



Understanding Harmful Algal Blooms: Causes, Impacts and Control Measures

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ABSTRACT

Algal blooms are rapid, excessive growth of phytoplankton, which is an escalating threat to aquatic ecosystems, coastal economies, and public health, driven by anthropogenic nutrient enrichment and changing climatic scenarios. This ephemeral phenomenon can trigger a cascade of adverse impacts, such as toxin production, oxygen depletion in water bodies, massive mortalities of aquatic organisms, food chain disruption and even huge economic losses exceeding billions of dollars through aquaculture devastation, tourism decline and drinking water contamination. Toxin-producing species such as cyanobacteria, diatoms, and dinoflagellates further accelerate mortality through neurotoxins and cytotoxic compounds that often lead to marine shellfish poisoning in humans. The control of HABs spans physical, chemical, and biological methods, each with distinct advantages and limitations. HABs remain a growing and multifaceted threat, which can lead to a cascade of events like ecosystem disruption, human poisoning and huge annual economic losses, so effective management requires moving beyond a single method approach and using integrated systems combining preventive and curative measures across aquatic ecosystems.

KEYWORDS

Eutrophication, Harmful Algal Bloom, Nutrients, Toxins, Climate Change

Introduction

Algal blooms are dense aggregations of phytoplankton cells of one or more species, manifesting as noticeable changes in water discolouration, foam production, and eventually invertebrate mortality or toxicity to humans (Padmakumar, Menon and Sanjeevan, 2012). Algal blooms are a rapid, ephemeral phenomenon when phytoplankton assemblages exceed their mortality rates in both freshwater and marine aquatic habitats. Blooms cause prominent discolouration in water owing to the presence of pigments, appearing as brown, red, mahogany, or green tides, which float on the surface in scums and cover beaches with biomass, exudates or foam. Blooms that can cause injury to animals or the ecology by producing toxins, depleting oxygen in water bodies, disrupting the ecosystems or interfering human activities, and contaminating drinking water regardless of the concentration, are called "harmful algal blooms" (HAB) (Feng *et al.*, 2024; Brenckman *et al.*, 2025). The blooms of these organisms are attributed to two primary factors: anthropogenic factors like nutrient enrichment, leading to eutrophication and natural processes, such as circulation, upwelling relaxation, and river flow. Their global occurrence has substantially increased since the 1980s, including a 44% increase from the 2000s to the 2010s, particularly in Asia and Africa (Feng *et al.*, 2024).

Causes of harmful algal bloom

Harmful algal blooms are caused by environmental conditions such as nutrient enrichment, water temperature, light availability, and water column stratification

(Lan *et al.*, 2024). The frequency, duration, and geographic extent of these blooms are primarily driven by anthropogenic nutrient enrichment and climate change (Brenckman *et al.*, 2025). Nutrient loading causes excessive phytoplankton development, high levels of chlorophyll, decreased biodiversity, and decreased water quality, and even high amounts of bacteria, scums, fungi, hypoxia, and ultimately anoxia are seen in more advanced phases (Kitsiou & Karydis, 2011). Agricultural runoff, waste water discharge, and industrial pollution introduce nitrogen, phosphorus, and silica, promoting bloom formation (Lim *et al.*, 2023). Climate change exacerbates this problem by altering precipitation patterns, increasing water temperature, and intensifying coastal upwelling, all of which are factors favouring algal proliferation (Brenckman *et al.*, 2025). Table 1 enlists the causes of harmful algal blooms

Table 1 Causes of harmful algal bloom

Factor		Details
	Nutrients	Runoff from agriculture, stormwater, road, and sewage, including point sources such as sewage and confined animal feed operation discharges. Atmospheric deposition and upwelling of ocean water. Nitrogen (N), Phosphorus (P), and Silicon (Si) are the primary nutrients

	Environmental conditions	Higher light intensities and rising temperature promote algal growth. Temperature is a key factor as it influences growth rate, toxin production, duration and species composition
	Seasonal factors	Warm water conditions (autumn and late summer) promote algal bloom
	Hydrodynamic factors	Moderate water turbulence, slow flow velocity, and stratification of the water column support algal growth. Clear water, as in reservoirs, lakes, quarries slow moving rivers, provides ideal habitat
	Climate change	Increase in water and air temperature, increases in droughts and flooding, changes in salinity, Higher atmospheric and aquatic CO ₂ concentrations, Ocean Acidification, sea level rise and coastal upwelling favour algal growth

Impacts

According to Hallegraeff (2003), there are three main categories of HAB-causing microorganisms. (1) Non-toxin-secreting species that alter the recreational value of the area by causing discoloration of the water or producing enormous amounts of foam, or cause high rates of fish mortality

via the drastic reduction of dissolved oxygen in water, due to the explosive increase in microalgal cell density; (2) Species that are not toxic to humans but affect the inhabiting fish by physically injuring the fish, for example, by obstructing their gills and/or by the production of ichthyotoxic substances; and (3) toxin-producing species can cause a range of neurological and gastrointestinal disorders through their uptake by the food chain. HAB can cause adverse impacts through two major mechanisms: toxin production and high biomass and organic matter production. The death and decomposition of bloom biomass depletes dissolved oxygen, creating hypoxic dead zones where aquatic organisms cannot survive (Hallegraeff, 2003; Messineo et al., 2024). Figure 1 illustrates the detrimental impacts of HABs. Toxin-producing species contaminate seafood and drinking water, causing increased water treatment costs and public health concerns due to various biotoxins. Beyond the risks of ingestion, the effects of HAB-derived toxins on human health include allergies, skin reactions, respiratory irritation, and potential long-term carcinogenic associations (Messineo et al., 2024). Cyanobacteria dominate freshwater habitats, producing microcystin and nodularin, which affect drinking water quality and tourism. Dinoflagellates and diatoms are two diverse categories of algae that are predominantly seen in marine habitats and are responsible for causing red tides and producing biotoxins, including Brevetoxin, azaspiracid, ciguater toxins, okadaic acid, saxitoxin, and domoic acid, causing neurotoxic shellfish poisoning (NSP), Azaspiracid Shellfish Poisoning (AZP), Ciguatera Fish Poisoning (CFP), Diarrhetic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), and Amnesic Shellfish Poisoning (ASP) in humans (Van

Dolah, 2000). These blooms can contaminate seafood, causing bans on fishery products and exports, and causing economic losses for fisheries (Hallegraeff, 2003). HABs can trigger huge economic losses exceeding billions of dollars annually through aquaculture devastation, tourism decline, loss of recreational values, and drinking water contamination. HABs cause serious ecological consequences, such as a decrease in biodiversity, loss of seagrass, coral bleaching, and fish and mammal mortality. HABs alter the trophic dynamics in aquatic environments by disrupting food web structures in several ways. For instance, due to nutrient enrichment, traditional primary consumers, such as zooplankton, are frequently outcompeted by HABs, which eventually causes a food web disruption and decrease in biodiversity. Phytoplankton serves as the base of the majority of marine food webs that provide provisional ecosystem services while also being a contributor of excess organic matter, often resulting in coastal eutrophication. A change in the species makeup of phytoplankton can aid in the prolific growth of detrimental algae and cause depletion of oxygen in water due to decomposition and can cause mass fish mortality and ecological collapse (Diaz et al., 2008).

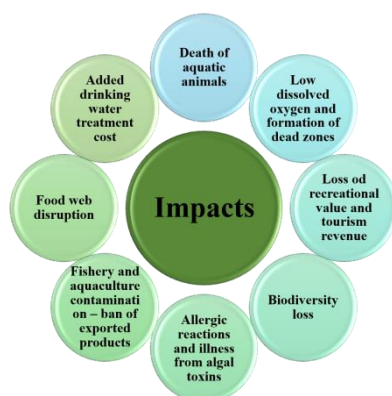


Figure 1 : Impacts of harmful algal bloom

Detection of algal blooms

Satellite remote sensing, molecular biotechnology, and machine learning-driven predictive models are integrated for effective algal biomass monitoring. Conventionally, algal bloom in a water body can be estimated in three ways, including quantifying chlorophyll a (CHL a), measuring carbon biomass, or by measuring the particulate organic carbon (POC) in a sample. In addition, analytical techniques like bioassays, biosensors, HPLC, LCMS, and continuous monitoring using sonde buoys and even portable algal bloom detectors like chlorophyll metres are also used for this purpose (Brenckman et al., 2025b).

Control measures and management

For the control of algal blooms, mechanical, biological, chemical, genetic and environmental control measures can be utilized (Anderson, 2009; Song et al., 2023). Physical methods include manual removal and other methods such as filtration, skimming, electrolysis, and water mixing, which can be performed using mechanical (pumps), hydraulic, or pneumatic mixers. Also, use of floating covers can avoid the proliferation of photosynthetic organisms. Methods such as ultraviolet radiation, centrifugal separation, magnetic separation, and air flotation are constrained by high energy costs and limited scalability to large water bodies (Zeng et al., 2023). Adding clay particles or flocculants controls algae, which helps to carry blooms to bottom sediments, but it raises certain environmental concerns. Another physical method is to pump out the surface algal

scums or blooms from lakes. Aeration and mixing are expensive, but effective and environmentally friendly algal control methods that maintain and refresh water bodies. Mechanical aeration leads to the reduction of algal growth by mixing algae deeper into the water column and starving them of light. In addition, it is also used to prevent and reduce the sediment phosphorus load available to the water column by decreasing the likelihood of anoxia. Ultrasound methods are also used to mitigate HAB and it works by a phenomenon known as acoustic cavitation, which occurs when sound waves of over 20 kHz travel through a liquid medium. A sound layer is created in the top layer of water by ultrasound waves and damage the buoyancy of the algal cells directly, causing them to sink to the bottom, where they are unable to photosynthesise due to a lack of light and dies eventually (Park et al., 2017).

Biological control agents, such as fish, bacteria, phage and fungi, which are used to control blooms (Anabtawi et al., 2024). The primary source of food for herbivorous fish are algae, and algal growth can be controlled by stocking fish such as tilapia and grass carp. *Microcystis aeruginosa*, a bloom forming algae, are removed by grazing on them by species such as bighead (Aristichthys nobilis), silver carp (*Hypophthalmichthys molitrix*), and freshwater mussel (*Hyriopsis cumingii*). Furthermore, bacterial secretions such as cyanobacterial substances and secondary metabolites, which release mucous-like secretions for self-defence and utilize entrapment techniques with antagonistic volatiles is also found useful for bloom control. Zooplanktons, such as cyclopoid copepods and calanoids,

reduce the cyanobacterial load in water by grazing on them. Algae are also used as a control agent in the bio-flocculation method, which involves the mediation of flocculants in the presence of microorganisms or the release of biodegradable macromolecular flocculants by microorganism (Yang et al., 2024). Biocontrol methods are eco-friendly, contamination-free, and low-cost removal strategy, but it has certain practical limitations and will not function at oxygen-poor conditions.



Figure 2: Chemical agents used for control of algal bloom

Algal blooms can be eliminated using chemical agents such as copper sulfate, triosyn, hydrogen peroxide, flocculants, and herbicides, which act rapidly and at low cost (Figure 2). However, algaecide-induced cell lysis releases intracellular toxins into water, creating secondary pollution (Anabtawi et al., 2024) (Kim et al., 2007). Hydrogen peroxide (H_2O_2) is a recommended and effective method for lysing cyanobacteria in lakes and ponds. In comparison, H_2O_2 price is low, has low toxicity for non-target species, and is selective among chemicals. Another method is the use of decomposed barley straw to control algae and cyanobacteria. Flocculants bind and settle the available phosphorous in the system, which leads to reduced phytoplankton growth. Flocculants such as sodium aluminate, aluminium sulfate, native clays, chitosan, and phoslock (lanthanum clay) prevent harmful algal blooms by controlling phosphorus levels (Sengco and Anderson, 2004; Lurling and Oosterhout, 2013).

Bioremediation, nutrient load reduction, and regulatory policies are the backbone of sustainable management. Responsible agricultural practices and waste reduction can be promoted by public awareness and community involvement. Artificial wetlands or pre-reservoirs upstream of water storage can be utilized as nutrient sinks which prevents the inflow of nutrients into storage. Planting trees and shrubs around a water body reduces the input of sediments and, therefore, nutrients into the water body. In addition, plants also provide shade to water bodies, which reduces the temperature and solar radiation reaching the water body. Managing whole catchment above the storage by reducing the use of fertilisers and

fencing off waterways to prevent stock access will also reduce soil erosion and amount of nutrients.

Conclusion

Harmful Algal Blooms are a global crisis driven by a dangerous mix of climate change, damaged environments and nutrient pollution in our waters. Tackling this problem requires teamwork, better technologies, and stronger environmental laws. There is an obvious need to comprehend HAB occurrences and create scientifically sound management and mitigation strategies as the world's population is growing, increasing the use of the coastal zone and demanding additional fisheries and recreational resources. Over the past 20 years, algal and toxin monitoring systems have been established worldwide, and this data should help us spot long-term trends and understand how these blooms shift from year to year. In this sense, research advancements are essential, driven by worldwide collaboration and coordination.

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