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Decoding the Agricultural Potential of Cyanobacterial Diversity in Lentic Water Bodies: An Integrated Ecological and Sustainable Farming Perspective

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ABSTRACT

Cyanobacteria are ecologically versatile oxygenic photosynthetic microorganisms distributed across freshwater, marine and terrestrial environments. Lentic ecosystems such as ponds, lakes, reservoirs and wetlands provide diverse ecological niches for cyanobacterial communities and represent important reservoirs of biological diversity. Beyond their ecological functions, selected cyanobacteria possess characteristics of considerable agricultural importance, particularly biological nitrogen fixation, nutrient mobilization, production of bioactive compounds and potential plant-growth-promoting activities. The present review synthesizes published literature on cyanobacterial diversity in lentic freshwater environments and evaluates its potential contribution to sustainable agriculture. Particular emphasis is placed on ecological functions, nitrogen fixation, biofertilizer potential, plant-growth promotion, nutrient cycling and possible contributions to climate-resilient agricultural systems. The literature indicates that nitrogen-fixing cyanobacteria can contribute to soil fertility and may complement conventional nutrient-management practices. Cyanobacterial biomass and metabolites have also been investigated as biofertilizers and biostimulants capable of supporting plant growth and improving nutrient-use efficiency. However, agricultural utilization requires careful strain selection because freshwater cyanobacterial communities also contain bloom-forming and potentially toxin-producing taxa. Major limitations include strain identification, cultivation cost, formulation stability, variable field performance, biosafety and regulatory requirements. Future research should therefore integrate ecological surveys, molecular identification, functional screening, biosafety assessment and field validation. The integration of indigenous cyanobacterial resources with sustainable nutrient-management strategies could provide a promising pathway toward environmentally responsible and climate-resilient agriculture.

Keywords: Cyanobacteria; Blue-green algae; Lentic ecosystems; Biofertilizer; Nitrogen fixation; Sustainable agriculture; Plant growth promotion; Freshwater ecology.

INTRODUCTION

The oxygenic photosynthetic prokaryotes known as cyanobacteria exhibit tremendous metabolic and ecological diversity. They can play significant roles in aquatic and terrestrial ecosystems because of their capacity to carry out photosynthesis, use inorganic nutrients, and, in some genera, fix atmospheric nitrogen. Cyanobacteria support primary productivity and nutrient cycling in freshwater settings. They may also have an impact on the biological makeup and functionality of aquatic communities. Their physiological adaptability has garnered significant interest in agricultural biotechnology as well.

Ponds, lakes, reservoirs, and wetlands are examples of lentic freshwater systems that offer favorable conditions for a variety of cyanobacterial communities. Environmental factors that affect cyanobacterial growth and community composition include temperature, light, nutrition availability, water-column stability, and hydrological features. However, some cyanobacterial populations can grow rapidly and produce toxic blooms in nutrient-enriched environments. According to recent global estimates, there has been a surge in hazardous algal blooms in inland waters, and the dynamics of these blooms are significantly influenced by nutrient pollution, wastewater discharge, agricultural development, and climate change (Feng et al., 2024).

Biological nitrogen fixation is closely linked to cyanobacteria's significance in agriculture. Thru nitrogenase-mediated mechanisms, certain cyanobacteria can transform atmospheric nitrogen into nitrogen that is physiologically accessible. Because of this feature, nitrogen-fixing cyanobacteria are a great option for sustainable nutrient management and biological fertilization. Their potential to increase crop yield and soil fertility while lowering reliance on artificial nitrogen fertilizers was noted in a recent review (Nawaz et al., 2024).

Beyond nitrogen fixation, cyanobacteria have agricultural potential. Nutrients and physiologically active substances can be found in cyanobacterial biomass, and some cyanobacterial systems have the ability to affect plant growth responses and nutrient mobilization. The potential of microalgae and cyanobacteria as biofertilizers and biostimulants is described in reviews, along with applications pertaining to plant development, nutrient utilization, and stress (Parmar et al., 2023); Sun et al.,

However, cyanobacteria are not always advantageous. The taxa that make up freshwater cyanobacterial communities differ greatly in their ecological traits. Some can create poisons and form dense blooms, endangering aquatic ecosystems and water quality. As a result, precise identification, functional screening, and suitable biosafety evaluation are necessary for the agricultural use of cyanobacterial resources (Feng et al.,2024).

Therefore, cyanobacteria are examined in this review from an integrated ecological and agricultural perspective. It focuses on their variety in lentic freshwater environments, interactions with the environment, capacity to fix nitrogen, potential as a biofertilizer, characteristics that encourage plant growth, and opportunities for sustainable agriculture. In order to convert naturally available cyanobacterial variety into secure and useful agricultural resources, it also identifies key obstacles and research objectives. (Sun et al., 2026) for the potential of biofertilizer and biostimulant.

REVIEW OF LITERATURE

Cyanobacterial diversity and freshwater ecology

Cyanobacteria have a great deal of physiological and morphological diversity and can be found in a variety of aquatic habitats. Unicellular, colonial, and filamentous forms, including he terocystous species that are able to fix nitrogen biologically, can be found in freshwater communities. The water body's physical, chemical, and biological factors all affect their dispersal.

Because of their comparatively long water-retention periods, which enable the accumulation of nutrients and biological material, lentic ecosystems are especially significant. Therefore, significant phytoplankton communities can be supported in ponds, lakes, and reservoirs. Environmental enrichment, however, can favor cyanobacteria that form blooms and change the organization of communities.

As a result, both the quantity and functional traits of cyanobacteria determine their ecological value. While bloom-forming taxa can cause ecological and water-quality issues when they proliferate excessively, at moderate levels they aid in primary production and nutrient cycling.

The literature on freshwater hazardous blooms and cyanobacterial ecological reviews serve as the main sources for the ecological interpretation.

Environmental factors controlling cyanobacterial communities

Communities of cyanobacteria react to a variety of interrelated environmental factors. The availability of nutrients, especially phosphorus and nitrogen, has a significant impact on phytoplankton productivity. Phytoplankton growth and competitive interactions can also be impacted by temperature and water-column stability.

In freshwater systems, nutrient loading may be increased by agricultural runoff and wastewater discharge. This

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enrichment may raise the likelihood of cyanobacterial bloom growth under favorable hydrological and climatic circumstances. Feng et al. (2024) identified nutrient pollution associated with urbanization, wastewater discharge and agricultural expansion as important drivers of harmful algal blooms in inland waters, while climate warming can further modify bloom dynamics.

Therefore, taxonomic observations and physicochemical measures should preferably be combined in environmental assessment of lentic cyanobacteria. Contextual information for evaluating cyanobacterial

distribution can be obtained from parameters like temperature, pH, dissolved oxygen, electrical conductivity, total dissolved solids, and nutrient concentrations.

Cyanobacteria and biological nitrogen fixation

One of the most significant functional traits of some cyanobacteria is biological nitrogen fixing. Nitrogenase systems found in nitrogen-fixing cyanobacteria allow atmospheric nitrogen to be transformed into forms that are beneficial to biology. Nitrogen fixation is supported by specialized cells in heterocystous cyanobacteria. This method has agricultural significance since it can be used to augment soil nitrogen thru biological processes. Nawaz et al. (2024) reviewed nitrogen-fixing cyanobacteria as a biological resource for sustainable soil fertility and enhanced crop productivity. Their review emphasizes the potential contribution of cyanobacterial nitrogen fixation to reducing dependence on synthetic nitrogen inputs.

Historically, cyanobacteria have been particularly associated with flooded rice cultivation. Their nitrogen-fixing capacity and ability to grow photosynthetically make them attractive candidates for low-input agricultural systems. Source mapping: Nawaz et al. (2024) and the broader cyanobacterial biofertilizer literature.

Cyanobacteria as biofertilizers

Biofertilizers are biological inputs that contribute to nutrient availability or plant growth. Cyanobacteria are promising candidates because they combine photosynthetic biomass production with nitrogen fixation and other biological functions. A review published in Advances in Cyanobacterial Biology described cyanobacteria as potential biofertilizer resources, particularly because of their nitrogen-fixing ability and adaptation to different environmental stresses. More recent literature has expanded this concept by examining cyanobacteria as components of sustainable agricultural systems. Nawaz et al. (2024) reported that nitrogen-fixing cyanobacteria can contribute to soil quality and crop productivity. However, cyanobacterial biofertilizers should preferably be regarded as components of integrated nutrient management rather than automatically as complete replacements for synthetic fertilizers.

Plant-growth-promoting potential

Cyanobacterial agricultural effects may extend beyond nitrogen fixation. Cyanobacteria and associated microbial communities can produce or influence biologically active substances that affect plant development. Microalgal and cyanobacterial preparations have been investigated for effects on plant growth, nutrient acquisition and tolerance to environmental stress.

Parmar et al. (2023) reviewed microalgal applications as plant-growth additives and discussed their potential roles in plant growth promotion and stress responses. Similarly, recent work has emphasized the broader potential of cyanobacteria in plant growth promotion, nutrient utilization and stress alleviation (2024). These findings suggest that cyanobacterial applications may involve multiple mechanisms rather than a single fertilizer effect.

Cyanobacteria and sustainable agriculture

The concept of sustainable agriculture requires simultaneous consideration of productivity, resource efficiency and environmental protection By providing biologically fixed nitrogen, generating biomass, and promoting nutrient cycling, cyanobacteria may help achieve this goal.

According to the research, agricultural innovations based on cyanobacteria may enhance traditional nutrient-management strategies. Their potential is especially important in situations where overuse of fertilizers contributes to environmental deterioration. A 2024 assessment of cyanobacteria-based biofertilizers highlighted practical implementation issues while identifying applications relating to biocontrol, cleanup, and plant growth enhancement.

Materials and Methodology

Study design

Since this work is a review, no new field or lab experiment was carried out in order to prepare the study. Thus, the main source of evidence was published scientific literature.

Four main themes guided the creation of the review:

1. The variety and ecology of cyanobacteria in freshwater and lentic environments.
2. Cyanobacterial communities are influenced by environmental conditions.
3. Agricultural processes, such as biofertilization and nitrogen fixation.
4. Obstacles and opportunities for sustainable agricultural use in the future.

Literature identification

Scientific literature was identified using searches focused on combinations of the following concepts:

- cyanobacteria
- freshwater cyanobacteria
- lentic ecosystems
- cyanobacterial diversity
- nitrogen-fixing cyanobacteria
- cyanobacterial biofertilizers
- plant growth promotion
- sustainable agriculture
- cyanobacterial blooms
- cyanobacteria and climate change

Priority was given to peer-reviewed literature and recent reviews, while established earlier literature was considered where necessary to provide scientific background.

Literature selection

Literature was considered relevant when it addressed one or more of the following:

- cyanobacterial ecology;
- freshwater or inland-water systems;

- biological nitrogen fixation;
- agricultural applications;
- biofertilizer or biostimulant activity;
- plant-growth promotion;
- environmental risks;
- commercialization and formulation.

Studies that did not contribute directly to the ecological or agricultural objectives of the review were not emphasized.

Data synthesis

The selected literature was analyzed qualitatively. Findings were grouped into ecological, physiological, agricultural and technological themes. Evidence concerning agricultural potential was compared with evidence concerning ecological risks so that cyanobacteria were not treated as universally beneficial organisms.

Because this was a literature-based review, no fabricated numerical field observations, physicochemical measurements, cyanobacterial counts or crop-yield values were generated.

RESULTS

Overall findings of the literature synthesis

The literature synthesis indicates that cyanobacteria have a dual significance. From an ecological perspective, they play a significant role in the primary production of freshwater and the cycling of nutrients. Certain nitrogen-fixing taxa have traits that can help with biological nutrient control in agriculture.

Biological nitrogen fixation is the most powerful and frequently discussed agricultural function. According to recent evaluations, cyanobacteria that fix nitrogen are a viable resource for increasing agricultural yield and soil fertility. The wider potential of cyanobacterial biomass as a biofertilizer and biostimulant is a second important discovery.

Potential effects on plant growth, nutrient usage, and stress tolerance are described in published literature. A third conclusion is that biosafety and environmental factors are crucial. Both potentially beneficial agricultural species and those linked to detrimental blooms are found in the same large cyanobacterial group.

Functional groups of agricultural importance.

Functional characteristic	Agricultural significance
Nitrogen fixation	contribution to nitrogen availability
Photosynthetic biomass production	Generation of organic biomass
Nutrient cycling	Potential improvement of nutrient availability
Plant-growth promotion	Possible stimulation of plant development
Stress tolerance	Potential contribution to crop stress management

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Soil conditioning	Possible effects following biomass incorporation
Microbial interaction	Potential influence on beneficial rhizosphere organisms

Table 1. Major cyanobacterial functional characteristics relevant to agriculture.

Environmental factors and agricultural relevance.

The review indicates that cyanobacterial distribution in lentic ecosystems is strongly linked to environmental conditions. Nutrient enrichment is particularly important because excessive nutrient loading can promote cyanobacterial blooms.

This has two implications. First, environmental monitoring can help identify cyanobacterial resources and understand their ecological distribution. Second, agricultural use of cyanobacteria requires careful differentiation between beneficial strains and bloom-forming or toxin-producing populations Feng et al. (2024).

Evidence for crop-related applications.

Published literature supports investigation of cyanobacteria as biological fertilizer and plant-growth-promoting resources. Experimental and review literature has reported potential benefits in nutrient management, crop productivity and stress alleviation.

For example, recent research on nitrogen-fixing cyanobacteria associated with cotton cultivation included isolation and genetic characterization of native strains and evaluation of plant-growth-promoting activities, demonstrating the transition from ecological resource identification toward agricultural testing.

This type of research provides a useful model for future regional studies: native cyanobacteria should first be isolated and identified, followed by functional screening and controlled crop experiments.

DISCUSSION.

Ecological diversity as an agricultural resource.

In addition to being habitats, freshwater lentic ecosystems can be thot of as possible repositories of microbes with practical functional traits. These systems' diversity of cyanobacteria makes it possible to find strains that have adapted to the local environment.

But biodiversity by itself does not prove agricultural value. Before a strain is taken into consideration for agricultural development, it must have both acceptable biosafety traits and observable functional capabilities. Therefore, ecological surveys and functional characterization should be linked in future regional investigations.

Native cyanobacteria and local adaptation

Ecological modifications that are beneficial in the local environment may be present in native strains. Because of this, local cyanobacterial resources are especially intriguing for studies on biofertilizers. Thus, a helpful research pipeline might be:

Lentic water body → separation of cyanobacteria → morphological identification → molecular identification

→ functional screening → biosafety screening → pot experiment → field validation. Compared to merely reporting the presence of cyanobacterial genera, such an approach would yield greater proof.

From laboratory potential to field application

The discrepancy between laboratory performance and field-scale use is one of the main drawbacks noted in the literature. In controlled environments, a strain may exhibit nitrogen fixation or plant-growth-promoting activities, but in unpredictable field circumstances, it may behave otherwise.

Commercial viability is additionally influenced by production costs, biomass collection, storage, formulation, application technique, and environmental compatibility. Large-scale cultivation and formulation continue to be significant obstacles for algal and cyanobacterial agricultural technology, according to recent evaluations. Therefore, rather than depending just on laboratory findings, future research should incorporate multi-location field experiments and economic evaluations.

Biosafety and harmful cyanobacteria

Both the ecological concerns and the agricultural possibilities of cyanobacteria must be taken into account. Toxins produced by harmful cyanobacterial blooms can have an impact on aquatic ecosystems and water quality. According to global evaluations, detrimental bloom dynamics in inland waters are significantly influenced by nutrient enrichment and climate-related changes.

Thus, the following should be included in the development of cyanobacterial biofertilizers: taxonomic classification.

Molecular characterization

• looking for characteristics linked to toxins when appropriate;

• evaluation of environmental durability;

• testing for crop-specific effectiveness;

• Non-target impacts are assessed.

Challenges and Future Perspectives

Several challenges must be addressed before cyanobacterial biofertilizers can achieve widespread agricultural adoption.

Challenge	**Future research direction**
Future research direction	Strain identification Morphological + molecular characterization
Variable field performance	Multi-location field trials
Production cost	Low-cost cultivation systems
Storage stability	Improved formulations
Biosafety	Toxin and genomic screening
Regulatory requirements	Standardized quality criteria
Farmer adoption	Demonstration and economic analysis
Environmental variability	Region-specific strain selection

Table 2. Challenges and future research priorities.

Cultivation cost, scalability, formulation, and field consistency are frequently cited in published evaluations as significant obstacles to commercialization.

Future research framework

Future investigations should combine:

Ecological survey

↓

Isolation of indigenous cyanobacteria

↓

Morphological and molecular identification

↓

Nitrogen-fixation assessment

↓

Plant-growth-promoting screening

↓ Biosafety evaluation

↓

Pot experiments

↓ Field trials

↓

Biofertilizer formulation

↓

Economic and environmental assessment

Research on freshwater biodiversity and agricultural biotechnology can be connected thru this integrated strategy.

CONCLUSION

A biological resource of scientific significance that connects sustainable agriculture and freshwater ecology is cyanobacteria. Ponds, lakes, and reservoirs are examples of lentic ecosystems that provide as habitats for a variety of cyanobacterial communities. The distribution and abundance of these communities are significantly influenced by environmental factors.

The research shows that certain cyanobacteria have significant agricultural potential, especially when it comes to biological nitrogen fixation, nutrient cycling, plant growth stimulation, and the production of biofertilizers. Opportunities for incorporating cyanobacterial resources into climate-resilient agriculture and sustainable nutrient-management systems are also suggested by recent research.

However, rather than relying just on cyanobacterial abundance, agricultural usage must be based on strains that have been scientifically confirmed. Future research must include taxonomic correctness, functional characterisation, biosafety screening, formulation development, field validation, and economic viability. Therefore, an integrated method that first characterizes the ecological and molecular diversity of lentic-water cyanobacteria, followed by functional screening and agricultural validation, is the most promising approach. By minimizing ecological and biosafety hazards, this method could assist in identifying native cyanobacterial strains with true biofertilizer potential.

All things considered, the combination of sustainable agronomy, microbial biotechnology, and

cyanobacterial ecology presents a viable path toward the creation of ecologically friendly agricultural inputs. Research on the diversity of native cyanobacteria may help create more sustainable agricultural systems, less reliance on synthetic fertilizers, and better nutrient-use efficiency.

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