Chapter 3
Rhizospheric Diversity of Cyanobacteria and Their Significance in Tropical Ecosystem

Samadhan Yuvraj Bagul, Ritu Vishwakarma, Shaloo Verma, Hillol Chakdar, and G. S. Bandeppa

Abstract Cyanobacteria are gram-negative diverse group of unicellular to filamentous photoautotrophs. They are found ubiquitously in nature. Ability of the cyanobacteria for nitrogen fixation and phosphorous solubilization makes them promising biofertilizers, and their plant growth-promoting potential in the rhizosphere makes them a suitable candidate for sustainable agriculture. Cyanobacteria in the rhizosphere and their importance in tropical ecosystems have been highlighted in this chapter.

Keywords Cyanobacteria · Diversity · Biofertilizer · Plant growth promotion · Tropical

3.1 Introduction

Cyanobacteria are gram-negative photosynthetic microorganisms involved in global oxygen supply and primary production of biomass in aquatic ecosystem. Cyanobacteria have also been reported for nitrogen fixation (N_2) and carbon dioxide (CO_2) sequestration, thus contributing toward the carbon and nitrogen economy of different ecological habitats (Singh et al. 2016; Wyatt and Silvey 1969). Cyanobacteria have a wider adaptability and are found in diverse ecological niches. Bagul et al. (2018) reported different types of heterocystous and non-heterocystous cyanobacteria from diverse ecological niches of India, including hot water spring of Odisha, cold regions of Leh and Uttarakhand, marine water from Odisha, and arsenic-contaminated field of Ballia, Uttar Pradesh. Cyanobacteria are also capable of tolerating biotic and abiotic stress such as salt, heavy metals, and drought and cold

S. Y. Bagul (✉) · R. Vishwakarma · S. Verma · H. Chakdar
National Bureau of Agriculturally Important Microorganisms, Kushmaur, Uttar Pradesh, India

G. S. Bandeppa
Indian Institute of Rice Research, Hyderabad, India

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conditions. Comprising about 150 genera with more than 2000 species, they exhibit remarkable diversity in their morphology, ranging from simple unicellular and colonial to complex filamentous forms with or without branching (Van den Hoek et al. 1995). They flourish in nitrogen-deficient environment. Cyanobacteria can grow in purely inorganic medium using light as energy and CO_2 and N_2 as sole carbon and nitrogen sources, respectively (Wyatt and Silvey 1969). Over several years, cyanobacteria have been utilized as biofertilizer in rice crop for nitrogen fixation along with plant growth-promoting activities. Inoculation of cyanobacteria into the rice field has been practiced in many tropical countries which helps in reducing the cost of expensive chemical fertilizers. Cyanobacterial extracts have been reported to have a significant response to food crops like wheat, maize, rice, tomato, and cucumber (Priya et al. 2015; Bidyarani et al. 2016; Gayathri et al. 2017). Cyanobacteria have the ability to produce extracellular substances and modulate pH, temperature, and redox activity, besides playing a role in the volatilization of ammonia and methane generation; therefore, application of cyanobacteria in the rice field directly or indirectly has been utilized in the management and productivity of rice ecosystem (Prasanna et al. 2002). A group of heterocyst-forming cyanobacteria such as *Anabaena*, *Calothrix*, *Hapalosiphon*, and *Nostoc* have also been reported to enhance soil microbial parameters, seed germination, and yield of rice crop (Obana et al. 2007; Prasanna et al. 2013; Hussain and Hasnain 2012; Mazhar et al. 2013; Karthikeyan et al. 2007).

3.2 Rhizospheric Diversity of Cyanobacteria in Tropical Ecosystem

The rhizosphere is the region of large number of microbial population and diversity. Higher metabolic activity in the rhizosphere region related to the successful production of crops and increase soil fertility. However, abundance of cyanobacteria and its diversity are meagerly explored in the rhizosphere of crop plants. The general belief that cyanobacteria are obligate phototrophs has been perhaps the major reason for the dearth of information on these organisms in this niche (Karthikeyan et al. 2009). Soil enzymes play a vital role which regulate elements' transformation in the soil and increase the fertility of the soil. The process of elemental transformation is the result of microbial activity as microorganisms have a role in nutrient cycling; thus, both soil fertility and microbial activity are generally closely related, leading to differences in yields and changes in various soil parameters (Nain et al. 2010). The rhizospheric diversity has been reported by many research groups from different tropical countries including India, Sri Lanka, Iraq, Saudi Arabia, Singapore, etc. The cyanobacteria that are reported to dominate in the rhizosphere are the population of non-heterocystous cyanobacteria. Adhikary and Baruah (2015) studied comparative diversity and composition of nitrogen-fixing cyanobacteria in three different land use systems of upper Assam, i.e., rice field, reserve forest, and coal field. Nitrogen-fixing cyanobacteria belonging to nine genera were isolated which included six heterocystous forms, viz., *Anabaena*, *Nostoc*, *Scytonema*, *Calothrix*, *Rivularia*, *Westiellopsis*, and three non-heterocystous forms, viz., *Lyngbya*, *Phormidium*, and *Oscillatoria*. The dominance of *Nostoc* and *Anabaena* in the reserve forests and rice fields, whereas both were missing in the coal-contaminated sites. *Oscillatoria* was the dominant genus, and the species belonging to this genus were abundant in coal field areas. Jena and Adhikary (2007) reported 56 taxa from eastern and northeastern states of the country belonging to 21 genera: *Chlorococcum* (*1*), *Treubaria* (*1*), *Pediastrum* (*9*), *Hydrodictyon* (*1*), *Botryococcus* (*1*), *Coenochloris* (*1*), *Radiococcus* (*1*), *Coenocystis* (*1*), *Oocystis* (*1*), *Glaucocystis* (*1*), *Chlorella* (*1*), *Kirchneria* (2), *Kirchneriella* (*1*), *Ankistrodesmus* (*10*), *Coelastrum* (*3*), *Actinastrum* (2), *Tetrastrum* (*1*), *Crucigenia* (*1*), *Crucigeniella* (*1*), *Desmodesmus* (*6*), and *Scenedesmus* (*9*). All these species were recorded first time from this region, and out of these, 16 species were reported first from India (Singh et al. 2018). Paddy ecosystem harbors nitrogen-fixing cyanobacterial species mainly dominated by *Nostoc*, *Anabaena*, *Tolypothrix*, *Aulosira*, *Cylindrospermum*, *Scytonema*, *Westiellopsis*, and several other genera commonly flourishing in Indian paddy (Nayak et al. 2004; Prasanna and Nayak 2007; Saadatnia and Riahi 2009). Bora et al. (2016) have isolated six strains of two closely related genera—*Nostoc* and *Cylindrospermum*—*Nostoc carneum*, *Nostoc hatei*, *Nostoc muscorum*, *Cylindrospermum muscicola* (strain A), *Cylindrospermum muscicola* (strain B), and *Cylindrospermum indicum* from terraced paddy field and jhum land of biodiversity hotspot zone of Assam, Northeast India. Debnath and Bhadury (2016) have isolated five abundant cyanobacteria from the rice fields of arsenic-affected Bengal Delta Plains (BDP) of South Asia and maintained in vitro. The characterized isolates resembled *Leptolyngbya* sp. (isolate LBK), *Nostoc* sp. (isolates NOC and NOK), and *Westiellopsis* sp. (isolates WEC and WEK) based on polyphasic taxonomy. Haider and Haifaa (2018) have identified 96 species, including four heterocystous species represented by *Anabaena*, *Calothrix*, *Cylindrospermum*, and *Nostoc*. However, the non-heterocystous species were represented by 13 species: *Aphanocapsa*, *Aphanothece*, *Arthrospira*, *Chroococcus*, *Gloeocapsa*, *Lyngbya*, *Merismopedia*, *Microcystis*, *Microcoleus*, *Oscillatoria*, *Phormidium*, *Schizothrix*, and *Spirulina*. Soil samples were collected from six different agricultural sites in Al Diwaniyah City, Iraq. The dominant species of cyanobacteria was *Oscillatoria*, followed by *Phormidium*, *Chroococcus*, *Gloeocapsa*, and *Lyngbya*. Several arid zones like Shantiniketan (West Bengal, India) and the Thar Desert along with Achrol, Jaisalmer, Manwar, and Pokhran (Rajasthan, India) have been studied for cyanobacterial diversity in India. In Shantiniketan, a novel cluster of *Scytonema* and *Tolypothrix* cyanobacteria has been found which possessed abundant scytonemin in a sheath of cells for protection from high solar irradiance (Kumar and Adhikary 2015). In the Thar Desert, the dominance of *Phormidium*, *Oscillatoria*, and *Lyngbya* followed by *Nostoc*, *Scytonema*, and *Calothrix* has been reported (Bhatnagar et al. 2008). Several novel strains of Oscillatoriales have been also reported from the Thar Desert by Dadheech et al. (2012). Silambarasan et al. (2012) in his study have isolated marine cyanobacteria from rhizosphere soil samples of the three mangroves, viz., Parangipettai, Ariyankuppam, and Mudasal Odai mangroves southeast coast of India. Jing et al. (2015) studied the diversity of the diazotroph communities in the rhizosphere sediment of five tropical mangrove sites with different levels of pollution along the north and south coastline of Singapore by pyrosequencing of the nifH gene and found that *Scytonema* sp. and *Pseudanabaena* sp., which belong to the Nostocales (heterocyst forming) order of cyanobacteria. Moreover, filamentous non-heterocystous cyanobacteria *Microcoleus* were detected at all five sampling sites. Amarawansa et al. (2018) found 13 different cyanobacteria genera from paddy soil crust in the intermediate and dry zones of Sri Lanka based on their morphological characteristics. Among them, six cyanobacteria genera were unicellular (*Chroococcus*, *Aphanocapsa*, *Aphanothece*, *Synechococcus*, *Johannesbaptistia*, *Microcystis*), and seven genera were filamentous types (*Lyngbya*, *Oscillatoria*, *Leptolyngbya*, *Pseudanabaena*, *Anabaena*, *Spirulina*, *Nostoc*).

3.3 Significance of Cyanobacteria in Tropical Ecosystem

3.3.1 Phytohormone Production

Cyanobacteria have been reported to produce phytohormones such as IAA, IBA, gibberellins, cytokinin, abscisic acid, and jasmonic acid (Manickavelu et al. 2006). Table 3.1 shows different cyanobacterial strains reported for phytohormone production. A non-heterocyst *Chroococcidiopsis* sp. MMG-5 has been studied and showed significant amount of IAA (25 μg/mL) production, and when co-treated with wheat, mung beans, and pea crop, it showed significant increase in shoot and root length (Ahmed et al. 2010a). Ahmed et al. (2010b) reported *Arthrospira platensis* MMG-9 with 194.3 μg/mL IAA production and with enhanced root and shoot parameters. *Anabaena vaginicola* has been reported to produce IBA and IAA, 2146.9 ng/g and 9.93 ng/g fresh weight, respectively. The effects of these strains have been evaluated and are found beneficial on several vegetable and herbaceous crops (Hashtroud et al. 2013). Prasanna et al. (2013) investigated the effect of *Anabaena* sp. (RPAN59/8) amended with compost and found enhanced growth parameters as well as enhanced quality of tomato fruit. Co-inoculation of plant growth-promoting rhizobacteria along with cyanobacteria has also been reported to increase the plant growth and grain yield significantly (Nain et al. 2010). Karthikeyan et al. (2007) investigated the potential of cyanobacteria on wheat along with different dose of chemical fertilizers; interestingly. all the treatments showed enhanced plant growth and yield parameters. A study with *Anabaena* and *Trichoderma viride* biofilm showed 12–25% increase in yield of soybean as well as enhanced microbial activity. Cyanobacterial association with *Gunnera* has shown production of arabinogalactan proteins that might have played important role in plant growth and development (Bergman et al. 1996). Kumar and Kaur (2014) studied the germination behavior of wheat seeds with cyanobacterial filtrate and found that germination, vigor index, and number of seedlings were higher as compared to untreated. The abovementioned studies

Table 3.1 Different cyanobacterial strains exhibiting phytohormone production

Cyanobacteria	Habitat	PGPR trait	Tryptophan concentration (μg/ml)	Production	Beneficiary crop	Reference
Phormidium sp. MI405019	Mangrove	IAA	50	11.71 μg/mg Chl a	Tobacco	Boopathi et al. (2013)
Anabaena Ck1	Rice endophyte	IAA	–	199.95 (ng/mL)	*B. oleracea* var. capitata	Hussain and Hasnain (2012)
Chroococcidiopsis Ck4	Rice endophyte	Cytokinin	–	9.20 (ng/mL)	*B. oleracea* var. *capitata*	Hussain and Hasnain (2012)
Fischerella muscicola NDUPC001	Rice field	IAA	500	286.82 μg/mL	Rice	Mishra et al. (2019)
Nostoc Pc	–	IAA	–	23 (pmol/mg Chl a)		Sergeeva et al. (2002)
Anabaena sp. CW1	–	IAA	–	11.43 μg/mL	–	Prasanna et al. (2010)
Anabaena vaginicola	Paddy field	IBA	–	1.275 (μg g^{-1} DW)		Shariatmadari et al. (2013)
Nostoc calcicola	Paddy field	IBA	–	2.958 (μg g^{-1} DW)		Shariatmadari et al. (2013)
Aulosira fertilissima	–	IAA	100	7.1 μg/mL		Kumar and Kaur (2014)

indicate that cyanobacteria could be a potential component in integrated nutrient management. The world is looking for organic farming; certainly cyanobacteria are one of the important catalysts that could play a vital role.

3.3.2 *Cyanobacteria as a Biofertilizer*

Sustainable agriculture is the present trend in agriculture that has gained an attention by reducing the use of chemical pesticides and inorganic fertilizers and increasing the use of biofertilizers as an alternative to improve crop yield (Nain et al. 2010). Cyanobacteria have the ability to fix atmospheric nitrogen. They are important component of rice ecosystem and known to fix 20–25 kg N/ha/season (Prasanna and Kaushik 2006). Cyanobacteria are categorized into heterocystous and non-heterocystous forms. Plate 3.1 depicts confocal and light microscopic images of heterocystous and non-heterocystous cyanobacteria. Heterocyst is a specialized structure and nitrogen fixation site. Filamentous cells form heterocyst when inorganic nitrogen source is deprived of cultivation medium (Fig. 3.1). These cells lack photosystem II and maintain microaerobic environment which is required for nitrogenase enzyme responsible for nitrogen fixation. PS I provides ATP for nitrogen fixation in this process which is an energy intensive process. Non-heterocyst-forming cyanobacteria fix atmospheric nitrogen by temporal (CO_2 fixation during day time and N_2 fixation at night) and spatial separation. However, a new study reveals the constitutive nitrogenase activity in the presence of light and oxygen by *Cyanothece* sp. ATCC 3051142 (Young et al. 2019). These findings could pave the way for auto mode of nitrogen fixation in plants in the future. Cyanobacteria mimic the photosynthesis of plants; however, its metabolism has been regarded as bacterial. Studies have shown that the artificial inoculation of cyanobacteria to marine mangroves has significant effect on germination and nitrogen fixation. The researchers indicated the use of cyanobacteria in affected area to establish mangroves (Toledo

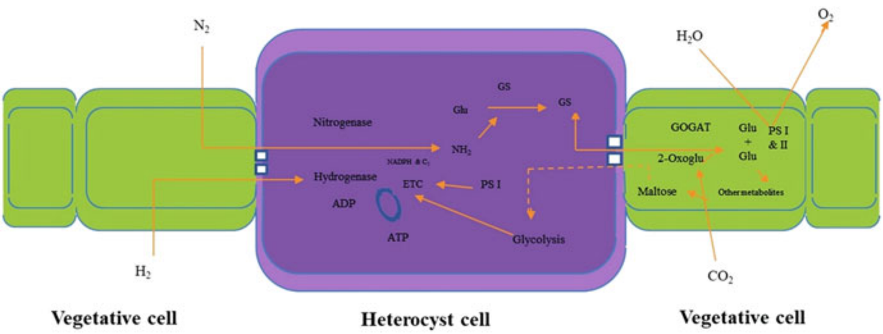

Plate 3.1 Confocal images of cyanobacteria (first row left to right, *Hapalosiphon* sp., *Nostoc* sp., *Calothrix* sp., *Leptolyngbya* sp.). Light microscopic images of cyanobacteria (second row left to right, *Tolypothrix* sp., *Hapalosiphon* sp., *Anabaena* sp., *Leptolyngbya* sp.)

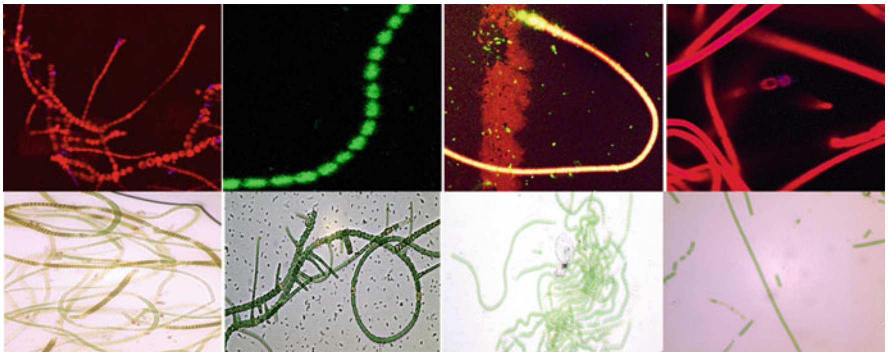

Fig. 3.1 Nitrogen fixation factory (heterocyst cell in cyanobacteria)

et al. 1995). Rice seedling treated with *Anabaena* sp. showed increased root and shoot length as compared to control plant as a result of nitrogen fixation by cyanobacteria (Saadatnia and Riahi 2009).

Phosphorous is another important nutrient required for plant growth after nitrogen. However, solubilization of mineral P is affected by different factors, and plant could take it easily. Reports suggest that cyanobacteria could solubilize inorganic phosphorous such as tricalcium phosphate, $FePO_4$, $AlPO_4$, hydroxyapatite ($Ca_5(PO_4)_3{}^{-}OH$), and rock phosphate. Yandigeri et al. (2011) investigated cyanobacteria for Mussoorie rock phosphate and tricalcium phosphate solubilization and found that *Westiellopsis prolifica* and *Anabaena variabilis* were able to solubilize it. Roychoudhury and Kaushik (1989) also reported P solubilization by cyanobacteria. Chinnusamy et al. (2006) have tested the combination of cyanobacteria, VAM fungi, *Azospirillum*, and PSB and found significant improvement of growth and yield in the plant. Nutritional status and fertility of the soil were also enhanced with these treatments. Stihl et al. (2001) reported alkaline phosphatase activity in *Trichodesmium* sp. Natesan and Shanmugasundaram (1989) studied the *Anabaena* ARM 310 for phosphate solubilization and found that this cyanobacterium was able to solubilize tricalcium phosphate. *Aulosira fertilissima* was able solubilize tricalcium phosphate (4.02 μg/mL) and showed improved seed vigor and growth of the wheat plant (Kumar and Kaur 2014). Cyanobacteria have the dual advantages of nitrogen fixation and P solubilization which make them suitable biofertilizer for agricultural use.

3.3.3 Advantages of BGA Biofertilizers

Cyanobacteria play an important role in the maintenance and build-up of soil fertility, consequently increasing rice growth and yield as a natural biofertilizer (Song et al. 2005). The other roles of cyanobacteria include:

1. Increasing soil pores with having filamentous structure and production of adhesive substances
2. Excretion of growth-promoting substances such as hormones (auxin, gibberellin), vitamins, and amino acids (Roger and Reynaud 1982; Rodríguez et al. 2006)
3. Increasing water-holding capacity through their jelly structure (Roger and Reynaud 1982)
4. Increasing soil biomass after their death and decomposition (Saadatnia and Riahi 2009)
5. Decreasing soil salinity (Saadatnia and Riahi 2009)
6. Preventing weeds' growth (Saadatnia and Riahi 2009)
7. Increasing soil phosphate by excretion of organic acids (Wilson et al. 2006)

3.4 Plant Protection Against Diseases and Pest

Cyanobacteria could produce induced systemic resistance by producing diverse range of biologically active molecules in the rhizosphere which elicit the plant growth under different stresses (Prasanna et al. 2009a, b, 2010). Cyanobacteria could protect plant by providing mechanical and physical strength of the cell wall. Physiochemical reactions are altered by producing defense-related chemicals against the phytopathogens. Major defense enzymes involved in plant growth are chitinase, phenylalanine ammonia lyase (PAL), polyphenol oxidase (PPOs), phenolics, and phytoalexins (Kloepper et al. 1992). Prasanna et al. (2013) showed enhanced production of defense enzymes 189% and 239% of PAL and PPO, respectively, resulting in increased plant growth parameters and bioprotection against *Fusarium* wilt of tomato. Radhakrishnan et al. (2009) studied the effect of cultural filtrate of *Calothrix elenkinii* on fungicidal and algicidal activity which showed promising result. The strain was also evaluated for plant growth promotion, and the dual advantages of plant growth promotion and biocontrol potential make the strain more suitable candidate for agricultural use. Biondi et al. (2004) have reported insecticidal as well as nematicidal activity of *Nostoc* ATCC53789 on *Helicoverpa armigera* and *Caenorhabditis elegans*. Prasanna et al. (2008) showed biocidal activity against phytopathogenic fungi with *Anabaena* strain. Cyanobacterial extracts have been reported to reduce the infection of *Botrytis cinerea* in strawberries and *Erysiphe polygoni* in turnips and tomato seedlings, besides reducing the growth of saprophytic organisms and soilborne fungal pathogens (Kulik 1996; Prasanna et al. 2013). Application of *Calothrix elenkinii* and augmentation with copper nanoparticles (CuNPs) exhibited 76% disease control efficacy in pathogen-challenged plants such as tomato as compared to control. Similarly, augmentation enhanced the chitosanase activity by 10% and 7%, compared to CuNPs and *Calothrix elenkinii* alone. Higher dehydrogenase activity and increased root and shoot length have been also recorded in the rhizosphere soil of diseased plants as compared to healthy plants. Total PLFA content in the soil also increased significantly by 1.4–3.3-fold, compared to the control (Mahawar et al. 2019).

References

Adhikary A, Baruah PP (2015) Comparative diversity and composition of nitrogen-fixing cyanobacteria in three different land use systems of upper Assam. Ethiop J Environ Stud Manag 8:727–737

Ahmed M, Stal LJ, Hasnain S (2010a) Association of non-heterocystous cyanobacteria with crop plants. Plant Soil. https://doi.org/10.1007/s11104-010-0488-x

Ahmed M, Stal LJ, Hasnain S (2010b) Production of indole-3-acetic acid by the cyanobacterium *Arthrospira platensis* strain MMG-9. J Microbiol Biotechnol 20:1259. https://doi.org/10.4014/jmb.1004.04033

Amarawansa RPUI, Balasooriya BLWK, Dandeniya WS, Suganthan B, Dasanyaka T (2018) Identification of cyanobacteria inhabiting paddy fields in intermediate zone and dry zone of Sri Lanka. Trop Agric Res. https://doi.org/10.4038/tar.v29i4.8259

Bagul S, Tripathi S, Chakdar H, Karthikeyan N, Pandiyan K, Singh A, Kumar M (2018) Exploration and characterization of cyanobacteria from different ecological niches of india for phycobilins production. Int J Curr Sci Appl Microbiol 7(12):2822–2834. https://doi.org/10.20546/ijcmas.2018.712.321

Bergman B, Matveyev A, Rasmussen U (1996) Chemical signalling in cyanobacterial-plant symbioses. Trends Plant Sci 1:191. https://doi.org/10.1016/1360-1385(96)10021-2

Bhatnagar A, Makandar MB, Garg MK, Bhatnagar M (2008) Community structure and diversity of cyanobacteria and green algae in the soils of Thar Desert (India). J Arid Environ 72:73. https://doi.org/10.1016/j.jaridenv.2007.05.007

Bidyarani N, Prasanna R, Babu S, Hossain F, Saxena AK (2016) Enhancement of plant growth and yields in Chickpea (*Cicer arietinum* L.) through novel cyanobacterial and biofilmed inoculants. Microbiol Res 188–189:97. https://doi.org/10.1016/j.micres.2016.04.005

Biondi N, Piccardi R, Margheri MC, Rodolfi L, Smith GD, Tredici MR (2004) Evaluation of *Nostoc* strain ATCC 53789 as a potential source of natural pesticides. Appl Environ Microbiol 70 (6):3313–3320

Boopathi T, Balamurugan V, Gopinath S, Sundararaman M (2013) Characterization of IAA production by the mangrove Cyanobacterium *Phormidium* sp. MI405019 and its influence on tobacco seed germination and organogenesis. J Plant Growth Regul 32:758. https://doi.org/10.1007/s00344-013-9342-8

Bora A, Gogoi HK, Veer V (2016) Algal Wealth of Northeast India. In: Bioprospecting of indigenous bioresources of North-East India. Springer, New York, NY, pp 215–228

Chinnusamy M, Kaushik BD, Prasanna R (2006) Growth, nutritional, and yield parameters of wetland rice as influenced by microbial consortia under controlled conditions. J Plant Nutr 29:857. https://doi.org/10.1080/01904160600651803

Dadheech PK, Abed RMM, Mahmoud H, Krishna Mohan M, Krienitz L (2012) Polyphasic characterization of cyanobacteria isolated from desert crusts, and the description of *Desertifilum tharense* gen. et sp. nov. (Oscillatoriales). Phycologia 51:260. https://doi.org/10.2216/09-51.1

Debnath M, Bhadury P (2016) Adaptive responses and arsenic transformation potential of diazotrophic Cyanobacteria isolated from rice fields of arsenic affected Bengal Delta Plain. J Appl Phycol 28:2777. https://doi.org/10.1007/s10811-016-0820-9

Gayathri K, Easwarakumar K, Elias S (2017) Probabilistic ontology based activity recognition in smart homes using Markov Logic Network. Knowl-Based Syst 121:173–184. https://doi.org/10.1016/j.knosys.2017.01.025

Haider AA, Haifaa MJ (2018) Effect of environmental factors on cyanobacteria richness in some agricultural soils. Geomicrobiol J 36:1. https://doi.org/10.1080/01490451.2018.1517196

Hashtroud MS, Ghassempour A, Riahi H, Shariatmadari Z, Khanjir M (2013) Endogenous auxins in plant growth-promoting Cyanobacteria-*Anabaena vaginicola* and *Nostoc calcicola*. J Appl Phycol 25:379. https://doi.org/10.1007/s10811-012-9872-7

Hussain A, Hasnain S (2012) Comparative assessment of the efficacy of bacterial and cyanobacterial phytohormones in plant tissue culture. W J Microbiol Biotechnol 28:1459. https://doi.org/10.1007/s11274-011-0947-4

Jena M, Adhikary S (2007) Chlorococcales (Chlorophyceae) of Eastern and North-eastern States of India. Algae 22(3):167–183. https://doi.org/10.4490/algae.2007.22.3.167

Jing H, Xia X, Liu H, Zhou Z, Wu C, Nagarajan S (2015) Anthropogenic impact on diazotrophic diversity in the mangrove rhizosphere revealed by nifH pyrosequencing. Front Microbiol 6:1172. https://doi.org/10.3389/fmicb.2015.01172

Karthikeyan N, Prasanna R, Nain L, Kaushik BD (2007) Evaluating the potential of plant growth promoting cyanobacteria as inoculants for wheat. Eur J Soil Biol 43:23. https://doi.org/10.1016/j.ejsobi.2006.11.001

Karthikeyan N, Prasanna R, Sood A, Jaiswal P, Nayak S, Kaushik BD (2009) Physiological characterization and electron microscopic investigation of cyanobacteria associated with wheat rhizosphere. Folia Microbiol 54(1):43–51. https://doi.org/10.1007/s12223-009-0007-8

Kloepper JW, Schippers B, Bakker PA (1992) Proposed elimination of the term endorhizosphere. Phytopathology 82:726–727

Kulik MM (1996) Actinomycetes, cyanobacteria and algae. In: Rhizoctonia species: taxonomy, molecular biology, ecology, pathology and disease control. Springer, Dordrecht

Kumar D, Adhikary SP (2015) Diversity, molecular phylogeny, and metabolic activity of cyanobacteria in biological soil crusts from Santiniketan (India). J Appl Phycol 27:339. https://doi.org/10.1007/s10811-014-0328-0

Kumar A, Kaur R (2014) Impact of cyanobacterial filtrate on seed germination behaviour of wheat. Int J Basic Appl Microbiol 1(1):11–15

Mahawar H, Prasanna R, Gogoi R (2019) Elucidating the disease alleviating potential of cyanobacteria, copper nanoparticles and their interactions in *Fusarium solani* challenged tomato plants. Plant Physiol Rep 24:533. https://doi.org/10.1007/s40502-019-00490-8

Manickavelu A, Nadarajan N, Ganesh SK, Ramalingam R, Raguraman S, Gnanamalar RP (2006) Organogenesis induction in rice callus by cyanobacterial extracellular product. Afr J Biotechnol 5:437. https://doi.org/10.5897/AJB05.363

Mazhar S, Cohen J, Hasnain S (2013) Auxin producing non-heterocystous Cyanobacteria and their impact on the growth and endogenous auxin homeostasis of wheat. J Basic Microbiol 53(12):996–1003. https://doi.org/10.1002/jobm.201100563

Mishra SK, Singh J, Pandey AR, Dwivedi N (2019) Indole-3-acetic acid production by the cyanobacterium Fisherella muscicola NDUPC001. Curr Sci 116

Nain L, Rana A, Joshi M, Jadhav SD, Kumar D, Shivay YS, Paul S, Prasanna R (2010) Evaluation of synergistic effects of bacterial and cyanobacterial strains as biofertilizers for wheat. Plant Soil 331:217. https://doi.org/10.1007/s11104-009-0247-z

Natesan R, Shanmugasundaram S (1989) Extracellular phosphate solubilization by the cyanobacterium *Anabaena* ARM310. J Biosci 14:203. https://doi.org/10.1007/BF02716680

Nayak S, Prasanna R, Pabby A, Dominic TK, Singh PK (2004) Effect of BGA-Azolla biofertilizers on nitrogen fixation and chlorophyll accumulation at different depths in soil cores. Biol Fertil Soils 40:67–72

Obana S, Miyamoto K, Morita S, Ohmori M, Inubushi K (2007) Effect of *Nostoc* sp. on soil characteristics, plant growth and nutrient uptake. J Appl Phycol 19(6):641–646. https://doi.org/10.1007/s10811-007-9193-4

Prasanna R, Kaushik BD (2006) Cyanobacteria in soil health and sustainable agriculture. Health Environ 3:91–105

Prasanna R, Nayak S (2007) Influence of diverse rice soil ecologies on cyanobacterial diversity and abundance. Wetl Ecol Manag 15:127. https://doi.org/10.1007/s11273-006-9018-2

Prasanna R, Kumar V, Kumar S, Yadav AK, Tripathi U, Singh AK, Jain MC, Gupta P, Singh PK, Sethunathan N (2002) Methane production in rice soils is inhibited by cyanobacteria. Microbiol Res 157:1–6. https://doi.org/10.1078/0944-5013-00124

Prasanna R, Nain L, Tripathi R, Gupta V, Chaudhary V, Middha S, Joshi M, Ancha R, Kaushik BD (2008) Evaluation of fungicidal activity of extracellular filtrates of cyanobacteria - possible role of hydrolytic enzymes. J Basic Microbiol 48:186. https://doi.org/10.1002/jobm.200700199

Prasanna R, Jaiswal P, Nayak S, Sood A, Kaushik BD (2009a) Cyanobacterial diversity in the rhizosphere of rice and its ecological significance. Industrial J Microbiol 49:89–97

Prasanna R, Nain L, Ancha R, Shrikrishna J, Joshi M, Kaushik BD (2009b) Rhizosphere dynamics of inoculated cyanobacteria and their growth-promoting role in rice crop. Egypt J Biol 11:26–36

Prasanna R, Gupta V, Natarajan C, Chaudhary V (2010) Allele mining for chitosanases and microcystin-like compounds in *Anabaena* strains. W J Microbiol Biotechnol 26:717–724

Prasanna P, Chaudhary V, Gupta V, Babu S, Kumar A, Singh R, Singh V, Shivay S, Lata N (2013) Cyanobacteria mediated plant growth promotion and bioprotection against *Fusarium* wilt in tomato. Eur J Plant Pathol 136:337–353

Priya H, Prasanna R, Ramakrishnan B, Bindya Rani N, Babu S, Thapa S, Renuka S (2015) Influence of cyanobacterial inoculation on the culturable microbiome and growth of rice. Microbiol Res 171:78. https://doi.org/10.1016/j.micres.2014.12.011

Radhakrishnan B, Prasanna R, Jaiswal P, Nayak S, Dureja P (2009) Modulation of biocidal activity of Calothrix sp. and Anabaena sp. by environmental factors. Biologia (Bratisl). https://doi.org/10.2478/s11756-009-0169-5

Rodríguez AA, Stella AM, Storni MM, Zulpa G, Zaccaro MC (2006) Effects of cyanobacterial extracellular products and gibberellic acid on salinity tolerance in *Oryza sativa* L. Saline Syst 2 (1):7

Roger PA, Reynaud PA (1982) Free — living blue — green algae in tropical soils. In: Dommergues YR, Diem HG (eds) Microbiology of tropical soils and plant productivity. Developments in plant and soil sciences, vol 5. Springer, Dordrecht, pp 147–168. https://doi.org/10.1007/978-94-009-7529-3_5

Roychoudhury P, Kaushik BD (1989) Solubilization of Mussoorie rock phosphate by cyanobacteria. Curr Sci 58:569–557

Saadatnia H, Riahi H (2009) Cyanobacteria from paddy fields in Iran as a biofertilizer in rice plants. Plant Soil Environ 55:207. https://doi.org/10.17221/384-pse

Sergeeva E, Liaimer A, Bergman B (2002) Evidence for production of the phytohormone indole-3-acetic acid by cyanobacteria. Planta 215(2):229–238

Shariatmadari Z, Riahi H, Seyed Hashtroudi M, Ghassempour AR, Aghashariatmadary Z (2013) Plant growth promoting cyanobacteria and their distribution in terrestrial habitats of Iran. Soil Sci Plant Nutr 59:535. https://doi.org/10.1080/00380768.2013.782253

Silambarasan G, Ramanathan T, Kathiresan K (2012) Diversity of marine cyanobacteria from three mangrove environment in Tamil Nadu Coast, South East Coast of India. Curr Res J Biol Sci 4 (3):235–238

Singh JS, Kumar A, Rai AN, Singh DP (2016) Cyanobacteria: a precious bio-resource in agriculture, ecosystem, and environmental sustainability. Front Microbiol 7:529. https://doi.org/10.3389/fmicb.2016.00529

Singh AK, Singh PP, Tripathi V, Verma H, Singh SK, Srivastava AK, Kumar A (2018) Distribution of cyanobacteria and their interactions with pesticides in paddy field: a comprehensive review. J Environ Manag 224:361. https://doi.org/10.1016/j.jenvman.2018.07.039

Song T, Martensson L, Eriksson T, Zheng W, Rasmussen U (2005) Biodiversity and seasonal variation of the cyanobacterial assemblage in a rice paddy field in Fujian, China. FEMS Microbiol Ecol 54(1):131–140

Stihl A, Sommer U, Post AF (2001) Alkaline phosphatase activities among populations of the colony-forming diazotrophic cyanobacterium *Trichodesmium* spp. (Cyanobacteria) in the red sea. J Phycol 37:310. https://doi.org/10.1046/j.1529-8817.2001.037002310.x

Toledo G, Bashan Y, Soeldner A (1995) In vitro colonization and increase in nitrogen fixation of seedling roots of black mangrove inoculated by a filamentous cyanobacteria. Can J Microbiol 41:1012. https://doi.org/10.1139/m95-140

Van Den Hoek C, Mann DG, Jahns HM (1995) Algae: an introduction to phycology. Cambridge University Press, Cambridge, p 623

Wilson AE, Sarnelle O, Tillmanns AR (2006) Effects of cyanobacterial toxicity and morphology on the population growth of freshwater zooplankton: meta-analyses of laboratory experiments. Limnol Oceanogr 51(4):1915–1924

Wyatt JT, Silvey JK (1969) Nitrogen fixation by *Gloeocapsa*. Science 165:908–909

Yandigeri M, Yadav A, Srinivasan R, Kashyap S, Pabbi S (2011) Studies on mineral phosphate solubilization by cyanobacteria *Westiellopsis* and *Anabaena*. Microbiology 80(4):558–565. https://doi.org/10.1134/s0026261711040229

Young J, Gu L, Hildreth M, Zhou R (2019) Unicellular cyanobacteria exhibit light-driven, oxygen-tolerant, constitutive nitrogenase activity under continuous illumination. bioRxiv 619353