e-ISSN No.: 2582-4228

Journal of Indian Association for Environmental Management

Journal homepage: www.http://op.niscair.res.in/index/php/JIAEM/index

Toxic (Harmful) Algal Blooms: Ecology, Drivers, Detection and Impacts

Damayanti Tammana*[1] and Dinesh Singh[2]

ICAR-Indian Sugarcane Research Institute, Lucknow, Uttar Pradesh

*Corresponding Author: damayantibiology@gmail.com

Submitted: 28 January 2026 Revised: 11 June 2026 Accepted: 11 June 2026

***Abstract*: Toxic algal blooms (TABs), also known as harmful algal-blooms (HABs), are proliferations of toxin-producing cyanobacteria and micro algae in freshwater and marine ecosystems. These blooms, exacerbated by nutrient enrichment and climate change, release potent toxins such as microcystins, saxitoxins, anatoxins, cylindrospermopsin, brevetoxins, domoic acid, and okadaic acid, which threaten human and animal health, aquatic biodiversity, and socio-economic stability. TABs compromise drinking water, fisheries, aquaculture, irrigation, and recreation. Advances in detection—including molecular tools, remote sensing, and predictive modeling—support early warning and mitigation. This review summarizes current knowledge on TAB taxonomy, toxin classes, environmental drivers, detection and monitoring, ecological and health impacts, management strategies and future research directions.**

Keywords: TABs, HABs, algal-bloom, Aquatic, ecology, Environment

I. Introduction

Harmful algal blooms (HABs), commonly termed toxic algal blooms (TABs), have emerged as a serious threat to environmental sustainability and public health worldwide (Francis G. A., 2026) (Fig 1, 2 & 3: Part of our ongoing research work on water quality analysis due to algal bloom proliferation). These blooms occur due to the excessive multiplication of toxin-producing cyanobacteria and microalgal species in freshwater and marine environments (Sukenik A. & Kaplan A., 2021; Griffith A.W. & Christopher J.G., 2020). Non-toxic blooms may cause hypoxia and aesthetic issues (Mishra et al., 2022), but toxic algal blooms release secondary metabolites hazardous to humans and animals (Kumar R., 2021). Eutrophication, land-use change, and climate warming are increasing the frequency and severity of TABs globally (Sinha E., Michalak A.M. & Balaji V., 2017).

The present review summarizes key aspects of HABs, including their classification, toxin composition, ecological drivers, detection techniques, associated impacts, and available management measures. Important toxin categories such as microcystins, saxitoxins, anatoxins, cylindrospermopsins, brevetoxins, domoic acid, and okadaic acid (Gao X., et al., 2024) are discussed together with newly recognized toxins like nodularins, azaspiracids, pectenotoxins, and yessotoxins. These compounds exhibit considerable structural variation and diverse modes of toxic action. Fresh water reservoirs and coastal zones of India report microcystin and saxitoxin contamination frequently (Laureano-Rosario et. al., 2021). Understanding TAB ecology, drivers, detection, impacts, and management is critical for mitigating their adverse effects.

The review examines the complex interplay of nutrient enrichment, climate change, and hydrological factors in driving bloom dynamics, with particular emphasis on mechanistic pathways such as temperature thresholds, thermal stratification, and elevated CO_2 levels that favor bloom formation and persistence by enhancing photosynthetic carbon fixation, particularly in cyanobacteria that possess efficient carbon concentrating mechanisms. This can shift competitive dynamics in favor of bloom-forming taxa, especially under nutrient-enriched conditions.

Rising water temperatures due to climate change are among the most critical drivers, as many cyanobacterial species exhibit optimal growth at temperatures above 25 °C, allowing them to outcompete other phytoplankton under warming conditions (Budziak M., et.a al., 2025). Elevated temperatures not only enhance growth rates but also stimulate toxin production in certain species, including *Microcystis* and *Cylindrospermopsis* (Mowe, M.A.D., 2015).

Fig 1: Algal bloom in a lake ecosystem

Fig 2: Algal bloom in fish pond ecosystem

(Ref: Part of our ongoing research work on water quality analysis due to algal bloom proliferation of Lucknow region)

Fig: 3 Sea weeds or macro algae from coastal areas

(Ref: Part of our ongoing research work on water quality analysis due to algal bloom proliferation of Goa region)

Thermal stratification, intensified by surface warming, reduces vertical mixing in lakes and reservoirs, creating stable, well-lit surface layers that favor buoyant cyanobacteria capable of regulating their position in the water column. Prolonged stratification also limits oxygen exchange, contributing to hypoxic conditions during bloom decay (Liu M., 2026).

Changes in precipitation patterns provide an additional pathway through which climate change affects HABs (https://colsa.unh.edu/blog/2023/11/causes-harmful-algal-blooms-understanding-factors-behind-phenomenon). Increased frequency of intense rainfall events enhances nutrient runoff from agricultural and urban landscapes, fueling bloom initiation, while drought conditions reduce water flow and flushing rates, allowing blooms to persist for extended periods.

Notable examples include the increasing frequency of cyanobacterial blooms in temperate lakes such as Lake Erie under warming conditions, and the expansion of HAB events in tropical and subtropical regions. Elevated temperatures and nutrient inputs act collectively in these regions (Gobler C.J., 2024). These mechanistic insights highlight the role of climate change not only as a driver of bloom occurrence but also as a factor influencing bloom toxicity, duration, and spatial distribution.

Regional variability is addressed through examples of both globally distributed and region-specific blooms. Special attention is given to the Indian context, where increasing HAB occurrences in freshwater and coastal systems are compounded by limited monitoring infrastructure, fragmented regulatory frameworks, and inadequate early warning systems.

Advances in detection and monitoring, including molecular techniques, high-throughput sequencing, satellite remote sensing, geographic information systems (GIS), and machine learning-based predictive models, are critically evaluated for their role in improving early warning capabilities (Izadi, M., et. al., 2021).

The review further highlights the multifaceted impacts of HABs on human health, ecosystems, and the economy, noting that many toxins are chemically stable, resistant to degradation during cooking, and lack specific antidotes, thereby posing persistent risks. Economic losses associated with HABs are substantial, affecting fisheries, aquaculture, tourism, and water treatment systems globally.

Case studies, including the 2014 water crisis (https://greatlakes.org/2019/08/five-years-later-lessons-from-the-toledo-water-crisis/; Helmer, J., 2020) and recurrent fish mortality events along the Kerala coast, illustrate the real-world implications of HABs (Abrahams R., 2023).

Finally, the review identifies key knowledge gaps, including the need to better understand toxin co-occurrence, climate-driven changes in toxin production, and the development of cost-effective, field-deployable monitoring tools.

Overall, this review emphasizes the necessity of interdisciplinary and region-specific strategies to mitigate HAB risks and ensure the sustainable management of aquatic ecosystems.

Taxonomy and diversity of HAB-associated toxins

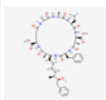
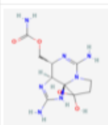
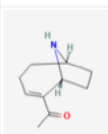
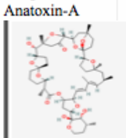
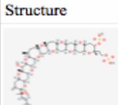
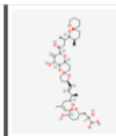
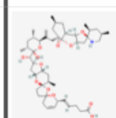
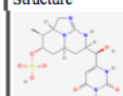
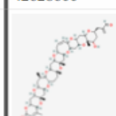
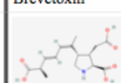
Cyanobacteria such as *Microcystis*, *Anabaena*, *Cylindrospermopsis* and certain marine micro algae cause the formation of TABs (Haffar, M.A., 2024). Key toxin classes include microcystins, saxitoxins, anatoxins, cylindrospermopsins, brevetoxins, domoic acid and okadaic acid (Table 1).

HAB-forming organisms encompass a taxonomically diverse group of cyanobacteria, dinoflagellates, diatoms, and other microalgae (https://www.cdc.gov/harmful-algal-blooms/about/types-of-harmful-algal-blooms.html).
Cyanobacteria such as *Microcystis*, *Anabaena*, and *Cylindrospermopsis* are predominant freshwater blooms (Tanvir R. U., 2021). Similarly, in the marine system, dinoflagellates (e.g., *Alexandrium*, *Karenia*) and diatoms (e.g., *Pseudo-nitzschia*) (Chai X., et. al., 2021) are found to be predominant marine blooms. These organisms produce a wide spectrum of toxins that vary in chemical structure, mode of action, and toxicity. Classical toxin groups include microcystins, saxitoxins, anatoxins, cylindrospermopsins,

brevetoxins, domoic acid, and okadaic acid (https://www.cdc.gov/harmful-algal-blooms/about/types-of-harmful-algal-blooms.html).

The structural diversity of these compounds underlies their varied toxicological mechanisms, ranging from inhibition of protein phosphatases (microcystins, nodularins) to interference with ion channels (saxitoxins, brevetoxins) and disruption of cellular metabolism (cylindrospermopsins). Inclusion of representative chemical structures (e.g., microcystin-LR, saxitoxin, domoic acid) is essential to provide mechanistic insights into their toxicity and environmental persistence.

TABLE 1
Taxonomy & major toxin classes of harmful algae

Toxin	Toxin chemical structure	Producer	Habitat	Mode of action	Impact
Microcystins	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Microcystin-LF#section=2D-Structure	*Microcystis*, *Anabaena*	Fresh water	Inhibit protein phosphatases	Liver toxicity, tumor promotion (Rapala et. al., 1997)
Saxitoxins	 Ref. https://pubchem.ncbi.nlm.nih.gov/compound/Saxitoxin	*Alexandrium*, *Cylindrospermopsis*	Marine	Blocks nerve signal transmission	Paralytic shellfish poisoning (Deng et. al., 2025).
Anatoxins	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Anatoxin-A	*Anabaena*, *Aphanizomenon*	Fresh water	Neurotoxin	Muscle paralysis, respiratory failure (Plata-Calzado et. al., 2022).
Pectenotoxins	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Pectenotoxin-2#section=2D-Structure	Dinoflagellates	Marine	Hepatotoxicity	Emerging toxins
Yessotoxins	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Yessotoxin#section=2D-Structure	Dinoflagellates	Marine	Cardiotoxicity	Emerging toxins
Okadaic acid	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Okadaic-Acid#section=2D-Structure	*Dinophysis*	Marine	Inhibits phosphatases	Diarrhetic shellfish poisoning (Lee et.al., 2016).
Nodularin	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Nodularin-R#section=2D-Structure	Nodularia	Brackish	Liver toxicity	Hepatotoxin
Azaspiracid	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/162403513#section=2D-Structure	Dinoflagellates	Marine	Gastrointestinal toxins	Emerging toxins
Cylindrospermopsin	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/42628600	*Cylindrospermopsis*	Fresh water	Inhibits protein synthesis	Liver and kidney toxicity (Kinnear S., 2010).
Brevetoxins	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Brevetoxin	*Karenia brevis*	Marine	Neurotoxin	Neurotoxic shellfish poisoning (Watkins e t. al., 2008).
Domoic acid	 Ref: https://pubchem.ncbi.nlm.nih.gov/compound/Domoic-Acid#section=2D-Structure	*Pseudo-nitzschia*	Marine	Excitatory neurotoxin	Amnesic shellfish poisoning (Jeffery et. al., 2004).

Environmental drivers & bloom dynamics

Toxic algal blooms (TABs) develop through the combined influence of nutrient availability, environmental conditions, and biological interactions. Elevated inputs of nitrogen and phosphorus originating from agricultural runoff, wastewater discharge, and aquaculture activities significantly stimulate algal proliferation. Cyanobacterial species are particularly successful under disturbed nitrogen-to-phosphorus (N:P) ratios because many possess the ability to fix atmospheric nitrogen or adapt to nutrient-limited environments (Kramer B.J., Turk-

Kubo K., Zehr J.P. & Gobler C.J., 2024). Environmental factors such as warm temperatures, thermal stratification, reduced water movement, and calm climatic conditions promote the formation of stable, illuminated surface waters that support the dominance of buoyant cyanobacteria. These processes are further intensified by climate change, which contributes to rising water temperatures, irregular rainfall patterns, extended stratification periods, and enhanced nutrient loading into aquatic systems. In addition, biological interactions including allelopathic effects, grazing pressure, viral activity, and associations with microorganisms also influence bloom initiation and persistence (Zhou et al., 2018). The subsequent microbial breakdown of accumulated algal biomass consumes dissolved oxygen, often resulting in hypoxic conditions that negatively affect aquatic food chains and overall ecosystem stability (Ahmad et al., 2024).

HABs in India: Occurrence, Monitoring & Challenges

Occurrences of harmful algal blooms (HABs) have been increasingly documented across a wide range of freshwater and marine ecosystems in India, largely due to the combined effects of eutrophication, expanding urbanization, and changing climatic conditions.

In marine and coastal regions, repeated bloom events along the Kerala coastline and the Arabian Sea, commonly associated with dinoflagellates like *Noctiluca scintillans*, have been connected with severe oxygen depletion and large-scale fish kill incidents (Sathishkumar R. S. et al., 2026).

According to Nayak A. R. et al., 2025, the HAB monitoring and surveillance in India remain fragmented and insufficiently coordinated. Current monitoring activities are mainly undertaken by organizations such as CSIR laboratories, ICAR institutes, and various state pollution control boards. However, the absence of a centralized and real-time national surveillance framework significantly limits rapid detection and early warning responses. In many regions, monitoring programs are conducted intermittently rather than continuously, reducing their effectiveness in predicting bloom outbreaks. Moreover, there is a lack of uniform implementation of standardized methods for toxin analysis, data reporting, and ecological risk evaluation.

In India, HAB management efforts are further hindered by low public awareness, limited use of remote sensing technologies, and inadequate integration of predictive modeling tools (Nayak A. R. et al., 2025). To overcome these limitations, there is a need for a nationwide HAB monitoring network supported by satellite-based observation systems and affordable field-level diagnostic technologies specifically adapted to Indian environmental conditions.

Regional specificity vs global distribution of TABs

Many harmful algal bloom (HAB) events show strong geographic specificity that is influenced by local hydrographic features, climatic factors, and water chemistry (Anderson D. M. et al., 2027). For example, blooms caused by *Karenia brevis*, commonly linked with "red tide" events, are mainly reported from the Gulf of Mexico, whereas *Nodularia spumigena* blooms are typically associated with the brackish ecosystems of the Baltic Sea (Lan J. et al., 2024). In the same way, bloom outbreaks driven by seasonal coastal upwelling processes are often restricted to particular marine regions where such oceanographic conditions prevail.

In contrast, several bloom-forming genera such as *Microcystis*, *Anabaena*, and *Alexandrium* exhibit a broad global distribution across freshwater and marine systems (Choudhary B. 2025). These taxa possess adaptive traits, including tolerance to variable nutrient conditions, buoyancy regulation, and resilience to temperature fluctuations, enabling them to proliferate in diverse environmental settings. The expansion of such globally distributed species has been further accelerated by climate change, eutrophication, and anthropogenic disturbances.

This dual pattern of region-specific and cosmopolitan distribution highlights the importance of both localized monitoring strategies tailored to regional conditions and broader, globally coordinated surveillance frameworks. Understanding these spatial patterns is essential for improving predictive models and implementing effective management strategies across different ecological and geographic contexts.

Detection, monitoring & forecasting

Detection and forecasting of TABs integrate field, molecular, and computational approaches (Alexander H., 2024). Traditional methods such as microscopy, pigment analysis, immunoassays, and toxin quantification remain essential. Molecular techniques, including PCR and qPCR, allow detection of toxin biosynthesis genes (Antonella P. & Luca G., 2013)**.** In addition to these approaches, recent advancements have significantly improved the resolution and predictive capacity of HAB monitoring systems. High-throughput sequencing and meta barcoding provide insights into microbial community composition and bloom succession (Gibson K., Song H. & Chen N., 2022). These techniques also facilitate the identification of toxin-producing genes and emerging harmful taxa that may not be detectable through conventional methods.

In situ sensors enable continuous monitoring, while satellite-based remote sensing (MODIS, Sentinel-2, Sentinel-3) captures spatial and temporal bloom patterns (Rodríguez-Benito C.V., Navarro G. & Caballero I., 2020). Satellite remote sensing has emerged as a powerful tool for large-scale monitoring, enabling the detection of chlorophyll-a concentrations, phycocyanin pigments, and surface scums across vast spatial extents.

However, limitations remain in detecting subsurface blooms and distinguishing between toxic and non-toxic species.

Statistical, hydrodynamic and machine learning are used during predictive modeling which facilitates early warning, management and planning (Zahir M. et. al., 2024). Predictive modeling has evolved from traditional statistical approaches to advanced machine learning and artificial intelligence-based systems. These models integrate environmental parameters such as temperature, nutrient concentrations, hydrodynamics, and meteorological data to forecast bloom events with increasing accuracy. Early warning systems based on these models are particularly valuable for water resource management and public health protection.

Integrating multi-source data streams and improving accessibility of monitoring technologies remain key priorities for enhancing HAB surveillance (Zahir M. et. al., 2024).

Human, animal, and ecosystem impacts

TABs threaten human health, animal populations, and ecosystem integrity (https://www.niehs.nih.gov/health/topics/agents/algal-blooms). Human exposure occurs via contaminated drinking water, seafood, or recreational contact, causing liver toxicity, neurotoxicity, and gastrointestinal illness, with potential long-term risks like neurodegenerative diseases and cancer (Lee et. al., 2022). Livestock, pets, and wildlife are susceptible to toxin-induced mortality. Ecologically, TABs reduce biodiversity, cause hypoxia, disrupt food webs, and lead to fish kills (Oh et. al., 2023).

Many cyanotoxins and marine phycotoxins, including microcystins, nodularins, saxitoxins, and domoic acid, are chemically stable compounds that can persist in water bodies even after the visible bloom has dissipated (Mazur H. and Plinski M., 2021). Notably, several of these toxins exhibit significant resistance to thermal degradation; for example, microcystins and domoic acid are largely heat-stable and are not effectively degraded by conventional cooking processes such as boiling, steaming, or frying (Choudhary A. and Dhewa T., 2025).

The stability of these toxins found in drinking water and food products, specially fish and shell fish also complicates water treatment processes, as conventional methods may be insufficient to remove dissolved toxin fractions released following algal cell lysis. Advanced treatment techniques such as activated carbon adsorption, ozonation, and advanced oxidation processes are therefore required for effective toxin removal in drinking water systems (Verma S. et. al., 2023).

From a clinical perspective, there are currently no widely available, toxin-specific antidotes for most HAB-related poisonings (Grattan L. M. et al., 2016). Medical management is primarily supportive and symptomatic, focusing on stabilization of the patient, prevention of further exposure, and treatment of organ-specific effects such as hepatic or neurological damage (https://www.cdc.gov/harmful-algal-blooms/hcp/clinical-care/index.html). In cases of acute exposure, interventions may include activated charcoal administration (for recent ingestion), fluid therapy, and monitoring of liver and kidney function. Experimental therapies, including antioxidants and hepatoprotective agents, have shown some promise in mitigating toxin-induced damage, but their clinical application remains limited (https://www.cdc.gov/harmful-algal-blooms/hcp/clinical-care/index.html).

Given the persistence and resilience of HAB toxins, public health strategies must emphasize preventive measures, including routine monitoring of water supplies, advisories against consumption of contaminated water or seafood, and public awareness campaigns. These considerations highlight the need for integrating toxin stability into risk assessment frameworks and developing more effective treatment and mitigation strategies

Economically, blooms affect fisheries, aquaculture, tourism, recreation, and increase water treatment costs. The 2014 Toledo water crisis in the United States represents a critical example of HAB-related public health risk (https://greatlakes.org/2019/08/five-years-later-lessons-from-the-toledo-water-crisis/). This is one of the most well-documented freshwater HAB-related public health emergencies. In August 2014, a bloom of *Microcystis* spp. in Lake Erie produced high concentrations of microcystin-LR near the intake of the Collins Park Water Treatment Plant, which supplies drinking water to the city of Toledo, Ohio. Toxin concentrations exceeded the World Health Organization's provisional guideline value of 1 μg/L, reaching levels that rendered conventional treatment processes temporarily ineffective. As a result, approximately 400,000–500,000 residents were advised not to drink, cook with, or even boil tap water for nearly three days. The event In contrast, HAB-related events in Kerala, India, illustrate the challenges faced in tropical coastal systems where monitoring and response frameworks are less developed. Recurrent fish mortality events along the Kerala coast, particularly in the Arabian Sea, have been associated with blooms of dinoflagellates such as *Noctiluca scintillans* and other phytoplankton species. These blooms are often linked to nutrient enrichment from coastal runoff, upwelling processes, and anthropogenic inputs, including sewage discharge and agricultural effluents (Nayak A. R., 2025).

The socio-economic impacts of growth of algal bloom

The Toledo event revealed major weaknesses in existing water treatment systems, especially their limited effectiveness in eliminating dissolved cyanotoxins. It further emphasized the importance of continuous monitoring, rapid warning mechanisms, and adaptive management approaches. Following the incident, substantial efforts were directed toward watershed nutrient reduction, strengthening monitoring infrastructure, and implementing toxin-specific treatment technologies, making the Toledo outbreak an important example in the development of HAB management policies and response strategies.

In comparison, harmful algal bloom events reported from Kerala, India, demonstrate the difficulties associated with managing HABs in tropical coastal ecosystems where surveillance and response systems are comparatively less advanced. Repeated fish kill incidents along the Kerala coast and the Arabian Sea have frequently been linked with blooms of dinoflagellates such as *Noctiluca scintillans* and other phytoplankton species. Nutrient enrichment resulting from coastal runoff, seasonal upwelling, sewage disposal, and agricultural discharges generally associated with these blooms occurrence (Nayak A. R., 2025).

As algal blooms decay, microbial decomposition rapidly consumes dissolved oxygen, producing oxygen-deficient zones that can result in mass mortality of fish and other aquatic organisms. In certain cases, elevated ammonia levels and changes in water chemistry intensify physiological stress in marine life.

These contrasting examples demonstrate that HABs are both a global environmental issue and a regionally variable challenge in terms of preparedness and management capacity. Developed countries often possess advanced monitoring systems and treatment infrastructure, whereas developing regions continue to face limitations related to technical infrastructure, institutional coordination, and public awareness. Collectively, these case studies highlight the urgent requirement for integrated monitoring networks, effective nutrient control strategies, and region-specific management frameworks to minimize HAB-associated risks.

Apart from their immediate toxic effects, prolonged exposure to HAB toxins has raised significant concerns regarding chronic health impacts such as liver cancer, neurological disorders, and endocrine disruption. For example, microcystins are recognized as potent inhibitors of protein phosphatases and are considered possible human carcinogens (Lad A. et al., 2022).

Another important feature of many HAB toxins is their high chemical stability. At present, there are no specific antidotes available for most HAB toxin exposures, and treatment primarily relies on supportive clinical care aimed at relieving symptoms and preventing additional exposure.

Ecologically, HABs significantly influence aquatic ecosystems by altering community composition, lowering biodiversity, and disturbing trophic relationships. The decomposition of large algal biomass often leads to hypoxic or anoxic conditions, resulting in extensive fish kills and degradation of aquatic habitats. Such ecological disturbances can subsequently affect important ecosystem services, including fisheries production and natural water purification processes.

The socio-economic consequences of HAB events in Kerala are particularly severe for coastal populations and small-scale fishing communities that rely heavily on marine resources for income and food security. Sudden fish mortality events can cause major economic losses, interrupt seafood markets, and reduce public confidence in seafood quality and safety. Unlike the Toledo incident, where rapid communication systems and infrastructure responses were implemented, HAB events in Kerala often experience delays in detection, limited public warnings, and insufficient mitigation efforts (Jasna P. and Nehru S., 2021).

The financial impacts of toxic algal blooms are substantial and are increasingly being quantified at both regional and global levels. Recent studies estimate that HABs result in annual global economic losses of nearly USD 8–10 billion, affecting sectors such as fisheries, aquaculture, tourism, healthcare, and water treatment systems (Anderson D. M. et. al., 2000).

In developing nations such as India, the true economic burden of HABs is often underestimated despite the heavy dependence of local populations on aquatic resources for livelihood and sustenance. Fish kill incidents, contamination of drinking water supplies, and reductions in tourism activities can generate immediate economic hardship as well as long-term socio-economic instability. Furthermore, water treatment facilities frequently face higher operational expenditures because of the need for advanced purification technologies such as activated carbon filtration and ozonation for toxin removal (Barathan B.P. and Sarangi R.K., 2024).

These economic assessments clearly demonstrate the importance of incorporating financial considerations into HAB prevention and management programs. Strengthening monitoring systems, establishing effective early warning networks, and implementing nutrient reduction strategies not only help protect environmental and public health but also reduce economic losses and lower water treatment costs.

Mitigation & management

Effective management of TABs combines prevention, control, biological interventions, and policy measures. Nutrient reduction through watershed management, best agricultural practices, and buffer zones or wetlands prevents eutrophication (Bojanowski et. al., 2025). In-lake interventions include chemical algaecides, aeration, artificial mixing, ultrasound treatment, and flocculation to suppress blooms (https://www.lgsonic.com/how-to-prevent-algal-blooms/). Biological approaches involve macrophyte restoration, filter-feeding organisms, and algicidal bacteria (Wimalasena et. al., 2023). Drinking water treatment using activated carbon, ozonation, advanced oxidation, and membrane filtration ensures toxin removal (Loganathan, K., 2017). Regulatory frameworks, guided by WHO guidelines and national advisories, support safe water and recreational standards (https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/water-safety-and-quality/drinking-water-quality-guidelines). The World Health Organization has set a provisional guideline value of 1 µg/L for microcystin-LR in drinking water, which is based on lifetime exposure and aims to minimize risks of liver toxicity and potential carcinogenic effects. In addition to drinking water standards, recreational exposure thresholds have also been proposed, with concentrations above 20 µg/L of microcystins considered to pose moderate health risks, and higher levels associated with increased likelihood of adverse effects such as skin irritation, gastrointestinal illness, and respiratory symptoms.

Other countries and agencies, including the United States Environmental Protection Agency, have developed health advisory levels for cyanotoxins, particularly for sensitive populations such as infants and children, reflecting the heightened vulnerability of these groups (https://www.epa.gov/habs/epa-drinking-water-health-advisories-cyanotoxins). For example, lower advisory limits have been recommended for short-term exposure in drinking water to account for differences in body weight and water intake.

The inclusion of such quantitative thresholds is critical for risk assessment, regulatory enforcement, and water treatment decision-making. However, in many developing regions, including India, the implementation and monitoring of these guideline values remain limited.

Chemical control methods, while effective for rapid bloom suppression, require careful consideration due to their ecological implications (Choudhary B., 2026). Commonly used algaecides such as copper sulfate and hydrogen peroxide-based formulations can exert toxic effects on non-target organisms, including fish, zooplankton, and beneficial microbial communities (Lurling M. et al., 2025). Moreover, the rapid lysis of algal cells following chemical treatment can result in the release of intracellular toxins into the water column, potentially exacerbating toxicity in the short term.

Biological control strategies offer a more environmentally sustainable alternative and have gained increasing research attention. Algicidal bacteria, including species of *Bacillus*, *Pseudomonas*, and *Streptomyces*, can inhibit algal growth through mechanisms such as production of lytic enzymes, secretion of bioactive compounds, and competition for nutrients (Wang J. et al., 2026). Additionally, grazing by zooplankton and the restoration of macrophyte communities can help regulate algal populations. While promising, these approaches are still largely in experimental or pilot stages, and their effectiveness under field conditions requires further validation (Ladds M. et. al., 2025).

Chemical algaecides are widely used for the rapid suppression of algal blooms, with commonly applied agents including copper-based compounds (e.g., copper sulfate), hydrogen peroxide formulations, and modified clays (Zhang J. et.al., 2026). While these treatments can effectively reduce algal biomass in the short term, their application is associated with several ecological and operational limitations. Hydrogen peroxide-based treatments are generally considered more environmentally compatible due to their rapid degradation into water and oxygen; however, their effectiveness can vary depending on bloom density and environmental conditions (Lurling M. et al., 2025).

A critical concern associated with chemical control is the lysis of algal cells, which can lead to the rapid release of intracellular toxins such as microcystins into the surrounding water (Chow C. W. K., 1999). This transient increase in dissolved toxin concentrations may pose heightened risks to aquatic organisms and complicate drinking water treatment processes. Additionally, repeated application of algaecides may alter community structure, potentially promoting the dominance of resistant or more toxic species.

Given these limitations, the use of chemical algaecides should be carefully managed and integrated with other strategies such as nutrient reduction and biological control. Site-specific assessments, appropriate dosing, and post-treatment monitoring are essential to minimize unintended ecological impacts and ensure safe and effective HAB mitigation.

At a broader scale, integrated watershed management remains the most effective long-term strategy for HAB prevention (Piehler M., 2008). This includes reducing nutrient inputs through sustainable agricultural practices, improving wastewater treatment, and restoring wetlands that act as natural nutrient sinks. Internationally, programs such as the UNESCO Intergovernmental Oceanographic Commission (IOC) HAB Programme support coordinated monitoring and research efforts; however, the absence of a unified global HAB surveillance system highlights the need for enhanced international collaboration.

Knowledge gaps & future directions

Key knowledge gaps include incomplete understanding of toxin regulation, co-occurrence mechanisms, and emerging toxins under climate stress. Standardized low-cost monitoring tools and field-deployable diagnostics are needed for resource-limited regions (Maniyar et. al., 2025). Omics approaches combined with AI and machine learning can enhance early warning and predictive capabilities (Xiao et. al., 2024). Citizen science initiatives provide additional monitoring coverage and public engagement (https://hab.whoi.edu/regions-resources/citizen-science-programs/). Interdisciplinary research integrating ecological, molecular, and computational approaches is crucial for developing proactive, sustainable strategies for TAB management (Mundhe, E., 2023).

Despite significant progress in HAB research, several critical knowledge gaps remain. The mechanisms governing toxin biosynthesis and regulation under varying environmental conditions are not yet fully understood.

Climate change introduces additional uncertainties, as rising temperatures, altered hydrological cycles, and increasing CO_2 levels may influence both bloom dynamics and toxin production in complex ways. Long-term, high-resolution datasets are needed to better understand these interactions and improve predictive models.

Technological advancements offer promising avenues for addressing these challenges. The integration of remote sensing, GIS-based spatial analysis, and artificial intelligence-driven predictive modeling can significantly enhance early warning systems. Additionally, the development of low-cost, portable biosensors and field-deployable diagnostic kits is essential for improving monitoring capacity, particularly in resource-limited regions.

Citizen science initiatives also represent a valuable complementary approach, enabling broader data collection and increasing public awareness. Future research should emphasize interdisciplinary collaboration, combining ecological, molecular, and computational approaches to develop robust, scalable, and sustainable HAB management strategies.

II. Conclusion

Toxic algal blooms are an escalating threat to aquatic ecosystems, human health, and socio-economic stability, intensified by nutrient enrichment and climate change. They disrupt ecosystems, reduce biodiversity, induce hypoxia, and pose severe risks to humans and animals. Advances in detection, monitoring, and predictive modeling improve management, but integrated strategies—including nutrient reduction, ecosystem restoration, biological and chemical control, and policy frameworks—are essential. Future approaches must combine novel technologies, standardized protocols, interdisciplinary research, and public engagement to safeguard water resources, maintain ecosystem resilience, and protect communities dependent on aquatic systems worldwide.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Department of Science and Technology for the research grant under DST WISE-SCOPE program to Dr. Damayanti Tammana, Principal Investigator that enabled the successful completion of this review work which is the main objective of the project work. There is no conflict of interest related to the work.

III. References

Abraham, R. (2023). Warming water and pollution amplify fish mortality in Kerala during summer. Mongabay 2023; https://india.mongabay.com/2023/05/warming-water-and-pollution-amplify-fish-mortality-in-kerala-during-summer/

Nayak, A. R., Kolluru,S. & Bhadury, P. Revisiting harmful algal blooms in India through a global lens: An integrated framework for enhanced research and monitoring. iScience 2025, 28(2): 111916. https://doi.org/10.1016/j.isci.2025.111916

Ahmad, N.B.; Jaafaru, M.S.; Isa, Z.; Abdulhamid, Y.; Kakudi, R.A.; Ugya, A.Y. & Meguellati, K. High pollution loads engineer oxygen dynamics, ecological niches, and pathogenicity shifts in freshwater environments. Journal of Hazardous Materials Advances 2024; 14:100425 (https://doi.org/10.1016/j.hazadv.2024.100425).

Choudhary, A. & Dhewa, T. Natural plant toxins in food: A comprehensive review of health implications, processing changes and regulatory challenges. Food Chemistry Advances 2025, 9:101139. https://doi.org/10.1016/j.focha.2025.101139

Alexander, H. Molecular forecasting of toxic bloom events. PNAS 2024; 121 (42): e2417139121 https://doi.org/10.1073/pnas.2417139121.

Anderson, D.M.; Kaoru, Y. & White, A.W. Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States, 2000, https://www.iatp.org/sites/default/files/Estimated_Annual_Economic_Impacts_from_Harmful.htm

Anonymous. How to prevent algal blooms in lakes and reservoirs. *LGSONIC* https://www.lgsonic.com/how-to-prevent-algal-blooms/

Anonymous. Drinking water quality guideline. Water Sanitation and Health. *World Health Organization* https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/water-safety-and-quality/drinking-water-quality-guidelines.

Anonymous. Algal Blooms. National Institute of Environmental Health Sciences https://www.niehs.nih.gov/health/topics/agents/algal-blooms

Anonymous. Types of Harmful Algal Blooms. CDC-Harmful Algal Bloom (HAB)-Associated Illness. https://www.cdc.gov/harmful-algal-blooms/about/types-of-harmful-algal-blooms.html

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Microcystin-LF

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Saxitoxin

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Anatoxin-A

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/42628600

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Brevetoxin

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Domoic-Acid#section=2D-Structure

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Okadaic-Acid#section=2D-Structure

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Nodularin-R#section=2D-Structure

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/162403513#section=2D-Structure

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Pectenotoxin-2#section=2D-Structure

Anonymous. https://pubchem.ncbi.nlm.nih.gov/compound/Yessotoxin#section=2D-Structure

Anonymous. https://www.cdc.gov/harmful-algal-blooms/hcp/clinical-care/index.html.

Anonymous. https://www.cdc.gov/harmful-algal-blooms/hcp/clinical-care/index.html).

Anonymous. https://greatlakes.org/2019/08/five-years-later-lessons-from-the-toledo-water-crisis/

Anonymous. https://www.researchgate.net/publication/393685813_A_Livelihood_Analysis_of_Small-Scale_Coastal_Communities_in_Kerala

Anonymous. Causes of harmful algal blooms: Understanding the factors behind the phenomenon. 2023, https://colsa.unh.edu/blog/2023/11/causes-harmful-algal-blooms-understanding-factors-behind-phenomenon

Anonymous. Blog on Five Years Later: Lessons From the Toledo Water Crisis. 2019

https://greatlakes.org/2019/08/five-years-later-lessons-from-the-toledo-water-crisis/

Anonymous. What causes nutrient pollution?, National Ocean Service, USA https://oceanservice.noaa.gov/education/tutorial-coastal/harmful-algal-blooms/habs01-sub-02.html.

Anonymous. Harmful Algae. U.S. National Office for Harmful Algal Blooms https://hab.whoi.edu/regions-resources/citizen-science-programs/

Antonella, P. & Luca, G. The quantitative real-time PCR applications in the monitoring of marine harmful algal bloom (HAB) species. Environmental Science and Pollution Research 2013; 20:6851–6862 doi:10.1007/s11356-012-1377-z.

Bojanowski, D.; Orlińska-Woźniak, P.; Wilk, P.; Wypych, A. & Szalińska, E. Efficiency of buffer zones in nutrient load reduction under climate change conditions (Nurzec River, eastern Poland). *CATENA* 2025; 257:109183 https://doi.org/10.1016/j.catena.2025.109183.

Budziak, M.; Ilicic, D.; Grossart, H-P.; Krztoń, W.; Walusiak, E.; Fyda, J. & Wilk‐Woźniak, E. Phytoplankton Under Pressure: Temperature, Precipitation and Cyanobacterial Blooms as Drivers of Chytrid Infections. Environ Microbiol Rep 2025;17(6):e70224. doi: 10.1111/1758-2229.70224

Chai, X.; Li, X.; Hii, K.S.; Zhang, Q.; Deng, Q.; Wan, L.; Zheng, L.; Lim, P.T.; Tan, S.N.; Mohd-Din, M. & Song, C.; Song, L.; Zhou, Y. & Cao, X. Blooms of diatom and dinoflagellate associated with nutrient imbalance driven by cycling of nitrogen and phosphorus in anaerobic sediments in Johor Strait (Malaysia). *Marine Environmental Research* 2021, 169: 105398. https://doi.org/10.1016/j.marenvres.2021.105398

Choudhary, B. Harmful algal blooms and management strategies for control in marine and freshwater aquatic ecosystems: A comprehensive bibliometric and network analysis from 1997 to 2024. *Journal of Hazardous Materials Advances* 2026, 101176. https://doi.org/10.1016/j.hazadv.2026.101176

Chow, C.W.K.; Drikas, M.; House, J.; Burch, M.D.& Velzeboer, R.M.A. The impact of conventional water treatment processes on cells of the cyanobacterium *Microcystis aeruginosa. Water Research* 1999, 33(15):3253-3262. https://doi.org/10.1016/S0043-1354(99)00051-2

Deng, H.; Shang, X.; Zhu, H;, Huang, N;, Wang, L. & Sun, M. Saxitoxin: A Comprehensive Review of Its History, Structure, Toxicology, Biosynthesis, Detection, and Preventive Implications. *Mar. Drugs* 2025, 23(7):277 doi: 10.3390/md23070277.

Donald, M. A.; Allan D. C. & Gustaaf, M. H. Progress in understanding harmful algal blooms (HABs): Paradigm shifts and new technologies for research, monitoring and management. *Ann Rev Mar Sci.* 2017, 4:143–176. doi: 10.1146/annurev-marine-120308-081121

Francis, G.A.; Ray, S.; Mukherjee, A.G.; Gopalakrishnan, A.V. & Vashishth, R. Harmful algal blooms in a changing world: linking bloom dynamics, biotoxin synthesis, and advanced monitoring strategies. *Environ Monit Assess* 2026; 198(5):414. DOI: 10.1007/s10661-026-15253-w

Gao, X.; , Wang, H.; Chen, K.; Guo, Y.; Zhou, J. & Xie , W. Toxicological and Pharmacological Activities, and Potential Medical Applications, of Marine Algal Toxins. Int J *Mol Sci.* 2024; 25(17):9194. doi: 10.3390/ijms25179194

Gibson, K.; Song, H. & Chen, N. Metabarcoding analysis of microbiome dynamics during a *Phaeocystis globosa* bloom in the Beibu Gulf, China. *Harmful Algae* 2022, 114:102217 https://doi.org/10.1016/j.hal.2022.102217.

Gobler, C.J.; Cecco, G.J.D.; Doherty, O.M. & Kramer, B.J. Decadal warming has intensified *Microcystis*-dominated cyanobacterial blooms in Lake Erie. *Limnology and Oceanography LETTERS* 2024, https://doi.org/10.1002/lol2.10406

Griffith, A.W. & Christopher, J.G. Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. *Harmful Algae* 2020; 91: 101590 https://doi.org/10.1016/j.hal.2019.03.008.

Haffar, M.A.; Fajloun, Z.; Azar, S.; Sabatier, J.M. & Khattar, Z.A. Lesser-Known Cyanotoxins: A Comprehensive Review of Their Health and Environmental Impacts. *Toxins (Basel)* 2024, 19;16(12):551. doi: 10.3390/toxins16120551

Helmer, J. Toledo's Blooming Algae Crisis. NRDC 2020; https://www.nrdc.org/stories/toledos-blooming-algae-crisis.

Izadi, M.; Sultan, M.; Kadiri, R.E.; Ghannadi, A. & Abdelmohsen, K. A Remote Sensing and Machine Learning-Based Approach to Forecast the Onset of Harmful Algal Bloom. *Remote Sens.* 2021, *13*(19): 3863; https://doi.org/10.3390/rs13193863

Jacoby, C.A. & Twardowski, M.S. Dynamics of microcystins and saxitoxin in the Indian River Lagoon, Florida. *Harmful Algae* 2021; 130: 102012 https://doi.org/10.1016/j.hal.2021.102012.

Jeffery, B.; Barlow, T.; Moizer, K.; Paul, S. & Boyle, C. Amnesic shellfish poison. *Food and Chemical Toxicology* 2004; 42(4):545-557 https://doi.org/10.1016/j.fct.2003.11.010.

Kinnear, S. Cylindrospermopsin: A Decade of Progress on Bioaccumulation Research. *Mar. Drugs* 2010; *8*(3): 542-564 doi: 10.3390/md8030542.

Kramer, B.J.; Turk-Kubo, K.; Zehr, J.P. & Gobler, C.J. Intensification of harmful cyanobacterial blooms in a eutrophic, temperate lake caused by nitrogen, temperature, and CO2. *Science of The Total Environment* 2024; 915:169885 https://doi.org/10.1016/j.scitotenv.2024.169885.

Kumar, R. Toxic Algae and Effects of Algal Poisoning in Animals and Human Beings. *World Journal of Environmental Biosciences* 2021; 10(1):9-12 https://doi.org/10.51847/8iu9ylaNgi.

Laureano-Rosario, A. E.; McFarland, M.; Bradshaw, II D.J.; Metz J.; Brewton, R.A.; Pitts, T., Perricone, C.; Schreiber, S.; Stockley, N.; Wang, G.; Guzmán, E.A.; Lapointe, B.E.; Wright, A.E.; Maniyar, C.B.; Raviprakash, K.; Kumar, A.; Seferian, M.A.; Fiorentino, I.R. & Mishra D.R. Low-Cost System to Support and Expand Cyanobacterial Harmful Algal Bloom Monitoring with New-Generation Ocean Color Satellites. *ACS ES&T Water* 2025, 5(11): 6246-6257 https://doi.org/10.1021/acsestwater.5c00301.

Mishra, P.; Naik, S.; Babu, P.V.; Pradhan, U.; Begum, M.; Kaviarasan, T.; Vashi, A.; Bandyopadhyay, D.; Ezhilarasan, P.; Murthy, M.V.R. & Panda, U.S. Algal bloom, hypoxia, and mass fish kill events in the backwaters of Puducherry, Southeast coast of India. *Oceanologia* 2022, 64(2):396-403 https://doi.org/10.1016/j.oceano.2021.11.003.

Mundhe, E. Interdisciplinary approaches and strategies for sustainable development. *Zenodo* 2022; Version v1. DOI:10.5281/zenodo.7847920, DOI:10.5281/zenodo.7847920.

Oh, J.W.; Pushparaj, S.S.C.; Muthu, M. & Gopal, J. Review of Harmful Algal Blooms (HABs) Causing Marine Fish Kills: Toxicity and Mitigation. *Plants* 2023; 12(23):3936 doi: 10.3390/plants12233936.

Lad, A.; Breidenbach, J.D.; Su, R.C.; Murray, J.; Kuang, R.; Mascarenhas, A.; Najjar, J.; Patel, S.; Hegde, P.; Youssef, M.; Breuler, J.; Kleinhenz, A.L.; Ault, A.P.; Westrick, J.A.; Modyanov, N.N.; Kennedy, D.J. & Haller, S.T. As We Drink and

Breathe: Adverse Health Effects of Microcystins and Other Harmful Algal Bloom Toxins in the Liver, Gut, Lungs and Beyond. *Life (Basel)* 2022,12(3):418. doi: 10.3390/life12030418.

Ladds, M. & Gobler, C.J. Zooplankton grazing can facilitate and control the proliferation of harmful algal blooms caused by *Dinophysis acuminata* in NY, USA, estuaries. *Harmful Algae*

2025, 142:102789. doi: 10.1016/j.hal.2024.102789

Lan, J.; Liu, P.; Hu , X. & ZhU, S. Harmful Algal Blooms in Eutrophic Marine Environments: Causes, Monitoring, and Treatment.*Water* 2024, *16*(17):2525; https://doi.org/10.3390/w16 172525

Lee, S.; Choi, B.; Kim, S.J.; Kim, J.; Kang, D. & Lee, J. Relationship between freshwater harmful algal blooms and neurodegenerative disease incidence rates in South Korea. *Environmental Health* 2022; 21(116), doi: 10.1186/s12940-022-00935-y.

Lee, T. C-H.; Fong, F. L-Y.; Ho, K-C. & Lee, F. W-F. The Mechanism of Diarrhetic Shellfish Poisoning Toxin Production in *Prorocentrum* spp.: Physiological and Molecular Perspectives. *Toxins* 2016; 8(10): 272 doi: 10.3390/toxins8100272.

Liu, M.; Huang, Q.; Li, H. & Zhu, G. Atmospheric heatwaves expand hypoxic zones in a deeply stratified mega-reservoir. *Ecological Indicators 2026,* 182:114565. https://doi.org/10.1016/j.ecolind.2025.114565

Lürling, M.; Liao, Z.; Kang, L.; Bishop, W.M. & Mucci, M. Effects of peroxide-based compounds on growth and toxicity of *Microcystis aeruginosa. Harmful Algae 2025,* 149:102930. https://doi.org/10.1016/j.hal.2025.102930

Lynn, M. G.; , Sailor, H.;., & J. G. Morris Jr. Harmful Algal Blooms and Public Health. *Harmful Algae* 2016, 57(B):2–8. doi: 10.1016/j.hal.2016.05.003

Mowe, M.A.D.; Porojan, C.; Abbas, F.; Mitrovic, S.M.; Lim, R.P.; Furey, A. & Yeo, D.C.J. Rising temperatures may increase growth rates and microcystin production in tropical *Microcystis* species. *Harmful Algae* 2015; 50: 88-98. https://doi.org/10.1016/j.hal.2015.10.011

Plata-Calzado, C.; Prieto, A.I.; Cameán, A.M. & Jos, A. Toxic Effects Produced by Anatoxin-a under Laboratory Conditions: A Review. *Toxins* 2022; 14(12): 861 doi: 10.3390/toxins14120861

Piehler, M.F. Watershed management strategies to prevent and control cyanobacterial harmful algal blooms. *Adv Exp Med Biol* 2008, 619:259-73. doi: 10.1007/978-0-387-75865-7_12.

Pliński, H.M.M. Stability of cyanotoxins, microcystin-LR, microcystin-RR and nodularin in seawater and BG-11 medium of different salinity. *OCEANOLOGIA* 2001*,* 43 (3): 2001. pp. 329–339.

Rapala, J.; Sivonen, K.; Lyra, C. & Niemelä, S.I. Variation of microcystins, cyanobacterial hepatotoxins, in *Anabaena* spp. as a function of growth stimuli. *Applied and Environmental Microbiology* 1997; 63(6):2206-2212 doi: 10.1128/aem.63.6.2206-2212.1997

Rodríguez-Benito, C.V.; Navarro, G. & Caballero, I. Using Copernicus Sentinel-2 and Sentinel-3 data to monitor harmful algal blooms in Southern Chile during the COVID-19 lockdown. *Marine Pollution Bulletin* 2020, 161(A):111722 doi: 10.1016/j.marpolbul.2020.111722.

Sarangi, R.K. & Barathan, B.P. Intensifcation and spread of algal blooms over two decades in the coasts of India. *Discover Oceans Review* | https://doi.org/10.1007/s44289-024-00035-4

Sinha, E.; Michalak, A.M. & Balaji, V. Eutrophication will increase during the 21st century as a result of precipitation changes. *Science* 2017; 357(6349):405-408 DOI: 10.1126/science.aan2409.

Sukenik, A. & Kaplan, A. Cyanobacterial Harmful Algal Blooms in Aquatic Ecosystems: A Comprehensive Outlook on Current and Emerging Mitigation and Control Approaches. Microorganisms 2021; 9(7):1472. doi: 10.3390/microorganisms9071472

Tanvir, R.U.; Hu, Z.; Zhang, Y. & Lu, J. Cyanobacterial community succession and associated cyanotoxin production in hypereutrophic and eutrophic freshwaters. *Environ Pollut* 2021; 290:118056. doi: 10.1016/j.envpol.2021.118056

Verma, S.; Kumar, P. & Štangar, U.L. A Perspective on Removal of Cyanotoxins from Water Through Advanced Oxidation Processes. *Glob Chall* 202;, 1:7(9):2300125. doi: 10.1002/gch2.202300125

Wang, J.; Xu, B. & Huang, L. Molecular Mechanisms of Algicidal Bacteria in Controlling Harmful Algal Blooms: Advances in Bacteria‐Algae Interactions. *Environ Microbiol Rep* 2026; 18(2):e70305. doi: 10.1111/1758-2229.70305

Watkins, S.M.; Reich, A.; Fleming, L.E. & Hammond, R. Neurotoxic shellfish poisoning. *Mar Drugs* 2008, 6(3):431-55 doi: 10.3390/md20080021

Wimalasena, S.D.M.K.; Niroshika, K.K.H. & Walimuni, S.W.S. Biological approaches used to control the algal bloom formation in aquatic environments: A Review. *Srilanka Naturalist Journal of Ecology and Research* 2023, 12(1):7-24.

Xiao, X.; Peng, Y.; Zhang, W.; Yang, X.; Zhang, Z.; Ren, B.; Zhu, G. & Zhou, S. Current status and prospects of algal bloom early warning technologies: A Review. *Journal of Environmental Management* 2014, 349:119510 https://doi.org/10.1016/j.jenvman.2023.119510.

Zahir, M.; Su, Y.; Shahzad, M.I.; Ayub, G.; Rahman, S.U. & Ijaz, J. A review on monitoring, forecasting, and early warning of harmful algal bloom. *Aquaculture* 2024, 593: 74135. https://doi.org/10.1016/j.aquaculture.2024.741351

Zhang, J.; Zhou, Q.; Jia, Y.; Han, J.; Zhao, S.; Pan, B. & Song, L. Low-dose high-efficiency sedimentation of bloom-forming cyanobacterium *Raphidiopsis raciborskii* using modified clays. *Harmful Algae* 2026, 103127. https://doi.org/10.1016/j.hal.2026.103127

Zhou, J.; Richlen, M.L.; Sehein, T.R.; Kulis, D.M.; Anderson, D.M. & Cai, Z. Microbial Community Structure and Associations During a Marine Dinoflagellate Bloom. *Front. Microbiol.* 2018, 9 doi:10.3389/fmicb.2018.01201.