Exploring the Significant Function of Nitrogen - Fixing Cyanobacteria in Rice Crop Improvement

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Abstract: ***The primary focus of this research is to analyse the significant part that nitrogen - fixing cyanobacteria play in boosting the development and production of rice crops. When it comes to agricultural soils, nitrogen, which is a necessary component for plant development, is frequently a factor that is restricting. To alleviate nitrogen deficits in rice fields, cyanobacteria, which are well - known for their exceptional capacity to fix nitrogen in the atmosphere, provide a solution that is both sustainable and environmentally beneficial. Unraveling the complex mechanisms that nitrogen - fixing cyanobacteria employ to contribute to the development of rice crops is the primary objective of this research. The study investigates the symbiotic interaction that exists between cyanobacteria and rice plants using a series of controlled experiments as well as field trials. In the process of colonizing the rhizosphere, cyanobacteria develop a mutually advantageous partnership with rice plants by supplying them with bioavailable nitrogen in return for root exudates generated by the rice plants. In addition, the research investigates the influence that this nitrogen - fixing capability has on the physiological and biochemical characteristics of rice plants. The improvement of nitrogen content, chlorophyll production, and general plant development are all topics that are investigated in this study. The findings provide light on the potential of cyanobacteria as a natural and sustainable supply of nitrogen, therefore lowering the reliance on synthetic fertilizers and minimizing the environmental consequences that relate to nitrogen runoff. Acquiring knowledge of nitrogen - fixing cyanobacteria and making use of their advantages is becoming increasingly important as worries about food security and sustainable agriculture become more widespread across the world. The insights that were gathered from this research led to the development of environmentally friendly agricultural techniques that increase rice crop yields while simultaneously promoting environmental sustainability. The research highlights the relevance of using the intrinsic biological nitrogen - fixing capabilities of cyanobacteria as a viable technique for the development of rice crops in a sustainable manner.***

Keywords: Nitrogen - fixing Cyanobacteria, Rice Crop Improvement, Symbiotic Relationship Rhizosphere, Bioavailable Nitrogen, Sustainable Agriculture, Eco - friendly Nitrogen Source and Plant Physiology.

1. Introduction

Importance of Nitrogen - Fixing Cyanobacteria in Rice Crop Improvement

Background

Rice is a crucial global food crop, feeding a significant portion of the world’s population. In China, rice is a staple for 65% of the population, and rice fields constitute 26% of the country's cultivated land (Zhao et al., 2009). Red soil, a prevalent soil type in China, presents challenges for agriculture due to its high acidity, low organic carbon (OC), and nutrient deficiencies. To address these challenges and meet food demands, farmers have historically relied on excessive chemical nitrogen (N) fertilizers, which exceed crop requirements and lead to significant N losses through various pathways, including ammonia (NH3) volatilization (Deng et al., 2014). This inefficiency not only reduces nitrogen use efficiency (NUE) but also results in environmental issues such as soil acidification, eutrophication, and air pollution (Behera et al., 2013; Ti et al., 2019).

1.1 Problem with Chemical Nitrogen Fertilizers

Excessive use of chemical N fertilizers in paddy soils leads to increased NH3 volatilization, which is the primary pathway of N loss, accounting for 9–40% of applied N (Liu et al., 2015). The rapid release of these fertilizers results in a high concentration of ammonium - N (NH4+ - N), exacerbating NH3 volatilization (Wang et al., 2018). The volatilized NH3 not only contributes to atmospheric pollution but also returns to land, causing further soil acidification and water eutrophication (Ti et al., 2019).

1.2 Potential of Green Manure and NFC Biofertilizers

Green manure, rich in organic N, offers a slower release of nutrients, reducing dependence on chemical fertilizers (Esperschutz et al., 2007). Nitrogen - fixing cyanobacteria (NFC) biofertilizers have demonstrated effectiveness in enhancing grain yields and improving soil properties (Vaishampayan et al., 2001; Song et al., 2021). Studies have shown that rice fields inoculated with NFC can see yield increases of 25–34.6%, with an average of 45 kg N ha−1 saved by reducing chemical N fertilizer inputs (Prasanna et al., 2015; Kollah et al., 2016). Additionally, NFC application has been beneficial in other crops, such as chickpeas, increasing yields by 50% and enhancing soil N fixation capacity and available N (Bidyarani et al., 2016).

NFC biofertilizers not only act as green manure in paddy fields but also improve soil health by secreting extracellular polysaccharides and growth - promoting hormones, enhancing soil carbon - sequestering microorganisms, and increasing soil organic carbon (SOC) and total nitrogen (TN) (Dron et al., 2012; Hashtroudi et al., 2012; Wang et al., 2015; Leong et al., 2021). In red paddy fields, increased SOC is crucial for stabilizing soil physical and chemical properties and promoting nutrient cycling.

1.3 Strategies to Mitigate NH3 Volatilization

Various strategies, including the use of urease inhibitors, biochar addition, deep plowing, and optimized water and

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fertilizer management, have been employed to mitigate NH3 volatilization (Wang et al., 2017; Zhang et al., 2017; He et al., 2019; Sun et al., 2019; Liu et al., 2020). While these methods have reduced NH3 losses and improved NUE, they often do not reduce the overall inputs of chemical N fertilizers, leading to other forms of N loss, such as N2O emissions and N leaching (Sun et al., 2015; Zhao et al., 2015; Chu et al., 2020).

1.4 Need for Further Research

Although NFC biofertilizers show promise as an alternative to chemical N fertilizers, there is limited research on their agronomic and environmental impacts when used to replace chemical fertilizers partially. This study aims to evaluate the effects of substituting part of the chemical N fertilizers with NFC biofertilizers on rice yield, NUE, and NH3 volatilization. Finally, NFC biofertilizers offer a sustainable alternative to chemical N fertilizers, potentially enhancing rice yields and improving soil health while mitigating environmental impacts. Further research is needed to fully understand their benefits and optimize their use in rice cultivation.

2. Identify the Topic and Scope

The broad topic chosen for this review is "The Role of Nitrogen - Fixing Cyanobacteria in Enhancing Rice Crop Yields and Sustainability. " This topic is significant because it addresses the critical issues of sustainable agriculture and food security, focusing on how natural biofertilizers can improve crop production while reducing environmental impacts. To narrow down the focus, this review will specifically examine several key aspects.

First, understanding the challenges posed by nitrogen deficiency in rice fields, particularly in red soil regions of China, is essential. Nitrogen is a critical nutrient for plant growth, but red soils are often characterized by low nitrogen content, which can limit crop yields (Zhao et al., 2009). This has led to the widespread use of chemical nitrogen fertilizers to meet crop needs.

Second, it is important to analyze the adverse effects of excessive chemical nitrogen fertilizers on the environment. Over - application of these fertilizers can cause significant nitrogen losses through ammonia volatilization, leaching, and runoff. Such losses not only reduce nitrogen use efficiency (NUE) but also contribute to environmental problems such as soil acidification, water eutrophication, and the formation of ammonium - containing aerosols, which affect air quality (Behera et al., 2013; Liu et al., 2015; Ti et al., 2019).

Third, exploring the mechanisms by which nitrogen - fixing cyanobacteria (NFC) operate, particularly Anabaena azotica, is crucial. These microorganisms can fix atmospheric nitrogen through specialized cells called heterocysts, providing a sustainable source of nitrogen to crops (Kollah et al., 2016). They form symbiotic relationships with rice plants, supplying bioavailable nitrogen in exchange for root exudates.

Fourth, evaluating the agronomic benefits of using NFC biofertilizers is essential. Studies have shown that the application of NFC biofertilizers can significantly increase soil organic carbon (SOC) and total nitrogen (TN) content in paddy fields, improve crop yields, and reduce the need for chemical fertilizers. For example, research indicates that rice yields can increase by 25 - 34.6% with NFC inoculation, and up to 45 kg N ha−1 of chemical fertilizer can be saved (Dash et al., 2016; Prasanna et al., 2015).

Fifth, reviewing results from controlled experiments and field trials conducted in different regions, with a focus on studies from the Ecological Experimental Station of Red Soil in Jiangxi province, China, provides practical insights. These studies demonstrate the effectiveness of NFC in improving soil properties and enhancing crop productivity (Deng et al., 2014; Wang et al., 2015). Finally, discussing how integrating NFC biofertilizers with traditional farming practices can lead to more sustainable agricultural methods is important. Combining NFC with reduced chemical fertilizer inputs can lower environmental pollution and enhance soil health. This approach aligns with global efforts to promote sustainable agriculture and food security, addressing both economic and environmental concerns (Vaishampayan et al., 2001; Song et al., 2021). By focusing on these specific areas, the review aims to provide a comprehensive understanding of the potential of nitrogen - fixing cyanobacteria in rice crop improvement and sustainable agriculture.

3. Symbiotic Interaction between Cyanobacteria and Rice Plants

Nitrogen - fixing cyanobacteria, particularly those belonging to the Nostocales order, play a crucial role in enhancing the growth and productivity of rice plants through symbiotic interactions in the rhizosphere (Fig - 1). These interactions are facilitated by several key mechanisms. The life cycle of Nostocales cyanobacteria is characterized by distinct stages that facilitate their adaptation to various environmental conditions and interactions with plants. In favorable conditions, these cyanobacteria form vegetative trichomes composed of cells capable of oxygenic photosynthesis. When nitrogen becomes limiting, some vegetative cells within the trichome differentiate into heterocysts, specialized cells dedicated to nitrogen fixation. Heterocysts are arranged in a semi - regular pattern along the filament, interspersed among vegetative cells.

Under conditions favoring dispersal or colonization, vegetative cells can transform into hormogonia, motile structures that exhibit positive chemotaxis towards plant root exudates. This enables hormogonia to effectively colonize new habitats, including the roots of plants like rice. In response to adverse environmental conditions, Nostocales cyanobacteria produce akinetes, which are dormant, spore - like cells resistant to desiccation and other stresses. Akinetes allow the cyanobacteria to survive harsh conditions over extended periods until favorable conditions return for germination and growth. This life cycle strategy of Nostocales cyanobacteria underscores their adaptive capabilities in forming symbiotic relationships with plants, particularly in enhancing nitrogen availability and promoting plant growth in agricultural and natural ecosystems. (Fig - 2):

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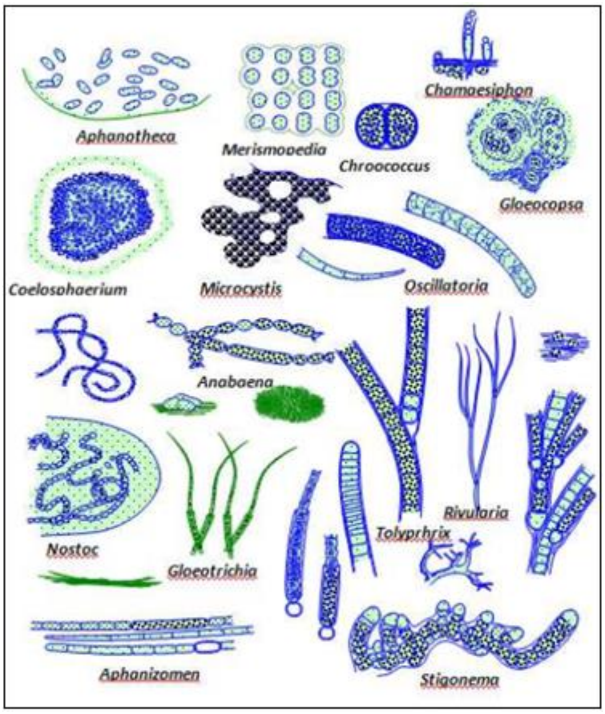

Figure 1: N2 - fixing cyanobacteria

3.1 Morphological Diversity and Nitrogen Fixation: Cyanobacteria such as Nostoc species exhibit diverse morphologies that include unicellular and filamentous forms. Filamentous species, particularly those capable of nitrogen fixation (heterocystous cyanobacteria), form specialized cells called heterocysts in response to nitrogen limitation. Heterocysts are essential for fixing atmospheric nitrogen into ammonia, which is then utilized by both the cyanobacteria and their plant hosts (Rippka et al., 1979; Fugita and Uesaka, 2022).

3.2 Regulation of Heterocyst Formation: The formation of heterocysts is controlled by regulatory proteins like HetR and diffusible peptides such as PatS and HetN. These proteins ensure the spatial distribution of heterocyst's along the cyanobacterial filaments, optimizing nitrogen fixation efficiency under varying environmental conditions (Yoon and Golden, 1998; Corrales - Guerrero et al., 2013; Flores et al., 2019).

3.3 Symbiotic Adaptations with Plants: In symbiosis with plants like rice, cyanobacteria undergo metabolic shifts from photoautotrophy to heterotrophy. This metabolic switch is supported by the plant's provision of organic carbon sources, enabling cyanobacteria to maximize nitrogen fixation rates. In return, cyanobacteria supply fixed nitrogen to the host plant, supporting its growth and development (Tredici et al., 1989; Söderbäck et al., 1990; Warshan et al., 2017).

3.4 Dispersal and Colonization: Cyanobacteria employ specialized motile structures known as hormogonia for dispersal and colonization. Hormogonia lack heterocysts and exhibit positive chemotaxis towards root exudates, facilitating their attachment and colonization of plant roots, including those of rice (Knight and Adams, 1996; Watts et al., 1999; Nilsson et al., 2006).

3.5 Survival Strategies: Akinetes are spore - like resting cells formed by Nostoc species, enabling them to survive adverse environmental conditions such as desiccation or extreme temperatures. Akinetes are characterized by thick cell walls and contain reserve materials that sustain the cyanobacteria during dormancy until conditions become favorable for germination and resumption of growth (Meeks et al., 2002; Kaplan - Levy et al., 2010; Garg and Maldener, 2021). These mechanisms highlight the adaptive strategies of nitrogen - fixing cyanobacteria in establishing symbiotic relationships with plants, particularly in enhancing nitrogen availability and promoting plant growth in agricultural contexts like rice cultivation.

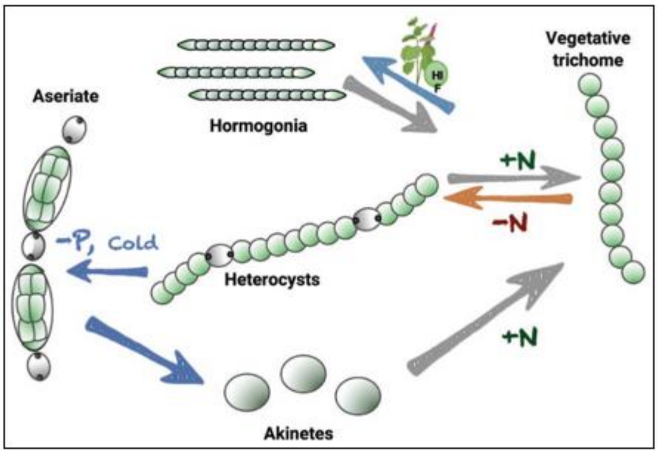

Figure 2: Nostocales Cyanobacteria Life Cycle

4. Impact on Physiological and Biochemical Characteristics

Nitrogen - fixing cyanobacteria play a significant role in enhancing the physiological and biochemical characteristics of plants, particularly in terms of nitrogen content, chlorophyll production, and overall plant development.

4.1 Nitrogen Content and Chlorophyll Production:

Nitrogen is an essential nutrient for plant growth, and its availability directly impacts chlorophyll synthesis, photosynthesis, and overall plant vigor. Cyanobacteria, such as those in the genus Nostoc, have the capability to fix atmospheric nitrogen into a form usable by plants. This process enriches the nitrogen content in plant tissues, promoting healthy growth and development. Studies have shown that plants associated with nitrogen - fixing cyanobacteria exhibit higher nitrogen concentrations compared to those relying solely on soil nitrogen (Gantar et al., 1991; Meeks and Elhai, 2002).

Furthermore, nitrogen availability positively influences chlorophyll production, a crucial pigment involved in photosynthesis. Cyanobacteria - mediated nitrogen fixation enhances chlorophyll synthesis, thereby boosting photosynthetic efficiency and contributing to increased biomass production in plants (Gantar et al., 1991; Tredici et al., 1989).

4.2 Environmental Benefits:

Using nitrogen - fixing cyanobacteria as a sustainable nitrogen source offers several environmental benefits:

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- **Reduced Reliance on Synthetic Fertilizers:** Synthetic fertilizers are a major source of environmental pollution through nitrogen runoff, which contributes to eutrophication of water bodies. By harnessing cyanobacteria to fix atmospheric nitrogen, farmers can reduce dependency on synthetic fertilizers, thereby mitigating environmental impacts associated with their production and use (Adams and Duggan, 2012; Warshan et al., 2018).
- **Mitigation of Nitrogen Runoff:** Nitrogen runoff from agricultural fields leads to water pollution and ecosystem degradation. Cyanobacteria - associated plants have been shown to effectively utilize fixed nitrogen, minimizing excess nitrogen leaching into groundwater or runoff into nearby water bodies (Rousk, 2022). Finally nitrogen - fixing cyanobacteria enhance plant nitrogen content, chlorophyll production, and overall growth by providing a sustainable and eco - friendly alternative to synthetic fertilizers. Their use not only promotes agricultural productivity but also contributes to environmental conservation by reducing nitrogen pollution in terrestrial and aquatic ecosystems.

5. Implications for Agriculture

Research on cyanobacteria presents promising implications for agriculture, focusing on sustainable practices and enhanced food security. By reducing reliance on synthetic fertilizers, improving soil health, and enhancing crop resilience, cyanobacteria offer innovative solutions to meet global agricultural challenges. These insights promote environmentally friendly practices while supporting increased productivity and resilience in agricultural systems worldwide.

5.1 Environmental Sustainability:

Research on cyanobacteria and their symbiotic relationships with plants offers significant contributions to enhancing environmental sustainability in agriculture:

- **Reduced Chemical Inputs:** By harnessing nitrogen - fixing cyanobacteria, farmers can reduce their reliance on synthetic nitrogen fertilizers. This approach minimizes the environmental footprint associated with fertilizer production, transport, and application, which includes greenhouse gas emissions, energy consumption, and nitrogen runoff into water bodies (Adams and Duggan, 2012; Santi et al., 2013).
- **Soil Health and Biodiversity:** Synthetic fertilizers can degrade soil health over time by altering microbial communities and reducing nutrient cycling efficiency. In contrast, cyanobacteria promote soil fertility by enriching nitrogen levels and fostering beneficial microbial interactions. This enhances soil biodiversity and resilience, contributing to sustainable agricultural practices (Meeks and Elhai, 2002; Warshan et al., 2018).
- **Water Quality Protection:** Excess nitrogen from synthetic fertilizers can leach into groundwater or runoff into surface waters, causing eutrophication and harm to aquatic ecosystems. Utilizing nitrogen - fixing cyanobacteria helps mitigate these environmental impacts by reducing nitrogen runoff and improving water quality in agricultural landscapes (Rousk, 2022).

5.2 Food Security

The implications of cyanobacteria research for global food security and sustainable agriculture practices are profound:

- **Enhanced Crop Yields:** Nitrogen is a critical nutrient for crop growth and productivity. By enhancing nitrogen availability through symbiotic relationships with cyanobacteria, farmers can potentially increase crop yields without escalating input costs. This is particularly beneficial in resource - limited regions where access to synthetic fertilizers is constrained (Gantar et al., 1991; Tredici et al., 1989).
- **Resilience to Climate Change:** Climate variability and extremes pose challenges to agricultural productivity. Cyanobacteria - mediated nitrogen fixation can enhance crop resilience by providing a stable and sustainable nitrogen supply, which improves plant vigor and tolerance to environmental stresses such as drought or soil nutrient deficiencies (Adams and Duggan, 2012; Warshan et al., 2018).
- **Promotion of Sustainable Practices:** Integrating cyanobacteria into agricultural systems aligns with sustainable agriculture principles, promoting practices that are environmentally sound, economically viable, and socially responsible. This approach supports long - term food security by ensuring food production systems are resilient, efficient, and less vulnerable to external shocks (Meeks and Elhai, 2002; Liu and Rousk, 2022). Finally, research on cyanobacteria highlights their potential to transform agriculture towards greater environmental sustainability and global food security. By reducing chemical inputs, improving soil health, and enhancing crop resilience, cyanobacteria offer promising solutions for sustainable agricultural practices that can meet the challenges of a changing climate and growing global food demand.

6. Conclusion

In conclusion, the reviewed literature underscores the significant role of nitrogen - fixing cyanobacteria in enhancing rice crop productivity through symbiotic relationships and nitrogen fixation. Studies have demonstrated that cyanobacteria, such as those from the Nostocales order, effectively colonize the rhizosphere, providing bioavailable nitrogen to rice plants in exchange for root exudates. This interaction not only boosts nitrogen content and chlorophyll production in rice but also enhances overall plant growth and development.

Looking ahead, future research should explore optimized application methods and further elucidate the molecular mechanisms underlying cyanobacterial symbiosis with rice plants. Such endeavors could refine agricultural practices by reducing dependence on synthetic fertilizers, mitigating environmental impacts like nitrogen runoff, and improving soil health.

The importance of integrating cyanobacteria into agricultural systems cannot be overstated. As global concerns over food security and sustainable farming practices escalate, leveraging cyanobacteria offers a promising avenue. Their ability to enhance crop yields while minimizing ecological footprints underscores their potential as a sustainable and environmentally friendly approach to meeting future agricultural challenges. Embracing cyanobacteria in agricultural strategies not only supports food production but also advances ecological stewardship for generations to come.

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