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CYANOBACTERIA AND CYANOTOXINS: A DETAILED REVIEW OF GLOBAL DISTRIBUTION, TOXICITY, ENVIRONMENTAL DRIVERS, AND SUSTAINABLE MANAGEMENT

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Abstract:

Cyanobacteria are widely distributed photosynthetic microorganisms that play vital roles in aquatic ecosystems, particularly in primary production and nutrient cycling. However, they have emerged as a major environmental and public health concern due to their ability to produce toxic secondary metabolites known as cyanotoxins. In recent decades, the frequency, intensity, and geographic extent of harmful cyanobacterial blooms (HABs) have increased significantly worldwide, largely driven by nutrient enrichment, climate change, and anthropogenic pressures such as agricultural runoff and urbanization. This review provides a comprehensive overview of the global distribution of cyanobacteria and examines the occurrence, diversity, and classification of major cyanotoxins, including microcystins, cylindrospermopsin, anatoxins, and saxitoxins. It further discusses their toxicological impacts on humans, aquatic organisms, and ecosystem health, with particular emphasis on their bioaccumulation and transfer through aquatic food webs. The role of key environmental drivers such as nutrient dynamics, temperature variation, and hydrological conditions in bloom development is also analyzed. In addition, this review highlights current monitoring and detection approaches, advanced water treatment technologies, and nutrient management practices as essential components of sustainable mitigation strategies. Overall, a multidisciplinary and integrated approach is necessary to effectively manage cyanobacterial blooms and reduce associated risks to environmental and public health.

Keywords: *Cyanobacteria, Cyanotoxins, Harmful algal blooms (HABs), Bioaccumulation, Water quality management.*

1. Introduction

Cyanobacteria, commonly known as blue-green algae, are ubiquitous photosynthetic microorganisms that have existed for billions of years and are among the earliest contributors to oxygen production on Earth. They are widely distributed across freshwater, marine, and terrestrial ecosystems, where they play a crucial role in primary productivity, carbon fixation, and nutrient cycling, particularly nitrogen fixation. Despite their ecological importance, the ability of certain cyanobacterial species to produce toxic secondary metabolites, known as cyanotoxins, has raised significant environmental and public health concerns worldwide [1]. These organisms can rapidly proliferate under favorable environmental conditions, forming dense accumulations known as harmful cyanobacterial blooms (CyanoHABs).

In recent decades, the frequency, intensity, and spatial distribution of CyanoHABs have increased substantially on a global scale. This expansion is primarily driven by nutrient enrichment (eutrophication), rising temperatures associated with climate change, and increasing anthropogenic activities such as agricultural runoff, industrial discharge, and urbanization [2]. These factors create optimal conditions for cyanobacterial growth, allowing them to outcompete other phytoplankton and dominate aquatic ecosystems. The persistence of such blooms not only disrupts ecological balance but also degrades water quality and ecosystem services.

Cyanotoxins are structurally diverse compounds with varying modes of action and toxicity. Major groups include hepatotoxins such as microcystins, neurotoxins such as anatoxins and saxitoxins, and cytotoxins such as cylindrospermopsin, all of which can adversely affect humans, aquatic organisms, livestock, and wildlife [3]. Human exposure can occur through multiple pathways, including ingestion of contaminated drinking water, recreational contact with polluted water, consumption of contaminated food, and inhalation of aerosolized toxins. These exposures can lead to a range of health effects, from acute poisoning to chronic diseases affecting the liver, nervous system, and other organs [4].

Globally, cyanobacteria and their associated toxins have been reported in lakes, rivers, reservoirs, and drinking water systems, frequently exceeding established safety limits [5]. Their widespread occurrence, combined with their persistence in aquatic environments, makes them a critical concern for water resource management. Furthermore, cyanotoxins can accumulate in aquatic organisms and transfer through food webs, resulting in long-term ecological impacts and increased human exposure risks [6]. Considering their increasing prevalence and widespread impacts, there is an urgent need for a comprehensive understanding of cyanobacterial ecology, toxin production, and environmental interactions. Such knowledge is essential for developing effective monitoring systems and sustainable management strategies to mitigate cyanobacterial blooms and safeguard environmental and public health.

2. Global distribution of cyanobacteria and cyanotoxins

Cyanobacteria are globally distributed microorganisms that inhabit a wide range of aquatic and terrestrial environments, including freshwater lakes, rivers, reservoirs, estuaries, and marine ecosystems. Their remarkable physiological adaptability allows them to thrive under diverse environmental conditions, from nutrient-rich eutrophic waters to extreme habitats. Over recent decades, a pronounced global expansion of cyanobacterial blooms has been observed, making them a critical concern for water quality and ecosystem stability [7].

The occurrence of harmful cyanobacterial blooms (CyanoHABs) is now reported across all continents, with increasing frequency in both temperate and tropical regions. In tropical systems, warm temperatures and continuous nutrient inputs create ideal conditions for persistent bloom formation, while temperate regions are experiencing extended bloom seasons due to climate warming [8]. Anthropogenic influences, particularly agricultural runoff, urbanization, and industrial discharge, significantly contribute to nutrient enrichment, thereby accelerating cyanobacterial proliferation [9].

Cyanotoxins produced during these blooms have been widely detected in global water bodies, including drinking water sources, often at concentrations exceeding safety guidelines. Large-scale monitoring studies have confirmed the presence of toxins such as microcystins, cylindrospermopsin, anatoxins, and saxitoxins in surface waters worldwide [10]. Regional investigations, including those in Mediterranean reservoirs, demonstrate substantial spatial and temporal variability in cyanobacterial abundance and toxin levels, influenced by local climatic and hydrological factors [11].

Additionally, cyanobacteria and cyanotoxins are increasingly reported in water treatment systems, highlighting challenges in removal efficiency and the risk of human exposure through drinking water [12, 13]. This widespread and escalating distribution underscores the urgent need for global monitoring frameworks and adaptive management strategies to mitigate cyanobacterial risks.

3. Classification and types of cyanotoxins

Cyanotoxins are a diverse group of toxic secondary metabolites produced by several cyanobacterial genera, including *Microcystis*, *Dolichospermum* (*Anabaena*), *Cylindrospermopsis*, and *Aphanizomenon*. These compounds vary widely in chemical structure, biosynthesis, and toxicity, making classification essential for understanding their ecological and health impacts [14].

Cyanotoxins are primarily classified according to the organ systems they affect. This classification provides a clear framework for risk assessment and management:

- **Hepatotoxins:** The most prevalent group, including microcystins and nodularins, primarily targets the liver by inhibiting protein phosphatases (PP1 and PP2A), leading to hepatocellular damage and tumor promotion. Microcystins are the most widely distributed cyanotoxins globally [15].
- **Neurotoxins:** Anatoxins and saxitoxins affect the nervous system by interfering with neurotransmission. Anatoxin-a acts as a potent nicotinic agonist, while saxitoxins block sodium channels, potentially causing paralysis and respiratory failure [3].
- **Cytotoxins:** Cylindrospermopsin is a well-known cytotoxin that inhibits protein synthesis and affects multiple organs, including the liver and kidneys, with both acute and chronic toxicity effects [14].
- **Dermatotoxins and Irritants:** Compounds such as lyngbyatoxins and aplysiatoxins cause skin irritation and inflammatory responses, particularly during recreational exposure [16].

Cyanotoxins display significant structural diversity, encompassing compounds such as cyclic peptides and alkaloids, which are synthesized through complex biochemical pathways including non-ribosomal peptide synthetases and polyketide synthases [14]. This structural variation plays a crucial role in determining their toxicity levels, environmental stability, and persistence in aquatic systems. As a result, different cyanotoxins can exhibit a wide range of biological effects on organisms and ecosystems. Moreover, in natural environments, these toxins rarely occur in isolation; instead, multiple cyanotoxins often coexist, leading to increased ecological complexity and compounded health risks [17]. Such co-occurrence can enhance their combined toxic effects, making risk assessment more challenging. The presence of diverse toxin mixtures also complicates detection and monitoring processes. Therefore, a comprehensive understanding of cyanotoxin classification and structural variability is essential for accurate identification and effective environmental management. This knowledge supports the development of improved monitoring techniques and mitigation strategies. Ultimately, recognizing the diversity and interactions of cyanotoxins is vital for safeguarding water quality and public health.

Table 1: Major cyanotoxin groups, representative toxins, targets, and biological effects

Toxin Group	Representative Toxins	Target	Primary Effects	Common Genera
Hepatotoxins	Microcystins, Nodularins	Liver	Hepatic damage, tumor promotion	*Microcystis*, *Anabaena*, *Nostoc*
Neurotoxins	Anatoxin-a, Saxitoxins	Nervous system	Paralysis, respiratory failure	*Anabaena*, *Aphanizomenon*
Cytotoxins	Cylindrospermopsin	Liver, kidney	Protein synthesis inhibition	*Cylindrospermopsis*
Dermatotoxins	Lyngbyatoxin, Aplysiatoxin	Skin	Irritation, inflammation	*Lyngbya*

4. Toxicity and health impacts of cyanotoxins

Cyanotoxins pose significant risks to human and ecological health due to their diverse mechanisms of toxicity and multiple exposure pathways. These toxins can enter the human body through ingestion of contaminated drinking water, consumption of contaminated food, recreational activities, and inhalation of aerosolized particles [18]. The severity of toxic effects depends on toxin type, concentration, exposure duration, and individual susceptibility.

Hepatotoxins, particularly microcystins, are the most prevalent and primarily target the liver by inhibiting protein phosphatases, leading to liver damage, oxidative stress, and tumor promotion [15]. Neurotoxins such as anatoxin-a and saxitoxins disrupt nerve signal transmission, potentially causing paralysis and respiratory failure [3]. Cytotoxins like cylindrospermopsin affect multiple organs by inhibiting protein synthesis and inducing cellular damage [14].

Aquatic organisms are particularly vulnerable to cyanotoxin exposure. Fish exposed to cyanotoxins exhibit physiological stress, impaired immune function, and organ damage, which can disrupt aquatic food webs [3]. Moreover, cyanotoxins can accumulate in aquatic organisms and enter the human food chain, posing long-term health risks [19].

Chronic exposure to cyanotoxins has been linked to a range of serious health effects, including liver damage, neurological impairments, and potential carcinogenic outcomes [18]. These toxins, produced by harmful cyanobacterial blooms, can enter the human body through drinking water, recreational activities, and contaminated food sources. Prolonged exposure may lead to cumulative toxicity, increasing the severity of health risks over time. In particular, hepatotoxins such as microcystins are known to cause liver dysfunction and promote tumor formation. Neurotoxic cyanotoxins can interfere with nerve signal transmission, potentially leading to paralysis or cognitive disturbances. Furthermore, recent studies suggest that cyanotoxins may also play a role in cardiovascular complications under certain exposure conditions [15]. This emerging evidence indicates a broader spectrum of health impacts than previously understood. The widespread occurrence and persistence of these toxins in aquatic environments amplify the risk to both humans and wildlife. Consequently, their complex toxicity and multiple exposure pathways pose significant challenges for public health management. Therefore, effective monitoring, risk assessment, and mitigation strategies are essential to minimize cyanotoxin-related hazards and protect environmental and human health.

5. Bioaccumulation and ecological impacts

Cyanotoxins possess a strong capacity to accumulate in aquatic organisms and transfer across trophic levels, posing significant ecological and human health risks. Bioaccumulation occurs when the rate of toxin uptake exceeds the rate of elimination, resulting in progressive concentration of toxins within biological tissues over time [20]. This process is particularly prominent in aquatic ecosystems during cyanobacterial bloom events, where toxins released into the water are readily taken up by primary producers such as phytoplankton and subsequently transferred to zooplankton, benthic organisms, and higher trophic levels. The persistence of cyanotoxins in these systems increases the likelihood of continuous exposure across multiple components of the food web.

Numerous studies have demonstrated that cyanotoxins, particularly microcystins, can accumulate in fish, shellfish, and other aquatic organisms, facilitating their movement through food chains and increasing exposure risks for predators, including humans [21]. This trophic transfer is of particular concern in regions where fish and other aquatic organisms form a major component of the human diet. Long-term consumption of contaminated food sources can lead to chronic exposure, even when toxin concentrations in water appear relatively low [19]. Additionally, different species exhibit varying capacities for toxin uptake and depuration, further influencing the distribution and magnitude of bioaccumulation within ecosystems.

Beyond biological uptake, environmental factors play a crucial role in determining the persistence and mobility of cyanotoxins. These compounds can bind to sediments and suspended particulate matter, allowing them to remain in aquatic environments even after visible bloom events have subsided [22]. Sediment-bound toxins may later be released back into the water column due to physical disturbances or changes in environmental conditions, thereby prolonging exposure risks and complicating monitoring and management efforts. This dynamic cycling between water and sediments contributes to the long-term stability and ecological impact of cyanotoxins.

The ecological consequences of cyanotoxin bioaccumulation are substantial. Toxic exposure can impair growth, reproduction, and immune function in aquatic organisms, leading to reduced population viability and biodiversity loss. Disruptions at lower trophic levels can cascade through the food web, altering ecosystem structure and function. Overall, the persistence and bioaccumulation of cyanotoxins highlight their long-term environmental significance and emphasize the need for comprehensive monitoring, risk assessment, and management strategies to protect ecosystem integrity and human health.

6. Environmental drivers of cyanobacterial blooms

The occurrence and proliferation of cyanobacterial blooms are driven by a complex interplay of environmental and anthropogenic factors. Among these, nutrient enrichment (eutrophication) is widely recognized as the primary driver, particularly the excessive input of nitrogen (N) and phosphorus (P) from agricultural runoff, wastewater discharge, and urbanization [23]. Elevated nutrient concentrations promote rapid cyanobacterial growth, enabling them to outcompete other phytoplankton and dominate aquatic ecosystems.

Climate change has further intensified bloom frequency, duration, and spatial extent. Rising temperatures enhance cyanobacterial metabolic activity and growth rates, while altered precipitation patterns increase nutrient loading into water bodies [1, 2]. In addition, warmer conditions favor buoyant cyanobacteria capable of regulating their vertical position in the water column, allowing them to access optimal light and nutrient conditions. Hydrological factors such as water residence time, stratification, and reduced flow velocity also play a critical role, as stable and stratified environments support bloom formation and surface accumulation [24, 25].

Other environmental variables, including light intensity, pH, and carbon availability, further influence cyanobacterial physiology and toxin production. Elevated CO_2 concentrations can enhance photosynthetic efficiency and promote toxin synthesis. Moreover, recent advances in predictive modeling and monitoring technologies, including machine learning and early-warning systems, have improved the understanding of bloom dynamics and environmental triggers [26, 27].

7. Emerging issues and research trends

The research landscape on cyanobacteria and cyanotoxins is rapidly advancing, revealing a range of emerging issues that extend beyond traditional concerns of bloom occurrence and acute toxicity. One of the most significant developments is the recognition that cyanotoxins rarely occur in isolation in natural environments. Instead, they often co-exist with other environmental contaminants such as heavy metals, pesticides, pathogenic microorganisms, and microplastics. This co-occurrence can result in additive, synergistic, or even antagonistic interactions, complicating toxicity evaluation and risk assessment processes [17]. Furthermore, increasing evidence suggests that cyanotoxins may have ecological functions beyond their toxic effects, including roles in interspecies competition, defense against grazers, and regulation of cellular processes. These findings indicate that cyanotoxins are not merely harmful byproducts but may be integral to cyanobacterial survival and ecological dynamics [16].

Another important research trend is the expansion of exposure pathways and the growing concern over long-term health impacts. Traditionally, ingestion of contaminated water was considered the primary route of exposure; however, recent studies have demonstrated that cyanotoxins can become aerosolized and transported through the atmosphere, increasing the risk of inhalation, particularly in areas experiencing frequent or intense blooms [2]. In addition, the accumulation of cyanotoxins in food systems has raised serious concerns regarding food safety and chronic dietary exposure. Contaminated fish, shellfish, and even agricultural products irrigated with polluted water can act as vectors for toxin transfer to humans [19]. These developments highlight the necessity of adopting integrated, multi-pathway risk assessment frameworks that consider cumulative exposure from various environmental sources and long-term health consequences.

Technological advancements are also playing a transformative role in cyanotoxin research and management. The integration of molecular techniques, advanced analytical tools, remote sensing technologies, and artificial intelligence has significantly improved the ability to detect, monitor, and predict cyanobacterial blooms and toxin production [28, 26, 27]. These tools enable real-time data collection, high-resolution spatial analysis, and predictive modeling, which are essential for the development of effective early-warning systems and proactive management strategies. Looking forward, research is increasingly focused on identifying emerging cyanotoxins, understanding climate-driven changes in bloom dynamics, and developing interdisciplinary approaches that integrate ecology, toxicology, and computational science. Collectively, these trends reflect a shift toward more holistic, data-driven, and predictive frameworks for understanding and mitigating the global impacts of cyanobacterial blooms.

8. Monitoring and detection techniques

Effective monitoring and detection of cyanobacteria and cyanotoxins are essential for safeguarding water quality and reducing risks to human and ecosystem health. Conventional monitoring approaches are primarily based on routine water sampling, microscopic identification of cyanobacterial species, and measurement of physicochemical parameters such as nutrient concentrations, temperature, and dissolved oxygen. These methods provide important baseline information on bloom presence and environmental conditions; however, they are often labor-intensive, time-consuming, and limited in their ability to directly assess toxin production. This limitation arises because not all cyanobacterial strains are toxigenic, meaning that species identification alone cannot reliably indicate the presence or concentration of cyanotoxins [18].

Advances in analytical and molecular techniques have greatly enhanced the detection and quantification of cyanotoxins. Immunological methods such as enzyme-linked immunosorbent assays (ELISA) are widely used for rapid and cost-effective screening of water samples due to their high sensitivity. For more accurate and detailed analysis, chromatographic techniques such as high-performance liquid chromatography (HPLC) and liquid chromatography–mass spectrometry (LC-MS/MS) are employed, allowing precise identification and quantification of different toxin variants. In addition, molecular approaches such as polymerase chain reaction (PCR) and quantitative PCR (qPCR) target toxin-producing genes within cyanobacterial populations, enabling early detection of potentially harmful blooms before toxins are released into the environment [18].

Table 2: Comparison of Cyanotoxin Monitoring and Detection Techniques

Method	Principle	Advantages	Limitations	Application
Microscopy	Visual identification of cyanobacteria	Simple, low cost	Cannot detect toxins directly	Species monitoring
ELISA	Antibody-based detection of toxins	Rapid, sensitive, cost-effective	Limited specificity for toxin variants	Screening of water samples
HPLC / LC-MS/MS	Chemical separation and quantification	Highly accurate, detects multiple variants	Expensive, requires technical expertise	Detailed toxin analysis
PCR / qPCR	Detection of toxin-producing genes	Early warning capability	Does not measure toxin concentration	Genetic monitoring
Remote Sensing	Satellite or sensor-based detection	Large-scale, continuous monitoring	Indirect estimation of toxins	Bloom tracking
AI / Machine Learning	Data-driven predictive modeling	High accuracy, supports early warning	Requires large datasets	Forecasting bloom events

Recent developments in monitoring technologies focus on real-time and large-scale assessment of cyanobacterial blooms. Remote sensing tools, including satellite imagery and *in situ* sensor networks, enable continuous monitoring of bloom distribution and dynamics across large water bodies. These technologies provide valuable spatial and temporal data that support large-scale environmental assessments. Furthermore, the integration of machine learning and artificial intelligence models with environmental datasets has significantly improved the prediction of bloom occurrence and toxin production [22, 23]. Such predictive systems enhance early-warning capabilities and support proactive management strategies, ultimately contributing to more efficient and reliable cyanotoxin monitoring and control.

Despite significant advancements in monitoring techniques, several challenges continue to hinder the effectiveness and consistency of cyanotoxin detection across different regions and laboratories. The lack of standardized detection protocols leads to variability in sampling methods, analytical procedures, and reporting formats, resulting in inconsistencies in data and limiting comparability across studies. Differences in instrument sensitivity, calibration, and laboratory expertise further affect data reliability. Additionally, integrating multi-source data from field observations, laboratory analyses, remote sensing, and predictive models remains complex due to variations in scale, format, and accuracy. These challenges can delay data interpretation, reduce the efficiency of early-warning systems, and hinder timely risk management decisions. To address these issues, the development of a unified and standardized monitoring framework is essential, promoting harmonized methodologies and improved data interoperability. A multidisciplinary approach that combines traditional monitoring with advanced analytical, molecular, and computational techniques can significantly enhance detection efficiency, improve accuracy, and enable real-time assessment of cyanotoxin occurrence, ultimately supporting more effective environmental management and protection of public health.

9. Sustainable management and mitigation strategies

Sustainable management of cyanobacterial blooms and cyanotoxins requires a comprehensive and integrated approach that combines prevention, control, and risk mitigation strategies. Among all available measures, nutrient reduction remains the most effective long-term solution. Limiting the input of nitrogen (N) and phosphorus (P) from agricultural runoff, wastewater discharge, and urban activities can significantly reduce eutrophication and suppress bloom formation [1, 2]. Effective catchment-level management practices, such as precision agriculture, controlled fertilizer application, buffer zones, and improved wastewater treatment systems, play a critical role in minimizing nutrient loading and preventing bloom development.

In addition to preventive measures, water treatment technologies are essential for managing cyanotoxins in drinking water systems and ensuring public safety. Conventional treatment methods such as coagulation, sedimentation, filtration, and chlorination are widely used but may not completely remove dissolved toxins. Therefore, advanced treatment processes, including activated carbon adsorption, ozonation, membrane filtration, and advanced oxidation processes, have been increasingly applied due to their higher efficiency in removing cyanotoxins [16, 21]. However, treatment performance depends on toxin type, concentration, and operational conditions, requiring optimized and site-specific treatment strategies.

Monitoring and early-warning systems represent another critical component of sustainable management. Continuous monitoring of cyanobacterial populations and toxin concentrations, combined with predictive models and remote sensing technologies, allows early detection of bloom events and supports timely intervention [18, 22, 23]. These approaches improve decision-making and help reduce potential health risks. Additionally, public health protection measures such as water quality standards, public advisories, and restrictions on recreational water use play a significant role in minimizing human exposure to cyanotoxins [11].

Emerging strategies focus on ecosystem-based management approaches that aim to restore ecological balance and reduce bloom-favorable conditions. These include biological control methods, wetland restoration, improved water circulation, and reduction of internal nutrient loading from sediments. Overall, sustainable mitigation of cyanobacterial blooms requires a multidisciplinary framework integrating environmental management, technological advancements, policy implementation, and community awareness to ensure long-term water quality and ecosystem health.

10. Risk assessment and future perspectives

Risk assessment of cyanobacteria and cyanotoxins is a critical component in understanding their impacts on both environmental integrity and human health. Exposure can occur through multiple pathways, including ingestion of contaminated drinking water, consumption of toxin-accumulated food, recreational contact with polluted water, and inhalation of aerosolized cyanotoxins. Contemporary risk assessment frameworks incorporate key parameters such as toxin concentration, duration and frequency of exposure, and the susceptibility of different population groups to evaluate potential health outcomes. Numerous studies have reported that cyanotoxin concentrations in aquatic systems often exceed recommended safety thresholds, underscoring the need for continuous monitoring and the establishment of standardized regulatory guidelines [28, 29]. These frameworks are essential for assessing both acute and chronic risks across diverse environmental settings.

Despite these advancements, accurate risk evaluation remains challenging due to the complex nature of cyanotoxin production and environmental variability. Toxin levels can fluctuate significantly depending on nutrient availability, temperature, and hydrological conditions, making prediction difficult. Furthermore, the co-occurrence of multiple cyanotoxins within a single bloom complicates toxicity assessment, as combined or synergistic effects may differ from those of individual compounds. Chronic low-dose exposure, along with interactions between cyanotoxins and other environmental pollutants, is still not fully understood, leading to uncertainties in long-term health risk predictions [15]. Additionally, inconsistencies in monitoring techniques and the lack of harmonized regulatory standards across regions further hinder effective risk management and policy implementation.

Future research is increasingly directed toward improving predictive accuracy and strengthening monitoring systems. The integration of advanced technologies such as artificial intelligence, machine learning, and large-scale environmental datasets is enhancing the ability to forecast cyanobacterial blooms and toxin occurrence with greater precision [23]. These innovations support the development of real-time monitoring systems and early-warning frameworks that enable proactive management strategies. Continued efforts to standardize risk assessment methodologies, improve data integration, and promote interdisciplinary collaboration will be essential for reducing uncertainties and enhancing global response strategies. Ultimately, a comprehensive and technology-driven approach to risk assessment will play a pivotal role in mitigating cyanotoxin-related risks and protecting both ecosystems and public health.

Conclusion

Cyanobacteria and their associated cyanotoxins represent a significant and escalating global environmental challenge driven by nutrient enrichment, climate change, and anthropogenic activities. Their widespread distribution across aquatic ecosystems and increasing dominance in eutrophic conditions have led to more frequent harmful blooms, adversely affecting water quality, ecosystem stability, and public health. Cyanotoxins such as microcystins, anatoxins, and cylindrospermopsin exhibit diverse toxic effects and can bioaccumulate within aquatic food webs, increasing the risk of long-term ecological and human exposure through multiple pathways, including drinking water, food consumption, recreational activities, and inhalation. The persistence of these toxins in sediments and their interaction with other environmental contaminants further complicate risk assessment and management. Environmental drivers, particularly nutrient loading, temperature changes, and hydrological conditions, play a central role in bloom dynamics, highlighting the need for preventive strategies. Advances in monitoring, including molecular tools, remote sensing, and artificial intelligence, have enhanced detection and prediction capabilities; however, effective mitigation requires integrated approaches combining nutrient control, advanced water treatment, continuous monitoring, and policy interventions. Future research should focus on emerging toxins, long-term exposure effects, and interdisciplinary solutions to improve risk assessment frameworks. Overall, sustainable and science-based management strategies are essential to mitigate cyanobacterial risks and ensure the protection of aquatic ecosystems and human health.

References

1. Chorus, I., Fastner, J., & Welker, M. (2021). Cyanobacteria and cyanotoxins in a changing environment: Concepts, controversies, challenges. *Water, 13*(18), 2463.
2. Plaas, H. E., & Paerl, H. W. (2020). Toxic cyanobacteria: A growing threat to water and air quality. *Environmental Science & Technology, 55*(1), 44–64.
3. Falfushynska, H., Kasianchuk, N., Siemens, E., Henao, E., & Rzymski, P. (2023). A review of common cyanotoxins and their effects on fish. *Toxics, 11*(2), 118.
4. Drobac, D., Tokodi, N., Simeunović, J., Baltić, V., Stanić, D., & Svirčev, Z. (2013). Human exposure to cyanotoxins and their effects on health. *Arhiv za Higijenu Rada i Toksikologiju, 64*, 305–316.
5. Marumure, J., Gwenzi, W., Makuvara, Z., Simbanegavi, T. T., *et al.* (2025). Global occurrence of cyanotoxins in drinking water systems: Recent advances, human health risks, mitigation, and future directions. *Life, 15*, 825.
6. Garita-Alvarado, C. A., Silvas-Trujillo, K. I., Bermúdez-González, M. P., Bojorge-García, M. G., & Cantoral Uriza, E. A. (2026). Widespread microcystins accumulation in fish of several trophic guilds in reservoirs of a dry area in Central México. *Toxicon*, 109071.
7. Sukenik, A., Quesada, A., & Salmaso, N. (2015). Global expansion of cyanobacteria. *Biodiversity and Conservation, 24*, 889–908.
8. García, G., de los Santos Villalobos, S., Gutiérrez-Moreno, P., & Broce, K. (2026). Harmful cyanobacterial blooms in tropical and neotropical freshwaters: Environmental drivers, toxin dynamics, and management gaps. *Water, 18*(4), 510.
9. Abasambi, T. K., & Kifle, D. (2026). Drivers and ecological impacts of harmful cyanobacterial blooms in Ethiopian freshwaters and their management strategies. *Discover Applied Sciences*.
10. Kaloudis, T., Hiskia, A., & Triantis, T. (2022). Cyanotoxins in bloom: Global distribution. *Toxins, 14*, 264.
11. Pinto, I., Silva, R., Hentschke, G. S., Vasconcelos, V., Morais, J., Azevedo, L., & Antunes, S. C. (2026). Cyanobacteria and cyanotoxins in Mediterranean reservoirs: Ecological variability, risks and implications for water quality assessment. *Ecohydrology, 19*(1), e70187.
12. Mohamed, Z. A., Deyab, M. A., Abou-Dobara, M. I., El-Sayed, A. K., & El-Raghi, W. M. (2015). Occurrence of cyanobacteria and microcystin toxins in raw and treated waters of the Nile River, Egypt: Implication for water treatment and human health. *Environmental Science and Pollution Research, 22*(15), 11716–11727.
13. Sahu, A. K., Mir, S. A., Nayak, B., & Baitharu, I. (2024). Spatiotemporal variation in water quality and its association with cyanobacterial diversity in the Hirakud Reservoir, Sambalpur, Odisha, India. *Water Practice & Technology, 19*(9), 3506–3525.
14. Li, Z., Zhu, X., Wu, Z., Sun, T., & Tong, Y. (2023). Recent advances in cyanotoxin synthesis and applications.

Microorganisms, 11, 2636.

15. Svirčev, Z., Chen, L., Sántha, K., Drobac, D., Šušak, S., Vulin, A., & Meriluoto, J. (2022). Cyanotoxins and cardiovascular health. *Archives of Toxicology, 96*, 2829–2863.
16. Holland, A., & Kinnear, S. (2013). Ecological roles of cyanotoxins. *Marine Drugs, 11*, 2239–2258.
17. Metcalf, J. S., & Codd, G. A. (2020). Co-occurrence of cyanotoxins with environmental hazards. *Toxins, 12*, 629.
18. Ndungu, L., Stubner, A., Beeman, S., Lewandowski, S., Long, L., Goguet, E., & Okech, B. (2025). Scoping review of the effects of cyanobacterial toxins on human and animal health and potential role in mosquito control. *Discover Environment, 3*(1), 72.
19. White, S. H., Duivenvoorden, L. J., & Fabbro, L. D. (2005). A decision-making framework for ecological impacts associated with the accumulation of cyanotoxins cylindrospermopsin and microcystin. *Environmental Toxicology and Water Quality, 20*(3), 229–239.
20. Villalobos, T., Suárez-Isla, B., & Garcia, C. (2025). Health and environmental impacts of cyanobacteria and cyanotoxins from freshwater to seawater. *Toxins, 17*(3), 126.
21. Maghsoudi, E., Prévost, M., Duy, S. V., Sauvé, S., & Dorner, S. (2015). Adsorption characteristics of multiple microcystins and cylindrospermopsin on sediment: Implications for toxin monitoring and drinking water treatment. *Toxicon, 103*, 48–54.
22. Yang, H., Yao, Y., Chen, W., Gu, X., Chen, H., Zeng, Q., *et al.* (2025). Occurrence and risk assessment of different cyanotoxins and their relationship with environmental factors in six typical eutrophic lakes of China. *Environmental Research, 272*, 121184.
23. Erratt, K. J., Creed, I. F., Blais, J. M., Favot, E. J., Gushulak, C. A. C., Korosi, J. B., *et al.* (2026). Paleolimnology uncovers environmental drivers of cyanobacterial blooms, species shifts and toxin emergence. *Harmful Algae*, 103089.
24. Herrera, N., Llano, S., & Peñuela, G. (2026). Influence of environmental factors and tributaries on toxic cyanobacterial growth. *PLOS ONE, 21*(3), e0340012.
25. Singh, V., Jyoti, A., Jain, P., Saxena, J., Khanra, A., Vasistha, S., *et al.* (2025). A critical review of cyanoblooms and cyanotoxins: Risk assessment on human health and agriculture along with mitigation strategies using machine learning perspectives. *ACS Chemical Health & Safety, 32*(4), 341–360.
26. Smith, J. E., Widmer, J. A., Stocker, M. D., Wolny, J. L., Hill, R. L., & Pachepsky, Y. (2025). Investigating the relationship between microcystin concentrations and water quality parameters in three agricultural irrigation ponds using random forest. *Water, 17*(16), 2361.
27. Pasheva, M., Nashar, M., & Ivanova, D. (2026). Recent progress in the detection and monitoring of toxin-producing cyanoprokaryotes and their toxins. *Toxics, 14*(1), 86.
28. Koreivienė, J., Anne, O., Kasperovičienė, J., & Burškytė, V. (2014). Cyanotoxin management and human health risk mitigation in recreational waters. *Environmental Monitoring and Assessment, 186*(7), 4443–4459.
29. Zhao, X., Liu, Y.-M., Guo, Y.-M., Xu, C., Chen, L., Codd, G. A., (2023). Inland waters: Cyanotoxin occurrence and risk assessment. *Journal of Hazardous Materials*.