Dryland Soil Research, Vol. 1, No. 2, pp. 59-66, 2025
Type of article: Original, Available online at www.dlsr.iut.ac.ir,
https://doi.org/10.47176/dlsr.01.02.1036

Potential of Cyanobacteria as Biofertilizers and their Ability to Produce Plant Growth-Promoting Substances

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(Received 12 April 2025, Accepted 25 May 2025)

ABSTRACT

One effective method for supplying essential nutrients to plants is through the utilization of the bioactivity of soil and the application of microorganisms that promote plant growth. Cyanobacteria, an important addition to biofertilizers, are gaining popularity for their multifaceted benefits in sustainable agriculture and ecosystem restoration. This study focused on the isolation of cyanobacteria from paddy fields, followed by purification and morphological identification of the strains. We evaluated several key parameters: phycobiliprotein content, nitrogenase activity, phosphate solubilization, auxin production, and siderophore production in Tabarestan Biotechnology Institute in 2018. Subsequently, the most effective strains were selected for pot cultivation of the rice cultivar Tarom Hashemi. The experiment was performed using a completely randomized design, including seven selected cyanobacterial strains and a control treatment, each replicated three times. The results indicate that among the isolated cyanobacteria, *Nostoc sp.* GGuCy-47 exhibited the highest production of phycobiliproteins. In terms of nitrogenase activity, *Cylindrospermum sp.* GGuCy-25 and *Anabaena sp.* GGuCy-42 demonstrated the most effective performance. Additionally, *Anabaena sp.* GGuCy-17 showed significant phosphate solubilization, achieving a concentration of 641 µg P/mL. For indole-3-acetic acid (IAA) production under L-tryptophan-free conditions, both *Chroococcous sp.* GGuCy-34 and *Anabaena sp.* GGuCy-42 were the most productive. Finally, *Anabaena sp.* GGuCy-21 and *Nostoc sp.* GGuCy-47 excelled in siderophore production. The highest seed yield (15.6 g/pot) was obtained in the treatment inoculated with the *Cylindrospermum sp*. strain GGuCy-25. These superior and promising selected strains have the potential to enhance the growth and yield of rice crops and may serve as superior candidates for the development of cyanobacterial biofertilizers following further testing in diverse paddy field conditions. Overall, this study documents the potential of cyanobacteria biofertilizers as a viable option compared to synthetic fertilizers for sustainable crop production and soil health improvement.

Keywords: Auxin, Nitrogen, Phosphate, Phycobili Protein, Siderophore.

1. Introduction

Contemporary agricultural practices predominantly depend on the application of synthetic fertilizers and pesticides, intensive tillage, and excessive water use. While these techniques have contributed to meeting the food demands of populations in many developing countries, they have also precipitated significant environmental challenges, including the degradation of soil fertility. Consequently, enhancing agricultural productivity necessitates the identification of technologies that can augment yield by optimizing limited resources without compromising environmental integrity (Purwani et al. 2021). Biofertilizers, often referred to as microbial inoculants, encompass beneficial microorganisms such as bacteria (e.g., *Azotobacter*), cyanobacteria (blue-green algae), and mycorrhizal fungi, which supply nutrients to plants, enhance soil fertility, and promote soil structural stability (Koller et al., 2012). Among these, cyanobacteria stand out as promising candidates for developing environmentally sustainable and eco-friendly agricultural practices (Singh et al., 2017).

Cyanobacteria are increasingly recognized as key microorganisms in the development of sustainable agricultural practices. Despite being prokaryotic organisms, they were categorized in 2008 within one of the nine phyla of algae, specifically the phylum Cyanobacteria. Presently, this extensive and morphologically diverse group of photoautotrophic prokaryotes is classified under the domain *Bacteria*. This classification distinguishes them clearly from eukaryotic algae, which are found in other domains (Ramakrishnan et al., 2023). Cyanobacteria consist of various large cellular structures that perform specialized functions. These structures include light-harvesting antennae, phycobilisomes, polyphosphate bodies, cyanophycin granules, polyhydroxyalkanoate (PHA) granules, carboxysomes, lipid bodies, thylakoid membranes, regions containing DNA, ribosomes, and gas vacuoles (Chittora et al., 2020; Purwani et al., 2021). Cyanobacteria play a critical role in maintaining and enhancing soil fertility, thereby acting as natural biofertilizers. Their key functions include: (a) the formation of porous soil and production of adhesives; (b) excretion of phytohormones

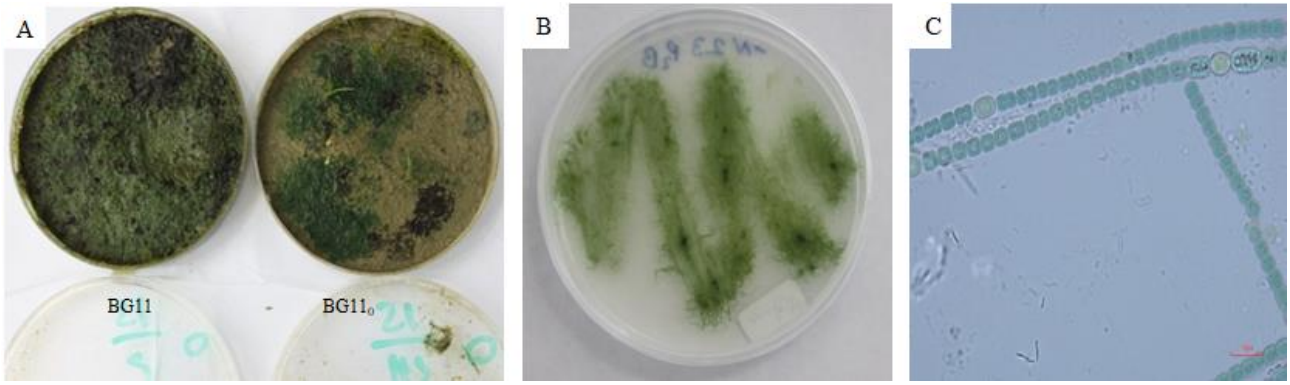

Figure 1. Different steps of isolation, purification and morphological identification of an isolated cyanobacterium sample**.**

(such as auxins and gibberellins), vitamins, and amino acids; (c) enhancement of soil water retention through gel-like structures; (d) increase of soil biomass through their life cycle and subsequent decomposition; (e) mitigation of soil salinity; (f) regulation of weed growth; (g) enhancement of soil phosphorus availability through organic acid excretion; and (h) efficient adsorption of heavy metals to microbial surfaces, contributing to bioremediation efforts (Chittora et al., 2020).

Cyanobacteria are well-known for their biofertilizer capabilities, which can significantly enhance soil fertility and promote plant growth. In a greenhouse study, a notable increase in the growth, biochemical properties, and mineral composition of wheat was observed when treated with a suspension of the native soil cyanobacterium *Anabaena cylindrica*. This growth-promoting effect was attributed to the intracellular or released bioactive compounds of *A. cylindrica*, including polysaccharides, proteins, and the phytohormone indole-3-acetic acid, as well as essential nutrients such as nitrogen, phosphorus, and potassium (Hakkoum et al., 2025). The adoption of biofertilizers derived from biological materials or various microorganisms sourced from natural habitats represents a sustainable strategy for enhancing crop quality and yield (Raimi et al., 2021). Numerous studies have demonstrated that cyanobacteria possess significant biological potential to enhance plant growth, development, and resilience against both biotic and abiotic stresses (Kholssi et al., 2022; Massey and Davis, 2023; Alvarez et al., 2024). Recently, aquatic cyanobacteria have also emerged as valuable sources of biofertilizers and biostimulants, providing promising commercial opportunities for agriculture and the agro-industry (Gonçalves, 2021; Bao et al., 2021). However, research focused on soil cyanobacterial-based biofertilizers remains limited (Jose et al., 2024; Minaoui et al., 2024). Soil cyanobacteria are recognized as photosynthetic microorganisms that offer both economic and environmental benefits for improving crop productivity and soil fertility (Gonçalves et al., 2021; Massey and Davis, 2023).

As the global population continues to rise, there is an increasing demand for healthy, pollution-free food (Singh et al., 2017). Rice (*Oryza sativa* L.) is a critical cereal crop, serving as the staple food for more than half of the world's population. To meet the growing global demand, continuous efforts must be made to enhance rice yield (Zhang et al., 2023). Free-living cyanobacteria can fix approximately 25 to 30 kg of nitrogen per hectare during the rice growing season, while the Azolla-Anabaena system can contribute between 20 to 40 kg of nitrogen per hectare within just 25 days to rice crops (Setiawati et al., 2018). Given the biotechnological potential of cyanobacteria in agriculture, there is a pressing need for comprehensive studies on these organisms. The aim of this study to evaluate the identified strains in terms of their production of plant growth stimulants, secondary metabolites, and their overall effects on the growth and yield of rice under pot cultivation conditions.

2. Materials and Methods

Sampling of paddy soils in Guilan province to a depth of 10 cm (5 simple samples from each field or sampling location) was randomly collected from 20 fields and transported to the laboratory. Soil samples were cultured according to the soil cyanobacterial culture method (Kaushik, 1987). Isolates were identified morphologically using light microscopy and cyanobacterial identification keys (John et al., 2003).

The concentrations of phycoerythrin (PE), phycocyanin (PC), and allophycocyanin (AP) were estimated using empirical relationships, and the total phycobilisome protein content for each sample was determined (Bermejo et al., 2002), that these models are often developed using reflectance data, particularly in the spectral regions where these pigments absorb light. The capacity for molecular nitrogen fixation was assessed using the acetylene reduction assay (ARA) method, with analysis performed via gas chromatography (GC) (Soltani et al., 2006). The phosphate solubilization rate was measured in a liquid culture medium with 0.3% tricalcium

Table 1. Amount of photosynthetic pigments (μg.mL^{-1}) of some cyanobacteria isolated from rice soil in Guilan

Cyanobacterial strain	Allophycocyanin	Phycocyanin	Phycoerythrin	Phycobiliprotein Total	Chlorophyll a
Phormidium sp. GGuCy-11	3.78	9.44	17.53	30.76	0.237
Synechococcus sp. GGuCy-15	4.01	3.00	1.98	8.99	0.154
Oscillatoria sp. GGuCy-16	1.25	5.83	11.12	18.20	0.985
Chroococcus sp. GGuCy-35	1.49	43.94	1.50	46.94	1.184
Anabaena sp. GGuCy-17	7.01	13.42	8.43	28.86	0.219
Anabaena sp. GGuCy-21	14.13	23.66	31.62	69.41	0.382
Cylindrospermum sp. GGuCy-25	16.13	47.92	1.57	65.62	0.270
Hapalosiphon sp. GGuCy-32	1.76	5.43	1.11	8.30	0.256
Westillopsis sp. GGuCy-39	1.41	8.14	1.12	10.67	0.351
Anabaena sp. GGuCy-41	1.20	3.55	1.32	6.07	0.771
Anabaena sp. GGuCy-42	15.06	15.40	23.16	53.62	0.290
Calothrix sp. GGuCy-43	3.36	6.52	6.14	16.02	0.281
Nostoc sp. GGuCy-46	19.85	51.46	4.40	75.71	0.345
Nostoc sp. GGuCy-47	28.99	63.54	1.01	93.54	0.429

phosphate (Aliasgharzad et al., 2009). The production of indole-3-acetic acid (IAA) by cyanobacteria was evaluated according to the method outlined by Shrivastava and Kumar (2011). Additionally, a semi-quantitative assessment of the siderophore production capacity of cyanobacteria was conducted using CAS-Agar culture medium (Ito and Butler, 2006). A pot experiment was conducted to assess the effects of seven selected cyanobacterial strains on the growth, yield, and yield components of rice (*Oryza sativa*) cultivar Tarom Hashemi. The selected strains were characterized based on their capacity to fix atmospheric nitrogen and solubilize insoluble phosphorus, and included *Cylindrospermum* sp. GGuCy-25, *Anabaena* sp. GGuCy-42, *Calothrix* sp. GGuCy-43, *Anabaena* sp. GGuCy-23, *Anabaena* sp. GGuCy-17, *Chroococcus* sp. GGuCy-34, and *Hapalosiphon* sp. GGuCy-32. The experiment employed a completely randomized design with seven cyanobacterial inoculation treatments and a control, each replicated three times, at the Tabarestan Agricultural Genetics and Biotechnology Research Institute. Each pot was filled with five kilograms of paddy field soil (0–20 cm depth), which was submerged for two weeks prior to planting. The cyanobacterial inoculum comprised a 15-day-old liquid culture; 50 mL of suspension (optical density 0.550 nm) was mixed with 20 g of sterile perlite (2–3 mm diameter) and placed at a depth of 5 cm in each pot's soil. The pots were maintained in a greenhouse with a light intensity of 3000 lux, temperatures ranging from 30 to 35°C, and humidity at 75%, with watering occurring twice weekly. At 115 days after sowing, during physiological maturity, plants were harvested en masse, and parameters including number of spikes, plant height, grain and straw yields, spike length, and the number of full and empty seeds per spike were measured (Bahmanyar et al., 2012). Statistical analyses were performed using SAS software, and mean comparisons were conducted using Duncan's multiple range test at a significance level of 5%.

3. Results and Discussion

Initial cultures of cyanobacterial samples were established in BG_{11} and BG_{110} culture media, alongside morphological studies of the resulting colonies, leading to the observation and isolation of 60 cyanobacterial strains. Ultimately, 30 pure strains were isolated through successive cultures, representing the orders *Chroococcales*, *Oscillatoriales*, *Nostocales*, and *Stigonematales*.

Among the isolated strains, *Nostoc* sp. GGuCy-47, *Nostoc* sp. GGuCy-46, *Anabaena* sp. GGuCy-21, *Cylindrospermum* sp. GGuCy-25, and *Anabaena* sp. GGuCy-42 demonstrated superior quantities of phycobiliproteins (Table 1). Phycobiliproteins, located on the stromal surface of the thylakoid membrane, are responsible for the characteristic coloration of cyanobacteria and can comprise approximately 40–50% of the total protein content in cells cultivated under low light conditions (Sekar and Chandramohan, 2008). These proteins function as primary photoreceptor antennas for photosystem II (PSII). Notably, strains with elevated levels of phycobiliproteins also exhibited enhanced nitrogen fixation capacities. In particular, *Cylindrospermum* sp. GGuCy-25 and *Anabaena* sp. GGuCy-42 displayed the highest nitrogenase activity among the evaluated strains.

Table 2. Values of nitrogenase activity, phosphate solubilization, auxin and siderophore production in some cyanobacterial strains

Cyanobacterial strain	Inorganic phosphorus* (µgP/ml)	Siderophore (µmol/ml.day)	Auxin (µg/µg Chla)	Nitrogenase activity (nmol C_2H_4/h)
Chroococcus sp. GGuCy-34	53.1	1.51	14.98	11.25
Anabaena sp. GGuCy-17	641.0	3.95	10.81	22.63
Anabaena sp. GGuCy-23	102.2	3.44	8.45	22.92
Cylindrospermum sp. GGuCy-25	130.4	4.68	4.67	56.31
Hapalosiphon sp. GGuCy-32	81.8	4.00	5.23	22.23
Anabaena sp. GGuCy-42	79.6	3.38	10.83	38.56
Calothrix sp. GGuCy-43	61.1	3.31	2.56	26.47
Synechococcus sp. GGuCy-15	24.3	1.86	9.28	11.49
Oscillatoria sp. GGuCy-16	49.4	2.58	8.55	22.23

* Dissolution of inorganic phosphorus was measured after 15 days of incubation.

The nitrogenase activity of the isolated cyanobacterial strains varied significantly, ranging from 4.46 nmol ethylene/h in *Phormidium* sp. GGuCy-12 to 56.31 nmol ethylene/h in *Cylindrospermum* sp. GGuCy-25. The highest nitrogenase activity was recorded for *Cylindrospermum* sp. GGuCy-25, as well as for *Anabaena* sp. GGuCy-42, *Calothrix* sp. GGuCy-43, *Anabaena* sp. GGuCy-23, *Anabaena* sp. GGuCy-17, and *Hapalosiphon* sp. GGuCy-32 (Table 2). Heterocyst formation in these cyanobacterial strains tends to increase under low light conditions, contingent upon the availability of carbon and ATP, both of which are supplied by photosynthesis and oxidative metabolism. It has been demonstrated that nearly 40% of the nitrogen fixed by cyanobacteria is utilized by rice plants (Vaishampayan et al., 1998). Nitrogen-fixing cyanobacteria, known for their efficient green manure properties, have considerable potential to improve soil quality. A nitrogen-fixing cyanobacterial strain (*Anabaena azotica* SJ-1), isolated from local Mollisol soil, and was investigated by Li et al. (2025) to assess its impact on rice plant growth and to elucidate the associated mechanisms. The results indicated that *Anabaena azotica* SJ-1 significantly enhanced rice plant growth, particularly in low-yielding soils (dry weight of rice spikes increased by 38–74 % in high-yielding soils and 107–157 % in low-yielding soils). This study underscores the significant potential of nitrogen-fixing cyanobacteria to improve the quality and efficiency of degraded Mollisol soils (Li et al., 2025).

Phosphorus dissolution after 15 days of incubation ranged from 53.1 to 641 µg P/mL. *Anabaena* sp. GGuCy-17 exhibited a significant advantage over the other strains in terms of phosphate solubilization capacity, yielding 641 µg P/mL, followed by *Cylindrospermum* sp. GGuCy-25 with 130.4 µg P/mL (Table 2). Notably, the concentration of inorganic phosphorus in the supernatant decreased over time, particularly on the 30th day, likely due to changes in the growth stage of the strains and the conversion of phosphorus to an organic form, as cyanobacteria serve as efficient reservoirs for phosphorus. Based on pH measurements of the culture medium, strains capable of solubilizing phosphorus generally exhibited lower pH levels, as medium acidification is a microbial process that facilitates the solubilization of inorganic phosphate (Yandigeri et al., 2011). Hakkoum et al. (2025) attributed the effect of increasing wheat growth by inoculation with the *Anabaena cylindrica* to the production of intracellular or released bioactive compounds by the cyanobacteria, such as polysaccharides, proteins, the plant hormone indole acetic acid (IAA), nitrogen, phosphorus, and potassium. Gheda and Ahmed (2015) revealed that *Nostoc kihlmani* and *Anabaena cylindrica* living biomass application improved growth and the N, P, and K content of wheat plants. Furthermore, the rise in phosphorus content in wheat plants under cyanobacterial treatments may be partially attributed to the production of organic acids by the cyanobacteria. These acids lower soil pH, facilitating the conversion of unavailable phosphorus into forms accessible to plants (Hakkoum et al. 2025).

In the assessment of auxin production among the isolated strains, *Chroococcous* sp. GGuCy-34 and *Anabaena* sp. GGuCy-42 produced 14.98 and 10.83 µg indole-3-acetic acid (IAA) per µg chlorophyll, respectively, in the treatment lacking L-tryptophan. In the presence of 100 mg/mL L-tryptophan, *Chroococcous* sp. GGuCy-34, *Synechococcus* sp. GGuCy-15, and *Anabaena* sp. GGuCy-42 generated the highest IAA quantities at 23.7, 17.46, and 15.81 µg IAA/µg chlorophyll a, respectively. When treated with 500 mg/mL L-tryptophan, *Synechococcus* sp. GGuCy-15 and *Oscillatoria* sp. GGuCy-16 produced the highest auxin levels, measuring 29.16 and 21.61 µg IAA/µg chlorophyll a, respectively (Table 2). Several studies have documented the production of the phytohormone IAA by both free-living and symbiotic cyanobacterial strains (Chittora et al., 2020). Perhaps, the most probable pathway for auxin biosynthesis

Table 3. Comparison of the average effects of cyanobacterial strains on the characteristics studied in the rice pot experiment (5% probability level)

Cyanobacters treatments	Plant height (cm)	Panicles Number per pot	Grain yield (g. pot^{-1})	Straw yield (g. pot^{-1})	Panicles length (cm)	Grain number of full	Grain number of empty
Control	120.4c	6.5b	11.93c	17.5c	23.9c	74.8b	14.7a
Cylindrospermum sp. GGuCy-25	136.1a	7.5ab	15.6a	18.2ab	26.1a	83.0a	9.0c
Anabaena sp. GGuCy-42	129.8b	7.8a	14.79ab	19.2a	24.6bc	76.1b	12.7ab
Calothrix sp. GGuCy-43	132.0ab	7.6ab	14.74ab	17.8ab	25.0ab	78.9ab	9.2c
Anabaena sp. GGuCy-23	135.5a	7.3ab	14.57ab	18.9ab	25.8ab	82.8a	10.0bc
Chroococcus sp. GGuCy-34	128.4b	7.4ab	14.68ab	17.3b	24.9bc	78.2ab	10.9bc
Hapalosiphon sp. GGuCy-32	135.3a	7.2ab	14.51ab	17.2b	26.0a	80.7ab	9.7c
Anabaena sp. GGuCy-17	127.6b	7.1ab	14.12b	17.3b	25.6ab	77.7ab	11.8bc

* The same Latin letter indicates no significant difference at the 5% probability level based on Duncan's multiple range test.

in algae is the tryptamine (TAM) pathway. The presence of the tryptophan decarboxylase enzyme has been demonstrated in the microalga *Chlamydomonas reinhardtii*. Several auxin biosynthetic enzymes documented in higher plants, such as C-S lyase and nitrilases, have also been observed in microalgae and cyanobacterial genera, which are the primary sources of auxin biosynthesis (Rathod et al., 2023). Mazhar et al., (2013) showed that cyanobacteria-produced auxin (0.20 to 1.63 µg mL^{-1} IAA) significantly impacted plant vegetative growth in a hydroponic system. Interestingly, the cyanobacteria produced more endogenous auxin than exogenous auxin in the presence of plants. This could be attributed to the plants releasing specific signals to trigger the production of higher levels of auxins in the cyanobacteria.

The highest siderophore production, as determined by the CAS-agar method, was observed in *Chroococcus* sp. GGuCy-34 and *Anabaena* sp. GGuCy-49, with values of 4.19 and 4.08, respectively. When assessed using the spectrophotometric method, *Cylindrospermum* sp. GGuCy-25 and *Hapalosiphon* sp. GGuCy-32 produced 4.68 and 4.00 µmol/mL/day, respectively (Table 2). Cyanobacteria, which are prokaryotic, photoautotrophic, Gram-negative microorganisms, predominantly produce hydroxamate-type siderophores (Ueno et al., 2019). Biochemical and genetic studies indicate that not all cyanobacteria possess a siderophore-based iron absorption system, and alternative iron uptake pathways exist within these organisms. The significance of superoxide-mediated iron reduction as an alternative method has been established in the cyanobacterium *Lyngbya majuscule*. Additionally, the metabolic cost associated with siderophore biosynthesis and transport is considerable (Lis et al., 2015).

Analysis of variance revealed that the effects of cyanobacterial treatments on grain yield were statistically significant at the 5% probability level, while their effects on plant height, panicle length, and empty grain percentage were significant at the 1% probability level. No significant differences were observed among treatments for the traits of tiller number, number of panicles per pot, number of full grains, and total grain count. Table 3 presents the comparison of mean values for grain yield, straw yield, and yield components across treatments. Among the treatments, *Cylindrospermum* sp. GGuCy-25 exhibited the highest grain yield, achieving 15.6 grams per pot, which was significantly higher (a 23.6% increase) than the control. The strains *Anabaena* sp. GGuCy-42, *Calothrix* sp. GGuCy-43, and *Chroococcus* sp. GGuCy-34 followed, respectively, with the highest grain yields. Regarding straw yield, there was a significant difference between inoculated treatments and the uninoculated control at the 5% level. The highest straw yield of 19.2 g per pot was observed with the *Anabaena* sp. GGuCy-42 treatment, representing an 8.9% increase over the control. Subsequently, the strains *Anabaena* sp. GGuCy-23 and *Cylindrospermum* sp. GGuCy-25 produced straw yields of 18.9 g and 18.2 g per pot, respectively.

These findings align with previous studies (Purwani et al. 2021; Prasna et al., 2013; Mishra et al., 2012). Purwani et al. (2021) found that the highest rice yield obtained by *Chlorogloea* sp. + *Nostoc* sp with 100% N, increased by 14.75%. Application of *Pseudanabaena* sp. + *Nostoc* sp. was increased rice grain yield and straw biomass by 11.47% and 37.49%, reduced N fertilizer by 25 to 50%,

and increased nutrient uptake of N, P, K by 43.73%, 34.80 %, 34.40%. Using cyanobacteria is a promising strategy to increase rice yield and reduce chemical fertilizers. Ghosh and Saha (1992) demonstrated that inoculating cyanobacteria at a rate of 43 kg ha^{-1} significantly increased soil nitrogen fixation, by more than 200% of the average. The impact of cyanobacterial inoculation was particularly pronounced during the maximum tillering and grain-filling stages, when nitrogen uptake was minimal, resulting in increased grain and straw yields. Furthermore, grain and straw yields were found to be significantly correlated with the rate of nitrogen fixation in flooded soils and within the root system during the respective tillering and maximum tillering stages.

The increased adoption of biofertilizers and natural biostimulants seeks to reduce dependence on chemical fertilizers and non-renewable resources. Cyanobacteria have shown the potential for promoting plant growth and offering systemic immune resistance to various environmental stressors (Renganathan et al., 2024a). These biofertilizers enhance the soil nutrient content and plant growth, thereby promoting sustainable organic agriculture. Cyanobacteria promote plant growth and soil health through distinct modes of application, such as biofertilizers and biostimulants. Studies have shown that the application of live cell suspensions, dry cell biomass, cell extracts, or algal and cyanobacterial hydrolysates can significantly improve the growth of economically important crops in laboratory, greenhouse, and field settings (Renganathan et al., 2024b).

4. Conclusion

Cyanobacteria are considered ideal biofertilizers for enhancing soil fertility and ensuring the long-term sustainability of production in paddy field ecosystems. Utilizing cyanobacteria as biofertilizers is regarded as one of the most promising environmentally friendly methods. As prokaryotic organisms, cyanobacteria have evolved to become exceptionally resilient and successful. Their practical application as a source of organic nitrogen fertilizer for rice cultivation has been thoroughly demonstrated. Cyanobacteria also possess significant nitrogen fixation capabilities and can solubilize inorganic phosphate compounds, which are vital for rice plant nutrition and hold considerable economic importance. Overall, the results indicate that the indigenous cyanobacteria isolates enhanced both the growth and yield of rice (variety Tarom Hashemi) under pot conditions, although the efficacy varied among strains. The highest grain yield was observed with *Cylindrospermum* sp. GGuCy-25, while the greatest straw yield was achieved with *Anabaena* sp. GGuCy-42. Additionally, their ability to produce indole-3-acetic acid and siderophores enables them to act as plant growth promoters, thereby enhancing plant development. To maximize the benefits of cyanobacteria, it is essential to apply these superior strains in practical settings. Developing region-specific seed stocks will facilitate the better establishment of cyanobacteria within their ecological niches, ultimately optimizing their contributions to crop productivity and sustainability. Overall, applying biological agents through optimizing rice growing environment to improve yield showed great potential.

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