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Mini-review

Harmful algal bloom: catastrophe of aquatic ecosystems and human health

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Abstract

Harmful algal blooms (HABs) are a catastrophic phenomenon in aquatic ecosystems globally, occurring in freshwater bodies and sometimes in marine and brackish waters, due to large numbers of cyanobacteria and microalgae, including dinoflagellates. HABs are dangerous and may be fatal to humans and animals due to toxicity and anoxic conditions. They also cause paralytic shellfish poisoning and kill fish in water bodies. Major factors include eutrophication, rising temperatures, stagnant water, and increased sunlight. Promising paths for early intervention are enabled by efficient monitoring and detection techniques, such as molecular biotechnology, artificial intelligence-driven predictive models, and satellite remote sensing. The negative consequences of HABs can be mitigated through sustainable management techniques such as bioremediation, nutrient load reductions, and regulatory measures. Public awareness and community involvement also play a critical role in preventing and mitigating HAB incidents by encouraging ethical farming methods, reducing waste discharge, and bolstering conservation initiatives. In this mini-review, the major causes and mitigation strategies for HABs have been outlined. In addition, modern strategies, policies, and the current status have been discussed.

Keywords: Catastrophic effect, Eutrophication, Harmful algal bloom, Mitigation, Public awareness, Toxicity

Introduction

Harmful algal blooms (HABs) have a detrimental impact on most coastal regions worldwide and numerous freshwater systems. Everyone agrees that over the past few decades, these blooms have become more detrimental to public health, ecosystem function, fisheries and aquaculture, and the recreation and tourism sectors. The term HAB encompasses a large and sometimes confusing array of species, life cycles, habitats, and impacts, making it difficult to characterize research, management, and mitigation efforts coherently, despite the general consensus that HAB impacts are rising [1]. In freshwater or other aquatic environments, HABs are rapid, excessive growths of algae or, occasionally, cyanobacteria that accumulate on or near the water's surface. These blooms can create poisons, deplete oxygen, and discolor water, posing major threats to people, wildlife, ecosystems, and the local economy [2].

Excessive nutrient inputs (nitrogen [N] and phosphorus [P]), favorable hydrology, and climate change increase the frequency and intensity of HABs [3]. The term "bloom" describes the sharp rise and subsequent fall in phytoplankton populations. The adverse effects that microalgal species have on aquatic creatures and ecosystems are referred to as "harmful." HABs, which are primarily caused by nutrient over-enrichment, can significantly alter trophic dynamics in aquatic environments. There are several ways in which these nutrient surpluses might disrupt food web dynamics. For instance, traditional primary producers like zooplankton are frequently outcompeted by HABs, which eventually results in decreased biodiversity [4]. Because herbivores rely on these primary producers to survive, a fall in their numbers could lessen grazing pressure and have repercussions for the entire ecosystem. In addition to the toxins produced by HABs, stormwater runoff-borne toxins have the potential to bioaccumulate in aquatic creatures' tissues, creating hazards higher up the food chain [5].

Numerous studies have demonstrated that eutrophication and climate change significantly affect the incidence and duration of HABs [6, 7]. Since the 20th century, a significant amount of domestic and industrial sewage containing nitrogen and phosphorus has been dumped into the ocean, lakes, rivers, and reservoirs, hastening the eutrophication of the world's waters due to population growth and the rapid development of industry and agriculture [6]. In these waters, where the nutrient load increases dramatically, HABs are also more commonly recorded. Additionally, over the past many years, the frequency and intensity of HABs in lakes worldwide have increased due to climate change [8]. These findings suggested that HABs are globalizing as both eutrophication and climate change are global problems. Since HABs have been the subject of numerous studies across a variety of fields, including ecology, marine sciences, plant sciences, and environmental sciences, multiple reviews addressing advances in HAB research from various perspectives have been published in recent decades [7].

Although the main causes of HABs, such as nutrient loading and thermal stratification, have been identified by modern research, there remain significant gaps in our ability to anticipate, monitor, and mitigate these harmful phenomena [9]. The major gaps include: (1) The extremely erratic correlation between algal volume (biomass) and actual toxicity is one of the most perplexing mysteries in HAB research; (2) Satellite remote sensing is quite good at tracking big, fully formed surface blooms, but it is not very useful during the initialization stage; (3) People know that HABs are made worse by climate change, but they don't fully understand how different shifting stressors interact at the same time; (4) The health effects of long-term, chronic exposure to low levels of aerosolized or water-bound cyanotoxins are little understood, despite the fact that acute poisoning from contaminated seafood is well-documented; (5) In order to assist local coastal governance in adapting to escalating climate hazards, current research is having difficulty bridging the gap between academic data modeling and practical, user-driven policy management [10, 11].

However, to better understand the globalization of HABs, there has been little focus on analyzing overall progress and emerging patterns. To address this challenge, we provide an overview of HAB research and highlight the main issues and potential solutions, including new trends.

Role of climate change-related factors for HABs

Climate change enhances HAB occurrence through warming, sea-level rise, and altered coastal dynamics. Climate-driven changes in salinity, CO_2, rainfall, and ocean circulation also promote HABs [12]. For instance, warmer water temperatures foster the growth of cyanobacterial HABs, which prefer warm, sluggish waters. Salinity levels are also expected to vary as a result of climate change. Water bodies in some areas will become more saline due to reduced freshwater discharge caused by severe droughts and increased evaporation. In other areas affected by winter and freezing rain, increased road salt use causes downstream watersheds to become more salinized. Another effect of climate change is increased air and aquatic CO_2 concentrations, which can hasten algal development by supplying more carbon for photosynthesis [8]. Increased CO_2 levels also make water bodies more acidic, which affects creatures that graze on algae and alters competition among algal species [13]. Rainfall patterns, already being disrupted by climate change, are projected to intensify longer droughts and larger rainfall events. HABs are fueled by intense rainfall, which boosts nutrient-rich runoff from land into aquatic systems. By increasing the extent of shallow, stable coastal waters, sea-level rise promotes the establishment of HABs. Lastly, it is anticipated that coastal upwelling occurrences may become more intense and change over time due to climate change [14]. Winds force surface waters offshore during upwelling, allowing nutrient-rich deep waters to ascend. When paired with increased nutrient runoff from terrestrial sources, these nutrient surges can promote algal growth, especially HABs [13].

Impact of HABs

Ecological impacts

Since most algal blooms consist of potentially toxic cyanobacteria, they pose considerable risks to aquatic ecosystems, biota, and people who use these water sources. The most detrimental bloom-forming organisms to aquatic ecosystems and trophic structure are cyanobacteria. Cyanobacterial blooms can also produce taste and odor compounds, increase water turbidity and pH, and reduce ecosystem services, including drinking water potability and recreational value [15]. Oxygen depletion, toxin generation and bioaccumulation, disruption of food webs, and habitat degradation are some of the ecological effects of HABs [16, 17]. The vicious cycle between eutrophication, climate change, and bloom decomposition, which may release additional nutrients and greenhouse gases, is another issue associated with algal bloom senescence [14].

Different algal blooms can significantly affect phytoplankton and zooplankton dynamics, as well as environmental conditions. Large amounts of oxygen are consumed during the decomposition of dead HABs, creating hypoxic or anoxic zones in the system. Fish, shellfish, and other aquatic species may suffocate to death as a result of such low oxygen levels. Toxins produced by HABs have the potential to bioaccumulate and be discharged into the marine environment [18]. Toxins produced by algae can bioaccumulate and be released into aquatic environments [3, 16]. When HABs outcompete phytoplankton, they can disrupt food webs by reducing the availability of filter feeders such as mussels and oysters. Top predators, such as dolphins, seagulls, and sharks, will eventually be affected by these toxins as they accumulate up the food chain. There are three major groups of phytoplankton, i.e., cyanobacteria, dinoflagellates, and diatoms, that can cause significant negative impacts on aquatic animals and humans (Table 1).

Economic impacts

The annual expenses for HABs in the United States (US) alone are estimated to be between $10 million and $100 million (https://coastalscience.noaa.gov/science). Many coastal and inland waters in the US and around the world are plagued by recurrent blooms of dangerous algae and cyanobacteria, which have a major negative economic impact on the nearby populations [1, 18]. HABs are a major economic burden on a global scale. The four main areas where these financial effects are focused are human health, commercial fishing, tourism and recreation, and monitoring and management.

Table 1: Major groups of phytoplankton causing harmful effects in the ecosystem.

Type	Common name	Typical color	Major risks	References
Cyanobacteria	Blue-green Algae (*Microcystis aeruginosa; Oscillatoria princeps; Anabaena variabilis*)	Green/Blue-green	Produce hepatotoxins (liver) and neurotoxins; common in freshwater lakes	[19]
Dinoflagellates	Golden Brown Algae (*Karenia brevis*)	Red/Rusty Brown	Can cause respiratory irritation in humans and massive fish kills	[20]
Diatoms	Golden Algae (*Pseudo-nitzschia australis*)	Brown	Produce domoic acid, which can cause amnesic shellfish poisoning (ASP)	[21]

According to a 2024 study by Alvarez et al. [22], the 2018 red tide HAB caused over USD 2.7 billion in tourism-related economic losses in Florida's coastal counties. The study pointed out that, in contrast to abrupt catastrophes like floods, the economic effects of HABs often develop gradually and require thorough evaluation to precisely measure [22].

Public health impacts

The effects of HABs on human health, community stability, and cultural legacy are numerous and go well beyond environmental harm. These effects are increasingly recognized as a serious threat to public health and the environment worldwide [23]. The ingestion of tainted seafood, skin contact during recreational activities, or inhalation of aerosolized toxins can all expose humans to HAB toxins (Table 2). Ciguatera, paralytic, neurotoxic, diarrheal, and amnesic shellfish poisoning are recognized illnesses linked to HAB. From mild skin irritation and upset stomach to serious brain damage or even death, symptoms can vary widely. Pets and children are especially vulnerable to serious infections from HAB exposure [23].

Mollusk poisoning typically happens during periods of algal bloom. Toxins found in fish can cause tetrodotoxin and ciguatera poisoning. Fish poisoning is more confined to certain areas of particular fish or reefs. Dinoflagellate *Pfiesteria* bloom episodes in estuaries along the middle and southern Atlantic coast indicate that human stress on the aquatic environment has resulted in fish fatalities and associated health risks [24]. The everyday routines and sense of security of affected communities may be disrupted by HABs. Freshwater supplies may become contaminated by toxic blooms, limiting public access to clean water and necessitating the closure of drinking water treatment facilities. Public confidence in governmental organizations and scientific institutions can be damaged by poor management or a lack of timely information about blooms [25].

Blooms can permanently change a community's view of the safety of their local environment, drinking water, and food sources, even though they are only temporary. Blooms diminish recreational activities such as swimming and boating, further affecting community well-being by degrading the visual quality of water bodies, often through discoloration and unpleasant odors [25].

Toxins released directly into the air or water can also be harmful to humans. This can happen naturally, as a result of turbulence-induced cell disruption, or as a result of human actions like water treatment. This condition is common in the Gulf of Mexico, where beachgoers and locals are exposed to pollutants from sea spray. Following inhalation, toxins may become stuck in the nose, throat, or lungs. Coughing, respiratory discomfort, and other illnesses are common signs of this [24]. Strong biotoxins produced by HABs target several bodily systems. The main symptoms caused by these toxins, e.g., gastrointestinal, neurological, or organ-specific damage, are typically used to classify them (Table 2).

HAB related risks across the human-animal-environment interface

HABs exemplify the interconnected nature of environmental, animal, and human health, with risks cascading across the human–animal–environment interface. Environmental changes such as nutrient pollution, rising water temperatures, altered precipitation patterns, and hydrological modifications promote the proliferation of toxin-producing algae and cyanobacteria [35]. These blooms can degrade water quality, reduce dissolved oxygen levels, and disrupt aquatic food webs, leading to fish kills, habitat loss, and declines in biodiversity. Aquatic organisms, including fish, shellfish, marine mammals, and birds, may accumulate algal toxins through direct exposure or trophic transfer, resulting in illness, reproductive impairment, or mortality.

The impacts on animal health can subsequently affect human populations. Contaminated seafood serves as a major pathway for human exposure to HAB toxins, causing illnesses such as paralytic, neurotoxic, amnesic, and diarrhetic shellfish poisoning [36]. Humans may also be exposed through drinking water, recreational activities, or inhalation of aerosolized toxins, leading to gastrointestinal, neurological, respiratory, and dermatological effects. In many cases, wildlife and domestic animal deaths provide early warning signals of environmental contamination and potential human health risks, highlighting their role as sentinels within the One Health framework [37].

Table 2: Toxins produced by HABs cause major health effects.

Toxin category	Specific toxin	Primary source	Major health effects	Ref.
Neurotoxins	Saxitoxins	*Alexandrium catenella* Dinoflagellates (Marine)	Blocks nerve signals; causes facial numbness, respiratory paralysis, and can be fatal (Paralytic Shellfish Poisoning)	[26]
	Brevetoxins	*Karenia brevis* (Marine/Red Tide)	Causes respiratory irritation when inhaled; nausea, vomiting, and slurred speech if ingested (Neurotoxic Shellfish Poisoning)	[27]
	Domoic Acid	*Pseudo-nitzschia australis* (Marine)	Leads to short-term memory loss, seizures, and neurological damage (Amnesic Shellfish Poisoning)	[28]
	Anatoxins	*Oscillatoria princeps, Anabaena variabilis* (Now *Dolichospermum*) Cyanobacteria (Freshwater)	Known as "Very Fast Death Factor", it causes rapid muscle twitching and respiratory failure	[29]
Hepatotoxins	Microcystins	*Microcystis aeruginosa* Cyanobacteria (Freshwater)	Attacks the liver, causing cell damage and internal bleeding; most common cyanotoxin worldwide	[30]
	Nodularins	*Nodularia spumigena* Cyanobacteria (Freshwater)	Similar to microcystins, it inhibits protein phosphatases, leading to liver damage	[31]
Multi-Organ	Cylindrospermopsins	*Cylindrospermopsis raciborskii* Cyanobacteria (Freshwater)	Inhibits protein synthesis, primarily damaging the liver and kidneys over several days	[32]
Gastrointestinal	Ciguatoxins	*Gambierdiscus toxicus* Dinoflagellate (Marine)	Causes temperature sensation reversal (hot feels cold), muscle pain, and chronic fatigue (Ciguatera Fish Poisoning)	[33]
Dermatotoxins	Lyngbyatoxin Aplysiatoxin	*Lyngbya majuscula* Cyanobacteria (Freshwater/Marine)	Causes skin rashes, blisters, and eye irritation upon direct contact	[34]

Beyond direct health impacts, HABs generate broader socioeconomic consequences that further cascade through human and ecological systems. Fisheries closures, losses in aquaculture production, restrictions on recreational water use, and declines in tourism can adversely affect human and ecological systems. Fisheries closures, losses in aquaculture production, restrictions on recreational water use, and declines in tourism can adversely affect livelihoods and food security, particularly in coastal and lake-dependent communities [38]. These interconnected effects demonstrate that HABs are not solely environmental phenomena but rather complex One Health challenges that require integrated monitoring, risk assessment, and management strategies spanning the ecosystem, animal, and public health sectors. Understanding these cascading pathways is essential for developing effective prevention and mitigation measures in a rapidly changing global environment.

Monitoring and mitigation of HABs

Over the past few decades, the nature of the HAB issue has changed significantly globally [18]. The quantity of toxic blooms, the associated financial losses, the kinds of resources impacted, and the quantity of poisons and poisonous species have all sharply increased. Storms, currents, and other natural phenomena have been blamed for some of this expansion, but human activity is also sometimes blamed. Humans have contributed by transporting toxic species in ballast water, and by adding massive and increasing quantities of industrial, agricultural, and sewage effluents to coastal waters [9]. In many urbanized coastal regions, these inputs have altered the size and composition of the nutrient pool, which has, in turn, created a more favorable nutrient environment for certain HAB species [39]. The steady expansion in the use of fertilizers for agricultural production represents a large and worrisome source of nutrients in coastal waters that promote some HABs. HABs can be effectively monitored and mitigated by combining physical, chemical, or biological control methods with early detection systems. Many of the management strategies used in response to HABs fall under the category of mitigation, which includes addressing an ongoing or current bloom and taking whatever is required or practical efforts to lessen adverse effects. The regular monitoring programs for toxins in shellfish, which are presently carried out in more than 50 nations, are clear examples [39, 40].

Emerging technologies for monitoring HABs

The most challenging and contentious aspect of HAB management is bloom control. Bloom control refers to measures that directly interfere with the bloom process to reduce, suppress, or eliminate HABs. Despite advances in HAB research, this remains one of the least developed areas of HAB science, with a relatively limited understanding and few widely accepted control methods. To fight or control an invasive or dangerous species, there are five broad types or tactics that might be employed. These consist of genetic, chemical, biological, mechanical, and environmental control. A number of them have been used for HAB species. The removal of HAB cells from the water by spreading clay across the water's surface, for instance, is one type of mechanical control. Many new technologies, such as satellite imagery, imaging flow cytobots, *in situ* sensors, flow imaging microscopy, and manual field sampling, are emerging and can significantly assist with the management issues we confront, as the HAB problem has been a major research focus worldwide (Table 3) [41, 42]. To provide early warnings, monitoring programs focus on both tracking environmental variables (such as nutrients) and directly detecting algal cells or toxins. Hence, a multi-layered approach is needed to overcome the problems related to HABs (Table 3) [43, 44].

Table 3: HAB monitoring strategies, their advantages, and limitations.

Technology/ method	Primary function	Advantages	Limitations	Ref
Satellite imagery (e.g., NASA/Sentinel-3)	Large-scale bloom tracking and quantification in coastal and lake regions	Near real-time data across massive areas; identifies bloom location and size	Low spatial resolution, depth, and vertical detection of HABs, cloud cover interference, and inability to assess toxicity	[41]
Imaging flowcytobots (IFCBs)	Automated microscope sensors that take images of algae and use AI for identification	Provides organism-level data every 30 minutes; identifies both harmful and benign species	Morphological ambiguity, inability to assess active toxicity, detritus interference, size constraints, and resolution	[42]
In-situ sensors (EXO NitraLED, etc.)	Continuous tracking of bulk indicators like chlorophyll, phycocyanin, nitrate, and pH	Tracks underlying biological drivers; identifies nutrient spikes that precede blooms	Organic matter noise, turbidity interference, sensor biofouling, and no toxin detection	[45]
Flow imaging microscopy	High-resolution laboratory imaging of particles	Differentiates cyanobacteria from debris; tracks population shifts quantitatively	Biofouling, colonial dissociation, motion blur, and frame rates, out-of-focus cells	[46]
Manual field sampling	Collection and laboratory analysis of water or shellfish samples	Confirms toxin levels precisely; essential for guiding beach and shellfish bed closures	Safety risks, temporal delays, cost-prohibitive and impractical, spatial variability	[42]

Mitigation and management strategies

To control lake and reservoir water quality, particularly for drinking water treatment, algal blooms must be addressed. As a result, the mechanisms governing nitrogen regulation and algal blooms in aquatic settings, as well as their avoidance and management, have emerged as crucial areas of research in the water environment and are urgent issues being addressed globally [47]. Finding innovative ways to lessen the negative effects of HABs is crucial. Several regulatory approaches must be used to address the problem of HAB abatement. Triosyn, hydrogen peroxide, and copper sulfate are examples of chemical treatments that have demonstrated effectiveness in a short amount of time. The term "microbial herbicides" is used to describe microbial communities. Therefore, bacteria, viruses, and protozoa are used as biological control agents for particular attention. Many microorganisms have algicidal properties and have been linked to the formation, execution, and breakdown of algal blooms [43, 44]. Similarly, many modern approaches, such as nano-aeration [48, 49], AI-based coagulants [50, 51], and ultrasonication [52], have become more popular for mitigating HABs. The details are presented in Table 4.

Table 4: HAB mitigation mechanisms and their positive and negative impacts.

Control method	Mechanism of action	Strengths	Limitations	Ref.
Clay flocculation	Clay particles (e.g., "yellow loess") combine with algal cells and sink them to the seafloor	Routinely used in South Korea/China; can kill algae by rupturing cell membranes	Can be expensive; potential for sediment burial; not yet routine in the U.S.	[53, 54]
Aeration /nano-aeration/ mixing	Disrupts water stratification by pumping air or water throughout the column	Maintains dissolved oxygen; disrupts the vertical migration of cyanobacteria	Costly operation; limited range for individual devices; can harm cold-water habitats	[48, 49]
Chemical coagulants (alum)/AI-based coagulants	Aluminum sulfate reacts to bind phosphorus and settle algae away from the surface	Long-term internal nutrient removal is effective at reducing phosphorus	Can impact pH levels; ineffective if external nutrient sources remain uncontrolled	[50, 51]
Upwelling systems	Transfers clean, deep water to the top of fish pens to create a protective "bubble"	Protects farmed fish from surface-level blooms	Primarily used in aquaculture, it does not treat the bloom itself	[55]
Floating treatment wetlands	Floating mats of emergent plants that trap and filter nutrients through their roots	Minimizes light penetration; utilizes natural processes with minimal technical attention	Excessive coverage can de-oxygenate water; plants only access the water column nutrients	[56]
Ultrasonication	Uses ultrasonic irradiation to disrupt the cyanobacteria cells' ability to float	No chemical residuals; potentially selective to cyanobacteria	May release toxins upon cell death, with limited success in large-scale field trials	[52]

Conclusion and future prospects

Harmful algal blooms have emerged as a growing environmental, public health, and socioeconomic challenge worldwide, driven by the complex interactions among climate change, nutrient enrichment, hydrological alterations, and ecosystem disturbances. Despite significant advances in HAB research, several critical knowledge gaps remain. These include an incomplete understanding of bloom initiation and termination mechanisms, limited predictive capacity for toxin production under changing environmental conditions, insufficient long-term monitoring datasets, and a lack of integrated assessments linking ecological, human, and animal health outcomes. Furthermore, the impacts of emerging and poorly characterized algal toxins on ecosystems and public health remain inadequately understood.

Future research should prioritize developing multidisciplinary monitoring networks that integrate remote sensing, molecular diagnostics, artificial intelligence, and environmental modeling to improve early warning systems and forecasting accuracy. Greater attention should also be directed toward understanding how climate variability and extreme weather events influence HAB dynamics, identifying the genetic and metabolic pathways that govern toxin synthesis, and evaluating sustainable mitigation and nutrient management strategies. Strengthening international data-sharing frameworks and harmonizing monitoring protocols will be essential for generating comparable datasets and supporting evidence-based management decisions across regions.

Importantly, HABs exemplify a quintessential 'One Health' challenge, as their consequences extend beyond aquatic ecosystems to affect human health, livestock, wildlife, food security, and economic sustainability. Exposure to HAB toxins through drinking water, recreational activities, and contaminated seafood poses significant risks to human populations, while domestic animals and wildlife often serve as sentinels of ecosystem health. Addressing HABs, therefore, requires an integrated One Health approach that fosters collaboration among ecologists, public health professionals, veterinarians, water resource managers, policymakers, and local communities. By bridging disciplinary boundaries and recognizing the interconnectedness of environmental, animal, and human health, future HAB management strategies can become more proactive, resilient, and effective in safeguarding both ecosystem integrity and societal well-being in an era of accelerating global change. A graphical abstract explaining the major drivers and impacts of HABs, as well as methods of control and mitigation, is shown in the supplementary figure (Figure S1).

Declarations and supplementary information

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Supplementary materials: Figure S1. A graphical abstract explaining the major drivers and impacts of HABs, as well as methods of control and mitigation.

Declaration regarding the use of generative AI and AI-assisted technologies in the writing process: Grammarly and ChatGPT are used to improve the text and correct the spelling and grammar.

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