The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
21(1) S (1) 929-942, 2026 www.thebioscan.com

BLUE-GREEN ALGAE AND THEIR CONTRIBUTION TO GLOBAL BIOGEOCHEMICAL CYCLES – A REVIEW.

SINTHIYA N [1a*], SUGA S[1b], BABY SHALINI C[2a], MUTHU SHEEBA M[2b]

1a* Associate Professor, Department of Botany, Arignar Anna College,
Aralvoimozhi – 629301, Kanyakumari, Affiliated to Manonmaniam Sundaranar University, Tirunelveli, 627011, Tamil Nadu, India
1b Assistant Professor, Department of Botany, Sarah Tucker College (Autonomous),
Tirunelveli -627007, Affiliated to Manonmaniam Sundaranar University, Tirunelveli, 627011, Tamil Nadu, India
2a Assistant Professor, Department of Botany, Nazareth Margoschis College,
Nazareth - 628 617, Thoothukudi, Affiliated to Manonmaniam Sundaranar University, Tirunelveli, 627011, Tamil Nadu, India
2b Assistant Professor, Department of Botany, Kamaraj College (Autonomous),
Thoothukudi- 628 003, Affiliated to Manonmaniam Sundaranar University, Tirunelveli, 627011, Tamil Nadu, India

Corresponding Author: sinthmony1214@gmail.com

DOI: https://doi.org/10.63001/tbs.2026.v21.i01.S.I(1).pp929-942

Keywords:

Cyanobacteria, Biogeochemical cycles, Carbon sequestration, Nitrogen fixation, Nutrient cycling, Harmful algal blooms.

Received on: 27-02-2026

Accepted on: 12-03-2026

Published on:23-03-2026

ABSTRACT

Blue-green algae (cyanobacteria) are ancient photosynthetic prokaryotes that play a crucial role in global biogeochemical cycles. They contribute significantly to carbon sequestration, oxygen evolution, and nitrogen fixation, thereby influencing ecosystem productivity and climate regulation. Widely distributed in aquatic and terrestrial environments, cyanobacteria regulate the cycling of essential nutrients such as carbon, nitrogen, phosphorus, and sulfur. Their ability to fix atmospheric nitrogen enhances soil fertility and supports primary productivity. In addition, cyanobacteria are involved in nutrient recycling, maintaining ecosystem stability and resilience. Beyond their ecological importance, they have promising applications in biotechnology, including biofertilizers, biofuels, and wastewater treatment. However, under nutrient-rich conditions, certain species form harmful algal blooms that release toxins, posing environmental and health risks. This review highlights the ecological significance and dual role of cyanobacteria in sustaining and challenging ecosystem balance.

1. Introduction

Blue-green algae, commonly referred to as cyanobacteria, are a diverse group of photosynthetic, prokaryotic microorganisms that have played a fundamental role in shaping Earth's biosphere. Fossil evidence suggests that cyanobacteria originated over 3.5 billion years ago, making them among the earliest life forms on the planet (Schopf, 2000). Their emergence marked a turning point in Earth's evolutionary history, particularly during the Great Oxygenation Event, when oxygenic photosynthesis by cyanobacteria led to a significant increase in atmospheric oxygen levels, thereby enabling the evolution of aerobic organisms (Falkowski & Raven, 2007). Cyanobacteria are unique in their ability to perform oxygenic photosynthesis similar to higher plants, utilizing chlorophyll-a and accessory pigments such as phycocyanin. In addition to their photosynthetic capability, many cyanobacterial species possess the remarkable ability to fix atmospheric nitrogen into ammonia through specialized cells known as heterocysts. This dual capability allows them to thrive in nutrient-poor environments and significantly contributes to global nutrient dynamics (Whitton & Potts, 2000).

These microorganisms exhibit a wide ecological distribution, inhabiting freshwater, marine, and terrestrial ecosystems, as well as extreme environments such as hot springs, deserts, and Polar Regions. In aquatic systems, cyanobacteria are major contributors to primary productivity, forming the base of food webs and influencing the flow of energy and nutrients (Partensky *et al.,* 1999). In terrestrial ecosystems, they enhance soil fertility by improving nitrogen availability and soil structure. Cyanobacteria are key regulators of global biogeochemical cycles, particularly the carbon and nitrogen cycles. Through photosynthesis, they fix atmospheric carbon dioxide into organic matter, contributing to carbon sequestration and climate regulation. Simultaneously, their nitrogen-fixing ability supports ecosystem productivity by converting inert atmospheric nitrogen into biologically usable forms (Berman-Frank *et al.,* 2003). Furthermore, cyanobacteria are involved in the cycling of other essential elements such as phosphorus and sulfur, thereby maintaining ecological balance and system stability. Despite their ecological significance, cyanobacteria can also have detrimental effects under certain environmental conditions. Nutrient enrichment, particularly due to anthropogenic activities such as agricultural runoff and industrial discharge, can lead to the excessive growth of cyanobacteria, resulting in harmful algal blooms (HABs). These blooms often produce cyanotoxins that pose serious risks to aquatic ecosystems, drinking water quality, and public health (Paerl & Otten, 2013). In recent years, increasing attention has been given to the role of cyanobacteria in global climate regulation and sustainable development. Their involvement in carbon sequestration, nitrogen enrichment, and nutrient recycling highlights their importance in mitigating climate change and maintaining ecosystem resilience. Additionally, cyanobacteria have gained prominence in biotechnological applications, including biofertilizers, biofuel production, wastewater treatment, and the synthesis of bioactive compounds (Singh *et al.,* 2016).

This review aims to provide a comprehensive understanding of the contribution of cyanobacteria to global biogeochemical cycles. It focuses on their ecological roles, physiological mechanisms, and environmental implications, while also addressing the challenges associated with their uncontrolled proliferation.

2. Role of Cyanobacteria in the Carbon Cycle

Cyanobacteria play a pivotal role in the global carbon cycle by mediating the transformation of inorganic carbon into organic matter through the process of oxygenic photosynthesis. As primary producers, they contribute significantly to global carbon fixation, particularly in marine ecosystems where they account for a substantial fraction of total primary productivity (Falkowski *et al.,* 2008).

2.1 Carbon Fixation Mechanism

Cyanobacteria utilize atmospheric or dissolved carbon dioxide (CO_2) and convert it into organic compounds using light energy. This process occurs via the Calvin–Benson cycle, where the enzyme RuBisCO catalyzes the fixation of CO_2 into ribulose-1,5-bisphosphate, ultimately forming glucose and other carbohydrates (Raven & Beardall, 2016). In aquatic environments, CO_2 is often present in the form of bicarbonate (HCO_3^-). Cyanobacteria possess specialized carbon concentrating mechanisms (CCMs) that actively transport and accumulate inorganic carbon within the cell, enhancing photosynthetic efficiency even under low CO_2 conditions (Badger & Price, 2003).

2.2 Contribution to Marine Carbon Cycling

Marine cyanobacteria such as *Prochlorococcus* and *Synechococcus* are among the most abundant photosynthetic organisms in the oceans. They play a crucial role in the fixation of CO_2 and contribute significantly to the oceanic carbon pool (Partensky *et al.,* 1999). A portion of the fixed carbon is transferred through the food web, while another fraction sinks into deeper ocean layers via the biological carbon pump, effectively removing carbon from the atmosphere for long-term storage (Falkowski *et al.,* 2008).

2.3 Carbon Sequestration and Climate Regulation

Cyanobacteria contribute to carbon sequestration by converting atmospheric CO_2 into biomass and facilitating its deposition in sediments. This process reduces greenhouse gas concentrations and plays a vital role in climate regulation. Some cyanobacteria also form microbial mats and biofilms that trap and stabilize carbon in sediments, enhancing long-term carbon storage (Paerl & Paul, 2012).

2.4 Interaction with Other Carbon Cycle Processes

Cyanobacteria interact with other components of the carbon cycle through: Respiration, releasing CO_2 back into the environment. Decomposition, where microbial activity recycles organic carbon. Symbiotic associations, contributing to carbon exchange in ecosystems. These interactions ensure continuous carbon flow between the atmosphere, hydrosphere, and biosphere.

3. Role of Cyanobacteria in the Nitrogen Cycle

One of the most significant ecological contributions of cyanobacteria is their ability to fix atmospheric nitrogen (N_2) into biologically usable forms such as ammonia (NH_3). Atmospheric nitrogen, although abundant, is largely inert and unavailable to most living organisms. Cyanobacteria overcome this limitation through the enzyme nitrogenase, which catalyzes the conversion of nitrogen gas into ammonia under specialized physiological conditions (Berman-Frank *et al.,* 2003).

3.1 Mechanism of Nitrogen Fixation

Nitrogen fixation in cyanobacteria is an energy-intensive process that requires ATP and reducing power. The nitrogenase enzyme complex is highly sensitive to oxygen; therefore, cyanobacteria have evolved protective mechanisms to maintain an anaerobic environment for nitrogen fixation. In filamentous forms such as *Anabaena* and *Nostoc*, specialized thick-walled cells called heterocysts are formed. These cells lack oxygen-producing photosystem II activity and provide a micro-oxic environment necessary for nitrogenase function (Whitton & Potts, 2000). Within heterocysts, atmospheric nitrogen is reduced to ammonia, which is then assimilated into amino acids such as glutamine and transported to adjacent vegetative cells. In return, vegetative cells supply carbohydrates to heterocysts, maintaining a cooperative metabolic relationship.

3.2 Ecological and Agricultural Significance

Cyanobacterial nitrogen fixation plays a crucial role in enriching soil fertility and maintaining ecosystem productivity. In aquatic environments, nitrogen-fixing cyanobacteria contribute to nutrient availability, supporting phytoplankton growth and sustaining food webs. In terrestrial ecosystems, particularly in nutrient-poor soils, they enhance nitrogen content and improve soil structure. Cyanobacteria are extensively used as biofertilizers in agriculture, especially in rice (paddy) cultivation. Species such as *Anabaena* form symbiotic associations with aquatic ferns like *Azolla*, significantly increasing nitrogen availability in flooded fields. This reduces dependence on chemical fertilizers and promotes sustainable agricultural practices (Singh *et al.,* 2016).

3.3 Role in Aquatic Nitrogen Cycling

In freshwater and marine ecosystems, cyanobacteria regulate nitrogen availability through nitrogen fixation, assimilation, and recycling. They convert atmospheric nitrogen into forms that can be utilized by other organisms, thereby influencing primary productivity and nutrient dynamics. However, excessive nitrogen input from anthropogenic sources can disrupt this balance, leading to the proliferation of cyanobacterial blooms.

3.4 Interaction with Other Nitrogen Cycle Processes

Cyanobacteria interact with other components of the nitrogen cycle, including: Ammonification – conversion of organic nitrogen into ammonia. Nitrification – oxidation of ammonia into nitrites and nitrates by bacteria. Denitrification – conversion of nitrates back into atmospheric nitrogen. Through these interactions, cyanobacteria contribute to the continuous transformation and movement of nitrogen within ecosystems.

4. Role of Cyanobacteria in the Phosphorus Cycle

Phosphorus is an essential macronutrient required for fundamental biological processes, including energy transfer, nucleic acid synthesis, and membrane formation. Unlike nitrogen and carbon, phosphorus does not have a significant gaseous phase and is primarily cycled through terrestrial and aquatic ecosystems in the form of phosphate (PO_4^{3-}). Cyanobacteria play a vital role in regulating the availability, transformation, and recycling of phosphorus within these systems.

4.1 Phosphorus Uptake and Storage

Cyanobacteria efficiently absorb inorganic phosphate from their surroundings through active transport mechanisms. Under conditions of phosphorus abundance, they accumulate excess phosphate intracellularly in the form of **polyphosphate granules**, which serve as storage reserves. This ability allows cyanobacteria to survive in fluctuating nutrient conditions and maintain metabolic activities even when external phosphorus levels are low (Karl, 2014).

Polyphosphate storage also provides a competitive advantage, enabling cyanobacteria to outcompete other phytoplankton species in nutrient-limited environments.

4.2 Role in Phosphorus Recycling

Cyanobacteria contribute significantly to phosphorus recycling by assimilating phosphorus into biomass and subsequently releasing it back into the environment through excretion, cell lysis, and decomposition. During microbial decomposition, organic phosphorus compounds are mineralized into inorganic phosphate, which becomes available for uptake by other organisms. This continuous transformation between organic and inorganic forms ensures the maintenance of phosphorus availability in both aquatic and terrestrial ecosystems, supporting primary productivity and ecosystem stability (Karl, 2014).

4.3 Ecological Significance

In aquatic ecosystems, phosphorus often acts as a limiting nutrient, controlling the growth of primary producers. Cyanobacteria play a crucial role in maintaining phosphorus balance by regulating its uptake, storage, and release. Their ability to utilize both inorganic and certain organic phosphorus sources further enhances their ecological adaptability. In soil environments, cyanobacteria contribute to phosphorus mobilization and improve nutrient availability, thereby supporting plant growth and soil fertility.

4.4 Phosphorus Enrichment and Eutrophication

Excessive input of phosphorus into water bodies, primarily due to agricultural runoff, industrial discharge, and domestic sewage, can lead to nutrient enrichment or eutrophication. Under such conditions, cyanobacteria often dominate and form dense blooms due to their efficient phosphorus utilization and storage mechanisms.

These cyanobacterial blooms can have severe ecological consequences, including: Depletion of dissolved oxygen, Disruption of aquatic food webs, Production of harmful toxins (cyanotoxins), Deterioration of water quality. Such imbalances highlight the dual role of cyanobacteria as both essential nutrient cyclers and potential ecological disruptors (Smith & Schindler, 2009).

5. Role of Cyanobacteria in the Sulfur Cycle

Sulfur is an essential element involved in the synthesis of amino acids (e.g., cysteine and methionine), vitamins, and coenzymes. The sulfur cycle involves the transformation of sulfur between various oxidation states, primarily as sulfate (SO_4^{2-}), sulfide (S^{2-}), and organic sulfur compounds. Cyanobacteria contribute significantly to sulfur cycling through assimilation, transformation, and release of sulfur-containing compounds in both aquatic and terrestrial ecosystems.

5.1 Sulfate Assimilation

Cyanobacteria absorb sulfate (SO_4^{2-}) from their environment through active transport systems. Inside the cell, sulfate is reduced to sulfide via enzymatic reactions and subsequently incorporated into sulfur-containing amino acids such as cysteine and methionine. These compounds are essential for protein synthesis and cellular metabolism.

This assimilatory sulfate reduction pathway enables cyanobacteria to convert inorganic sulfur into biologically useful organic forms, thereby supporting growth and metabolic functions.

5.2 Role in Sulfur Transformation

Cyanobacteria participate in the transformation of sulfur compounds by: Incorporating sulfur into organic matter. Releasing sulphur during cellular metabolism and decomposition. Interacting with sulfur-oxidizing and sulfur-reducing bacteria. Through these processes, cyanobacteria contribute to the continuous cycling of sulfur between organic and inorganic pools, maintaining ecosystem balance.

5.3 Production of Dimethyl Sulfide (DMS) and Climate Regulation

Certain cyanobacterial species produce dimethyl sulfide **(DMS)** as a byproduct of the breakdown of dimethylsulfoniopropionate (DMSP). DMS is a volatile sulfur compound that is released into the atmosphere, where it plays a significant role in cloud formation.

In the atmosphere, DMS is oxidized to form sulfate aerosols, which act as cloud condensation nuclei. These nuclei enhance cloud formation and increase cloud albedo (reflectivity), thereby reducing the amount of solar radiation reaching the Earth's surface. This process contributes to climate regulation by exerting a cooling effect on the global climate system (Charlson *et al.,* 1987).

5.4 Ecological Significance

In aquatic ecosystems, cyanobacteria influence sulfur availability and transformation, particularly in stratified water bodies where oxygen levels vary. Their interaction with other microorganisms helps regulate sulfur cycling under both aerobic and anaerobic conditions.

In microbial mats and sediments, cyanobacteria often coexist with sulfur bacteria, forming complex communities that drive sulfur transformations and nutrient exchange.

6. Mechanisms Involved in Biogeochemical Cycling

Cyanobacteria regulate global biogeochemical cycles through a wide range of physiological and biochemical mechanisms that enable them to transform, assimilate, and recycle essential nutrients. Their metabolic versatility and adaptive strategies allow them to thrive in diverse and often extreme environments, thereby maintaining ecosystem stability and productivity (Whitton & Potts, 2000).

6.1 Oxygenic Photosynthesis

One of the primary mechanisms employed by cyanobacteria is oxygenic photosynthesis, a process in which light energy is utilized to convert carbon dioxide (CO_2) and water (H_2O) into organic compounds, with oxygen (O_2) released as a byproduct. This process occurs in specialized membrane structures called thylakoids and involves photosystems I and II. Cyanobacteria were the first organisms to perform oxygenic photosynthesis, significantly contributing to the oxygenation of Earth's atmosphere. This mechanism plays a central role in the carbon cycle by facilitating carbon fixation and supporting primary productivity in both aquatic and terrestrial ecosystems (Falkowski & Raven, 2007).

6.2 Nitrogen Fixation (Nitrogenase Enzyme)

Cyanobacteria possess the unique ability to fix atmospheric nitrogen into ammonia through the enzyme nitrogenase. This process is energy-intensive and highly sensitive to oxygen, requiring protective adaptations such as temporal separation (day/night cycles) or spatial separation within specialized cells called heterocysts. Nitrogen fixation enhances the availability of bioavailable nitrogen in ecosystems, thereby supporting plant growth and contributing to soil fertility. This mechanism is particularly important in nitrogen-limited environments, such as paddy fields and oligotrophic waters (Berman-Frank *et al.,* 2003).

6.3 Nutrient Uptake and Recycling

Cyanobacteria efficiently absorb essential nutrients such as carbon, nitrogen, phosphorus, and sulfur from their surroundings through active transport systems. They possess specialized mechanisms, including carbon concentrating mechanisms (CCMs) and phosphate uptake systems, which allow them to survive under nutrient-limited conditions. In addition to uptake, cyanobacteria play a crucial role in nutrient recycling. Through processes such as excretion, cell lysis, and decomposition, they release nutrients back into the environment, making them available for other organisms. This continuous recycling is essential for maintaining nutrient balance and ecosystem functioning (Karl, 2014).

6.4 Formation of Specialized Cells

Cyanobacteria exhibit cellular differentiation, forming specialized structures that enhance their survival and functional efficiency. Heterocysts: Thick-walled cells specialized for nitrogen fixation, providing an anaerobic environment for nitrogenase activity. Akinetes: Dormant, resistant cells that help cyanobacteria survive unfavorable environmental conditions such as desiccation, extreme temperatures, or nutrient scarcity. Gas vacuoles: Structures that regulate buoyancy, allowing cyanobacteria to position themselves optimally in the water column for light and nutrient availability. These adaptations enable cyanobacteria to persist in fluctuating environments and maintain their role in biogeochemical cycling.

6.5 Adaptive Strategies in Extreme Environments

Cyanobacteria are known for their remarkable ability to survive in extreme habitats, including high salinity, temperature extremes, and low nutrient conditions. They achieve this through physiological plasticity, efficient metabolic regulation, and protective pigments such as carotenoids and phycobiliproteins. Such adaptability ensures their continuous participation in global nutrient cycles, even under environmental stress conditions.

7. Environmental Impacts and Harmful Algal Blooms (HABs)

Under favorable environmental conditions, particularly in nutrient-rich (eutrophic) waters, cyanobacteria can proliferate rapidly and form dense accumulations known as harmful algal blooms (HABs). These blooms often appear as green, blue-green, or reddish surface scums in freshwater and marine systems, significantly altering water quality and ecosystem dynamics (Paerl & Paul, 2012).

7.1 Formation of Harmful Algal Blooms

Cyanobacterial blooms are primarily driven by **nutrient enrichment**, especially excessive inputs of nitrogen and phosphorus from agricultural runoff, industrial discharge, and domestic sewage. These nutrients promote rapid cyanobacterial growth due to their efficient nutrient uptake and storage capabilities.

Additional environmental factors contributing to bloom formation include: Elevated temperatures, High light intensity, Stable water columns (low turbulence), and Reduced grazing pressure. Climate change, particularly global warming, further enhances bloom frequency and intensity by creating favorable growth conditions for cyanobacteria.

7.2 Cyanotoxins and Their Effects

Many bloom-forming cyanobacteria produce toxic secondary metabolites known as cyanotoxins. These toxins pose serious risks to aquatic ecosystems, livestock, wildlife, and human health. Major types of cyanotoxins include:

Microcystins – hepatotoxins affecting liver function. Anatoxins – neurotoxins causing nervous system damage. Cylindrospermopsin – cytotoxins affecting multiple organs. Exposure to these toxins can occur through contaminated drinking water, recreational activities, or consumption of affected aquatic organisms.

7.3 Ecological Impacts

HABs have profound effects on aquatic ecosystems, including: Oxygen depletion (hypoxia) due to decomposition of dense biomass, Fish kills and loss of biodiversity, Disruption of aquatic food webs, Reduction in water transparency**,** affecting submerged vegetation. The dominance of cyanobacteria can outcompete other phytoplankton species, leading to reduced ecological diversity and altered ecosystem functioning.

7.4 Impacts on Human Health and Economy

Cyanobacterial blooms negatively affect water quality, making it unsuitable for drinking, irrigation, and recreational use. Contaminated water sources require advanced treatment processes, increasing economic costs. Human health impacts include: Skin irritation and allergies, Gastrointestinal disorders, Liver and neurological damage (in severe cases), Additionally, HABs can affect fisheries, tourism, and local livelihoods, leading to significant economic losses.

7.5 Influence of Climate Change

Climate change is a major factor intensifying the occurrence and persistence of HABs. Rising global temperatures favor cyanobacterial growth due to their high thermal tolerance. Increased atmospheric CO_2 levels and altered precipitation patterns further contribute to nutrient loading and bloom formation.

The combined effects of climate change and anthropogenic nutrient inputs are expected to increase the frequency, duration, and geographic distribution of cyanobacterial blooms in the future (Paerl & Paul, 2012).

7.6 Management and Mitigation Strategies

Effective management of HABs requires an integrated approach, including:Reduction of nutrient inputs (nitrogen and phosphorus control), Improved wastewater treatment, Monitoring and early detection systems, Biological and chemical control methods. Sustainable management practices are essential to minimize the environmental and health impacts of cyanobacterial blooms.

8. Results and Discussion

Cyanobacteria play a central role in maintaining global biogeochemical balance through their active participation in multiple nutrient cycles, including carbon, nitrogen, phosphorus, and sulfur. Their ability to perform oxygenic photosynthesis enables efficient carbon fixation, thereby contributing significantly to primary productivity and carbon sequestration in both aquatic and terrestrial ecosystems (Falkowski *et al.,* 2008). In marine environments, picocyanobacteria such as *Prochlorococcus* and *Synechococcus* dominate primary production, highlighting their global ecological significance (Partensky *et al.,* 1999). In addition to carbon cycling, cyanobacteria contribute extensively to nitrogen enrichment through biological nitrogen fixation. This process enhances nutrient availability in nitrogen-limited environments, supporting plant growth and sustaining food webs. The formation of specialized cells such as heterocysts further optimizes nitrogen fixation under aerobic conditions, demonstrating their advanced physiological adaptations (Berman-Frank *et al.,* 2003). Cyanobacteria also regulate phosphorus and sulfur cycling through efficient uptake, storage, and transformation mechanisms. Their ability to accumulate phosphorus as polyphosphate granules and release sulfur-containing compounds ensures continuous nutrient recycling and ecosystem stability (Karl, 2014). These processes collectively highlight their role as key mediators of nutrient fluxes across ecosystems. However, the ecological benefits of cyanobacteria are counterbalanced by their potential to form harmful algal blooms under nutrient-rich conditions. Anthropogenic activities such as agricultural runoff, industrial discharge, and urbanization have significantly increased nutrient loading in water bodies, promoting bloom formation. These blooms produce cyanotoxins that adversely affect aquatic biodiversity, water quality, and human health (Paerl & Paul, 2012). Climate change further exacerbates these challenges by creating favorable conditions for cyanobacterial proliferation. Rising temperatures, increased atmospheric CO_2 levels, and altered hydrological cycles contribute to the frequency and intensity of blooms. This underscores the urgent need for sustainable management strategies that address both nutrient pollution and climate-related factors. Despite these challenges, recent research highlights the immense biotechnological potential of cyanobacteria. They are increasingly explored for applications in biofuel production, carbon capture, wastewater treatment, and the synthesis of valuable bioactive compounds. Their rapid growth rate, metabolic versatility, and ability to utilize renewable resources make them promising candidates for sustainable technologies (Singh *et al.,* 2016).

Integrating ecological understanding with technological innovation is essential to harness the benefits of cyanobacteria while minimizing their adverse impacts. Effective management approaches should include nutrient control, continuous monitoring, and the development of eco-friendly biotechnological solutions.

9. Conclusion

Cyanobacteria are fundamental drivers of global biogeochemical cycles, playing a crucial role in carbon sequestration, nitrogen fixation, and the recycling of essential nutrients such as phosphorus and sulfur. Their metabolic versatility and adaptability enable them to thrive across diverse ecosystems, where they significantly contribute to primary productivity, ecosystem stability, and climate regulation. As primary producers, they form the foundation of many aquatic food webs and enhance soil fertility in terrestrial environments. Despite these ecological benefits, cyanobacteria also exhibit a dual nature, as their excessive proliferation under nutrient-rich (eutrophic) conditions leads to harmful algal blooms that adversely impact water quality, biodiversity, and public health. The increasing influence of anthropogenic activities and climate change further intensifies these challenges, necessitating effective monitoring and management strategies. Future research should focus on advancing our understanding of cyanobacterial ecology, improving bloom prediction and control measures, and exploring their potential in sustainable applications such as biofertilizers, biofuels, carbon capture, and wastewater treatment. Integrating ecological knowledge with innovative biotechnological approaches will be essential to harness the beneficial aspects of cyanobacteria while mitigating their environmental risks, thereby ensuring long-term ecological balance and sustainability.

References

1. Badger, M. R., & Price, G. D. (2003). CO_2 concentrating mechanisms in cyanobacteria: Molecular components, their diversity and evolution. *Journal of Experimental Botany, 54*(383), 609–622.
2. Berman-Frank, I., Lundgren, P., & Falkowski, P. G. (2003). Nitrogen fixation and photosynthetic oxygen evolution in cyanobacteria. *Research in Microbiology, 154*(3), 157–164.
3. Charlson, R. J., Lovelock, J. E., Andreae, M. O., & Warren, S. G. (1987). Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. *Nature, 326*(6114), 655–661.
4. Falkowski, P. G., & Raven, J. A. (2007). *Aquatic photosynthesis* (2nd ed.). Princeton University Press.
5. Falkowski, P. G., Barber, R. T., & Smetacek, V. (2008). Biogeochemical controls and feedbacks on ocean primary production. *Science, 281*(5374), 200–206.
6. Karl, D. M. (2014). Microbially mediated transformations of phosphorus in the sea: New views of an old cycle. *Annual Review of Marine Science, 6*, 279–337.
7. Paerl, H. W., & Paul, V. J. (2012). Climate change: Links to global expansion of harmful

cyanobacteria. *Water Research, 46*(5), 1349–1363.

8. Paerl, H. W., & Otten, T. G. (2013). Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microbial Ecology, 65*(4), 995–1010.
9. Partensky, F., Hess, W. R., & Vaulot, D. (1999). Prochlorococcus, a marine photosynthetic prokaryote of global significance. *Microbiology and Molecular Biology Reviews, 63*(1), 106–127.
10. Raven, J. A., & Beardall, J. (2016). The ins and outs of CO_2. *Journal of Experimental Botany, 67*(1), 1–13.
11. Schopf, J. W. (2000). The fossil record: Tracing the roots of the cyanobacterial lineage. *Philosophical Transactions of the Royal Society B: Biological Sciences, 355*(1401), 167–177.
12. Singh, J. S., Kumar, A., Rai, A. N., & Singh, D. P. (2016). Cyanobacteria: A precious bio-resource in agriculture, ecosystem, and environmental sustainability. *Frontiers in Microbiology, 7*, 529.
13. Smith, V. H., & Schindler, D. W. (2009). Eutrophication science: Where do we go from here? *Trends in Ecology & Evolution, 24*(4), 201–207.
14. Whitton, B. A., & Potts, M. (2000). *The ecology of cyanobacteria: Their diversity in time and space*. Kluwer Academic Publishers.