effective translation of monitoring information into practical management decisions. Particular attention is also required to distinguish bloom presence from toxin-related risk because toxin production, exposure, and human-health impacts can vary substantially among species, strains, and environmental conditions.

Future progress should therefore focus on integrating complementary monitoring technologies with sustainable prevention and control strategies while strengthening field validation and ecological risk assessment. Greater coordination among researchers, environmental agencies, water-resource managers, public-health authorities, and policymakers will be essential for developing responsive and environmentally responsible HAB management frameworks. Such integrated approaches can improve early warning, reduce exposure risks, and support the long-term protection of aquatic ecosystems and water resources.

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