

Cyanobacterial Contributions on Agriculture– A Review

Abstract :

Purpose: This paper reviews the diverse agricultural applications of cyanobacteria for improving soil health, plant growth, and agricultural sustainability.

Research Method: The paper provides a literature review summarizing recent research on cyanobacteria's roles in soil aggregation, biofertilization, abiotic/biotic stress tolerance, yield improvements, carbon sequestration, and bioremediation. Both laboratory studies and field trials evaluating cyanobacteria's effects on soil properties and plant growth are discussed.

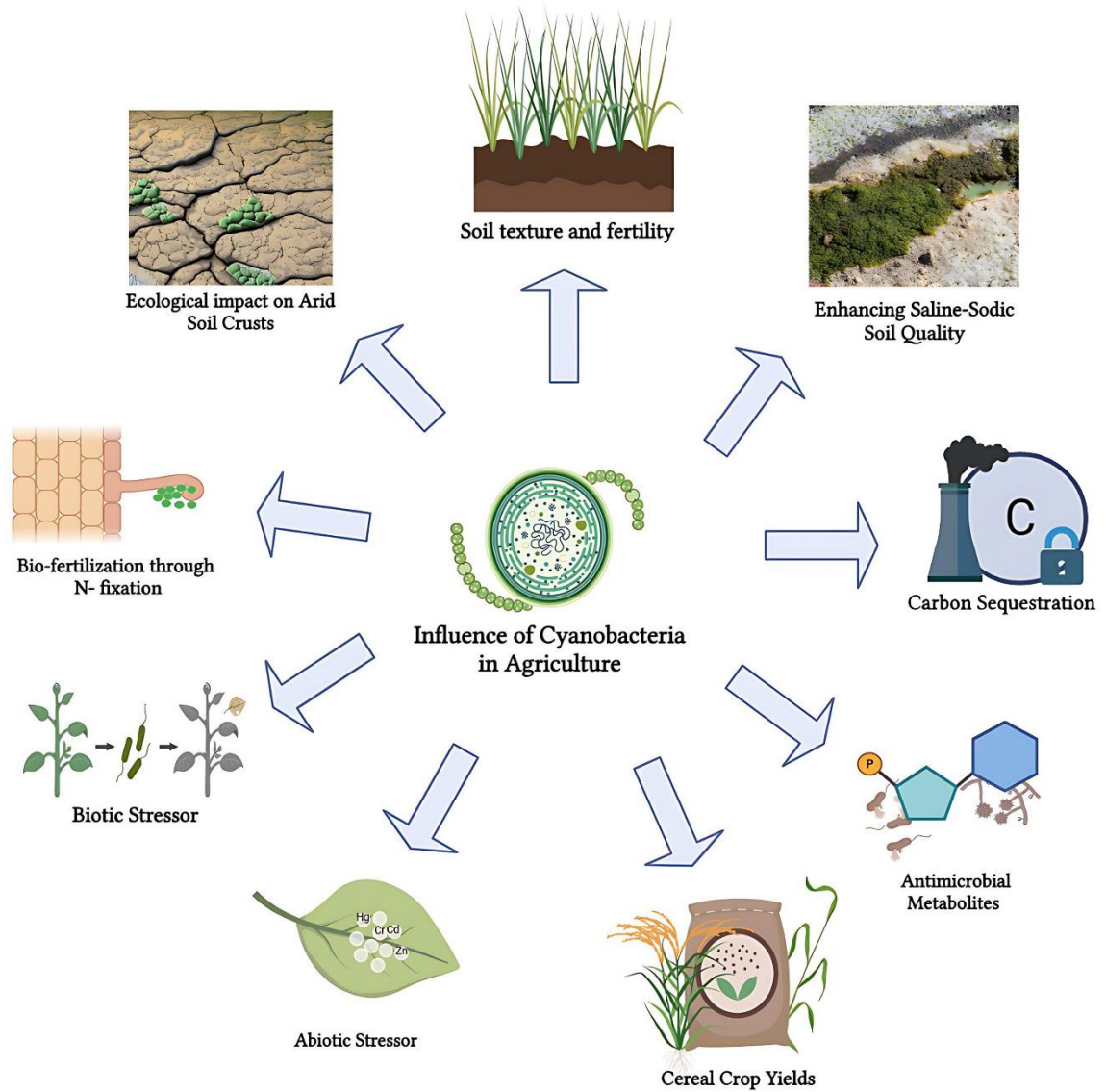
Findings: Cyanobacteria can enhance soil structure, provide fixed nitrogen, mitigate salinity stress, increase crop yields, and sequester carbon. Their stress adaptations, antimicrobial metabolites, and synergies with plants and microbes underpin many benefits. However, translating laboratory research into effective field inoculants remains challenging.

Research Limitation: Variability in effectiveness across cyanobacterial strains, plant species, and environments limits current understanding. More field testing is needed along with assessment of potentially negative impacts.

Originality/Value: This review highlights promising areas for cyanobacteria to promote agricultural sustainability while identifying knowledge gaps in genetics, plant-microbe interactions, and soil ecology that require further study. It emphasizes the need for locally-adapted, integrated solutions leveraging cyanobacteria's multifunctional traits.

Keywords: Cyanobacteria, Agriculture, Soil health, Biofertilizer, Bioremediation

GRAPHICAL ABSTRACT:



1. INTRODUCTION

Agriculture is critical to the survival of humans and the provision of food for the world's rising population. It is a scientific discipline that involves cultivating plants and rearing animals for a variety of reasons, including the production of food, fiber, and industrial raw materials. Agriculture is important because of its ability to provide nourishment, promote economic development, and contribute to societal well-being. Agriculture has the ability to maximize agricultural yields, increase livestock output, and reduce environmental impacts by implementing scientific methods and developments, making it a vital field of research and practice (Refrence)

Cyanobacteria, which have traditionally been classified as excellent oxygenic phototrophs, use photosynthesis to convert ambient CO₂ and water into organic molecules (Ward *et al.*, 2011). Recent discoveries have revealed unique cyanobacterial lineages characterized by the absence of genes linked to photosynthesis and CO₂ fixation processes. (Di Rienzi *et al.*, 2013; Soo *et al.*, 2014). Prominent among these non-photosynthetic cyanobacterial groups are 4C0d-2 and ML635J-21, delineated through the assembly of metagenomic genomes (Soo *et al.*, 2014; Soo *et al.*, 2019).

Cyanobacteria wield ecological significance across diverse ecosystems, spanning aquatic and terrestrial realms. Their propensity for symbiotic associations with various organisms including bryophytes, fungi, and *Azolla* underscores their ecological importance (Rai *et al.*, 2000). Within terrestrial landscapes, particularly in biological soil crusts, cyanobacteria occupy a pivotal role in shaping soil structure and influencing nutrient dynamics. Certain filamentous cyanobacteria produce extracellular polymeric substances that foster soil particle aggregation and enhance stability (Chamizo *et al.*, 2018). Notably, some cyanobacterial strains, such as *Nostoc* and *Anabaena*, have been exploited as biofertilizers, particularly in rice agriculture, leveraging their nitrogen-fixing properties to reduce dependency on traditional nitrogen fertilizers. (De, 1939; Zhang *et al.*, 2021).

Cyanobacteria have also demonstrated adaptive mechanisms for salinity stress, exemplified by their active expulsion of sodium ions and efficient transport of potassium ions (Singh *et al.*, 2022). This adaptability has incited explorations into their potential applicability for remediating saline-affected soils. Additionally, the nexus between cyanobacterial filaments and oxygenic photosynthesis

has been associated with prospective soil organic carbon sequestration, bearing implications for ecosystem carbon dynamics (Crouzet *et al.*, 2019).

The exploration of non-photosynthetic cyanobacterial lineages presents an evolving domain necessitating comprehensive investigation concerning their roles in carbon and nitrogen cycling processes (Soo *et al.*, 2017). nevertheless, knowledge gaps persist, spanning cyanobacterial diversity, taxonomy, ecological functions, and mechanistic insights (Hirose *et al.*, 2021). Addressing these gaps entails expanding culture collections and conducting comprehensive genomic analyses encompassing both cultivated and uncultured cyanobacterial cohorts (Fawley & Fawley, 2020).

2. SOIL TEXTURE AND FERTILITY

Cyanobacteria play a major role in improving soil structure and fertility. They act as ecological engineers that can modulate ecological processes in the soil and create habitats for other organisms (Jones *et al.*, 1994). The type of crust that forms on the soil surface depends on the amount of moisture present. Cyanobacteria are the first organisms to establish biological soil crusts in arid environments. As the crusts develop, other organisms may also thrive in them.

The addition of cyanobacteria under laboratory and field conditions has resulted in significant improvements in soil structure and aggregate stability (Wang *et al.*, 2009; Park *et al.*, 2017; Mugnai *et al.*, 2018). Cyanobacteria improve soil aggregate stability by producing filaments and extracellular secretions that act as binding agents (Mazor *et al.*, 1996). Chamizo *et al.* (2018) inoculated two cyanobacterial species, the non-N₂-fixing *Phormidium ambiguum* and the N₂-fixing *Scytonema javanicum*, into different textured soils. After 90 days, cyanobacterial inoculation led to increased total exopolysaccharide content and soil penetration resistance with *P. ambiguum*, while total organic carbon and nitrogen contents increased with *S. javanicum*. The filaments and extracellular polysaccharides of cyanobacteria act as gluing agents to bind soil particles for enhanced aggregate formation (Chamizo *et al.*, 2018).

Cyanobacterization, or soil inoculation with cyanobacteria, is effective for stabilizing burned soils and restoring post-fire ecosystems (Chamizo *et al.*, 2019; Muñoz-Rojas *et al.*, 2021). Recently, Shantakumar *et al.* (2021) showed inoculation of acid soils with acid-tolerant cyanobacteria species led to improved soil aggregate stability. The cyanobacteria tested were able to decrease soil pH through organic acid production, as well as increase exopolysaccharide content which aids in soil aggregation (Shantakumar *et al.*, 2021). Cyanobacteria can establish symbiotic relationships with

bryophytes, fungi, Azolla, and Gunnera due to their ability to form heterocysts and hormogonia (Rai *et al.*, 2000). Heterocysts are specialized N₂-fixing cells that provide microoxic conditions for the oxygen-sensitive nitrogenase enzyme. Hormogonia are short mobile filaments that allow dispersal and colonization of new environments. The only angiosperm that can form symbiotic relationships with cyanobacteria is Gunnera (Rai *et al.*, 2000). This is likely because Gunnera stem glands provide an anaerobic environment suited for the oxygen-sensitive nitrogenase enzyme of cyanobacteria.

Cyanobacteria are a dominant group in biological soil crusts, where they contribute to soil fertility and structure (Büdel *et al.*, 2016). Cyanobacterial diversity varies in crusts depending on factors like crust age, soil texture, climate, and geography. Common cyanobacteria in biocrusts include *Microcoleus*, *Chroococcidiopsis*, *Nostoc*, *Scytonema*, *Phormidium*, *Oscillatoria*, and *Nostoc* (Büdel *et al.*, 2016). The filamentous forms aid in soil binding and aggregation. Other physiological adaptations also allow crust cyanobacteria to survive in dry, high light conditions. The filaments and extracellular matrices of edaphic cyanobacteria improve soil aggregate stability by binding soil microbiota and particles over aggregates (Crouzet *et al.*, 2019). The exopolysaccharide sheath surrounding cyanobacterial filaments helps maintain soil moisture as well as protects cells from desiccation. Cyanobacteria synthesize specialized UV-absorbing pigments like scytonemin and mycosporine-like amino acids to shield from high irradiation in biological crusts (Lu *et al.*, 2022).

3. BIO-FERTILIZATION THROUGH NITROGEN FIXATION.

Cyanobacteria can fix atmospheric nitrogen (N₂) via spatial segregation of nitrogenase in heterocysts and temporal separation of N₂ fixation at night (Boyd and Peters, 2013). This characteristic has led to their application as biofertilizers, particularly in flooded rice paddies (De, 1939). The enzyme nitrogenase is particularly sensitive to oxygen, hence cyanobacteria have evolved ways to protect it and separate oxygenic photosynthesis from N₂ fixation (Boyd and Peters, 2013).

). These include upregulating N₂ fixation at night when oxygen levels are lower, and differentiation of heterocysts that have thicker cell walls and lack photosystem II to maintain an anaerobic cellular environment.

In rice fields, cyanobacterial biofertilizers can fix 25-30 kg of N ha/season/(Prasanna *et al.*, 2015). The symbiotic *Azolla-Anabaena* system can contribute 20-40 kg N ha⁻¹ to rice crops in about 25 days (Roger & Ladha, 1992). *Anabaena azollae* is the N₂-fixing cyanobacterium that lives in leaf

cavities of the aquatic fern *Azolla*. The cyanobacteria receive carbon from the *Azolla* host while providing fixed nitrogen. This symbiotic association allows *Azolla* to grow rapidly and accumulate high levels of nitrogen (Kellar & Goldman 1979). The steps for mass producing cyanobacterial biofertilizers for applications in rice cultivation in India have been established, with inoculum containing *Aulosira*, *Nostoc*, *Anabaena*, and *Tolypothrix* (Chittora *et al.*, 2020). *Aulosira*, *Nostoc* and *Anabaena* are common filamentous, heterocystous cyanobacteria used in rice agriculture.

The cyanobacterium *Anabaena azotica* can partially substitute nitrogen fertilizers in rice fields by 30-50% while sustaining yields (Zhang *et al.*, 2021). *Anabaena azotica* is a heterocystous, filamentous cyanobacterium capable of providing significant amounts of biologically fixed nitrogen. Replacing a portion of chemical nitrogen fertilizers with this organism can reduce costs and environmental impacts while maintaining crop productivity. Cyanobacteria solubilize phosphates to a limited extent. They can sequester phosphorus as polyphosphates to mitigate stress (Mukherjee *et al.*, 2015). Polyphosphate metabolism allows cyanobacteria to accumulate and store phosphorus when it is available in excess, and then utilize it for growth during phosphorus starvation conditions. This adaptation helps cyanobacteria thrive in soils and waters where phosphorus levels fluctuate.

Cyanobacteria are mostly used as phototrophic plant biostimulants that provide fixed carbon, nitrogen, and phytohormones to promote plant growth (Santini *et al.*, 2021). However, high inoculum rates and need for frequent irrigation hinder direct applications of cyanobacteria for soil conditioning (Metting & Rayburn, 1983). Their agronomic applications as biofertilizers or bio-stimulants depend largely on successful commercial production. Mass culturing cyanobacteria can be challenging due to their relatively slow growth compared to other microbes. Contamination issues also commonly impact large-scale cyanobacterial cultivation intended for agricultural uses (Borowitzka, 1999).

4. ECOLOGICAL IMPACT ON ARID SOIL CRUSTS

Biological soil crusts containing cyanobacteria are abundant in arid and semi-arid environments, where they play a major role in improving soil structure, fertility, hydrology, and C and N fixation (Belnap *et al.*, 2016). Crusts dominate ground cover in drylands across about 35% of the Earth's land surface (Smith *et al.*, 2019). Filamentous cyanobacteria like *Microcoleus* contribute to soil stabilization in crusts by producing extracellular matrices that bind and glue together soil particles (Büdel *et al.*, 2016). *Microcoleus* produces copious amounts of exopolysaccharides that aid in soil

aggregation and moisture retention. The filamentous morphology also facilitates binding of soil particles (Rossi *et al.*, 2017).

Other common crust cyanobacteria are *Chroococcidiopsis*, *Nostoc*, *Scytonema*, *Phormidium*, *Oscillatoria*, and *Nostoc* (Büdel *et al.*, 2016). *Chroococcidiopsis*, in particular, has remarkable adaptations to survive extreme aridity. It has a multilayered, highly melanized cell wall and the ability to enter long-term dormancy (Caiola & Billi, 2007). *Nostoc* and *Scytonema* can fix N₂ in crusts, while *Oscillatoria* contributes to C cycling. Inoculation of cyanobacteria from biological crusts into soils can increase carbon and nitrogen fixation, thereby improving fertility in arid lands (Kheifam & Roohi, 2020). For example, inoculation of *Nostoc commune* into degraded soils significantly increased total nitrogen and organic carbon content compared to uninoculated soils (Roncero-Ramos *et al.*, 2019). The added C and N from cyanobacteria improve conditions for plant establishment.

Cyanobacteria-based biocrusts have potential for restoring degraded drylands and mitigating desertification (Gholamhosseini *et al.*, 2021; Wang *et al.*, 2022). Biocrusts can be cultivated on-site then inoculated into degraded soils to kickstart ecological succession (Ayuso *et al.*, 2016). They improve fertility and provide microbial community structure lacking in eroded desert soils. Zhou and Zhang (2012) showed artificially cultivated biocrusts increased water runoff efficiency and reduced runoff sediment. Biocrusts can be used as green materials for rainwater harvesting in dry environments (Zhou & Zhang, 2012). The complex matrices formed by cyanobacterial exopolysaccharides absorb water like a sponge, capturing rainfall and reducing erosion (Rossi *et al.*, 2017).

Cyanobacteria in crusts possess various survival strategies to thrive in arid conditions, including synthesis of protective pigments and compounds, secretion of extracellular polysaccharides, and formation of microbial consortia (Lu *et al.*, 2022). To survive prolonged desiccation, crust cyanobacteria produce trehalose, a disaccharide sugar that helps preserve membranes and proteins (Harel *et al.*, 2015). Specialized UV-absorbing pigments like scytonemin and mycosporine-like amino acids shield cells from high irradiation (Xu *et al.*, 2022). Exopolysaccharides also aid in moisture retention (Bhunja *et al.*, 2018).

5. ENHANCING SALINE-SODIC SOIL QUALITY

Cyanobacteria can withstand and even thrive in salty and sodic soils because to a variety of physiological adaptations. They have salinity sensing and signaling mechanisms, as well as tolerance mechanisms for dealing with the negative effects of excessive salinity (Singh *et al.*, 2022).

Some key adaptations include active sodium efflux to prevent toxic accumulation, potassium transport systems to maintain homeostasis, production of organic osmolytes for osmotic balance, and modulation of enzymes to maintain metabolism under salt stress (Singh *et al.*, 2022).

Certain cyanobacteria strains can decrease the electrical conductivity, pH, and exchangeable sodium content in saline-sodic soils. Kaushik and Subhasini (1985) showed algalization with *Anabaena* spp. lowered these parameters. The ameliorative effect is attributed to active photosynthesis-driven sodium extrusion, based on radiotracer studies using ²²Na and ²⁴Na (Thomas, 1977). However, the ability to mobilize calcium for exchanging with sodium is likely needed for effective remediation of degraded alkali soils (Rao & Burns, 1991).

Pandey *et al.* (2005) found the alkali-tolerant cyanobacterium *Nostoc calcicola* was prevalent in the sodic soils of India. Further, its bicarbonate-resistant mutant strain was more effective than the wild type in decreasing soil pH in laboratory incubations (Pandey *et al.*, 2005; Jaiswal *et al.*, 2010). Bicarbonate toxicity is a key constraint in sodic soils, so bicarbonate-tolerant strains have potential for bio-amelioration (Jaiswal *et al.*, 2010). The cyanobacterium *Hapalosiphon fontinalis* decreased pH, electrical conductivity, and exchangeable sodium percentage (ESP) in saline soils (Singh & Dhar 2010). White cotton mealybug numbers were also reduced by 68% after *H. fontinalis* treatment due to changes in physicochemical properties. This demonstrates the bio-ameliorative and biocontrol potential of cyanobacteria.

Co-cultures of cyanobacteria with other microbes have shown promise as bio-remediating inoculants for salt-affected soils (Li *et al.*, 2019). Cyanobacteria can stimulate plant responses that mitigate salinity stress and maintain ion homeostasis (Brito *et al.*, 2022). However, the priming benefits depend on the plant and cyanobacterial species as well as growth conditions (Brito *et al.*, 2022). Overall, lab and field evaluation of cyanobacterial strains native to target saline-sodic soils will be important for developing effective microbial amelioration techniques. Their safety for crops over the long-term should also be assessed. Technological advances are needed to scale up preparation of cyanobacterial inoculum to restore large, severely degraded areas (Li *et al.*, 2019).

6. BUILDING RESISTANCE TO ABIOTIC STRESSORS

Soil salinization is a significant agricultural challenge affecting approximately 20% of irrigated lands worldwide. Cyanobacteria offer a promising solution to enhance salt tolerance in crops such as rice, wheat, and millet through various mechanisms, including nitrogen fixation, the release of

extracellular polysaccharides, compatible solutes, plant hormones, and antioxidative enzymes (Abbas *et al.*, 2015; Gheda & Ahmed 2015; Li *et al.* 2019). For instance, the inoculation of rice with halotolerant cyanobacteria like *Nostoc calcicola*, *N. linkia*, and *Anabaena variabilis* has been shown to increase root length, seedling growth, and grain yield under saline conditions by improving soil nitrogen content and biological activity (Hassan *et al.* 2018; Jan *et al.* 2017).

Similar benefits in the physical structure, nutritional status, and microbial activity of salt-affected soils have been shown by a consortium consisting of *Nostoc ellipsoforum* and *N. punctiforme*, which has improved millet and wheat development (Nisha *et al.* 2018). By controlling osmolytes and antioxidants through the synthesis of exopolysaccharides and plant hormones, *Anabaena sphaerica* and *Scytonema hofmanni* help rice and wheat tolerate salt (Kharwar *et al.*, 2022; Rodriguez *et al.* 2006).

In addition to salinity stress, cyanobacteria also play a vital role in enhancing drought tolerance in plants. Inoculation with *Microcoleus* sp. and *Nostoc* sp. has been shown to promote seed germination and seedling establishment, particularly in water-deficit conditions, benefiting dryland restoration efforts (Muñoz-Rojas *et al.* 2018). Furthermore, *Spirulina meneghiniana* and *Anabaena oryzae* have been found to increase lettuce growth under limited moisture conditions by modulating plant antioxidants and osmolytes (Ibraheem 2007).

Cyanobacteria exhibit impressive capabilities in heavy metal remediation by efficiently removing toxic heavy metals such as Cd, Cr, Cu, and Zn from contaminated soils. Species like *Anabaena variabilis*, *Nostoc muscorum*, *Aulosira fertilissima*, and *Tolypothrix tenuis* have been instrumental in reducing the levels of these metals in soils amended with coal fly ash (Kaur & Goyal 2018). *Oscillatoria* sp. and *Synechocystis* sp. have been successful in increasing wheat tolerance to Cr by decreasing bioavailable metal fractions (Faisal *et al.* 2005). Additionally, *Spirulina platensis* has been effective in restricting Cd translocation and enhancing antioxidants in maize grown in Cd-contaminated soils (Seifikalhor *et al.* 2019).

Another crucial application of cyanobacteria lies in pesticide detoxification, where they can degrade or sequester pesticides, including organophosphates, organochlorines, and herbicides, in both soil and water bodies, thus reducing their phytotoxicity. *Fischerella* sp. and *Scytonema hofmanni* have been known to mitigate the toxicity of methyl parathion by utilizing it as a phosphate source (Tiwari *et al.* 2017). *Synechocystis* sp. and *Phormidium* sp. have effectively bioabsorbed the neonicotinoid imidacloprid from soils (Aminfarzaneh & Duygu 2010). Furthermore, the inoculation of

Spirulina platensis has induced protective amino acids in bean plants, counteracting the effects of the herbicide fusilade (Osman et al. 2016).

Innovative approaches are emerging, such as plant genetic engineering using cyanobacterial genes, to develop stress-resilient crops. For example, transforming poplar with a heat shock protein (HSP70) gene from the halotolerant *Aphanothece halophytica* has resulted in increased tolerance to salinity, drought, and extreme temperatures (Takabe et al. 2008). Similarly, Arabidopsis lines expressing a water stress protein (WSPA1) from *Nostoc commune* have exhibited improved performance under saline conditions (Ai et al. 2014). Overexpression of *Anabaena* flavodoxin genes has enhanced tolerance against drought, heat, salinity, and oxidative stress in tobacco, creeping bentgrass, and alfalfa by modulating antioxidants and stress proteins (Tognetti et al. 2006; Li et al. 2017; Coba de la Peña et al. 2010).

7. BUILDING RESISTANCE TO BIOTIC STRESSORS

Cyanobacteria offer valuable properties for agricultural applications, including antibacterial activity against crop pathogens like *Pseudomonas aeruginosa*, *Ralstonia solanacearum*, and *R. syzygii*. For instance, research has shown that *Spirulina platensis*, *Nostoc sp.*, and *Stigonema sp.* filtrates can inhibit the growth of *P. aeruginosa* by releasing bioactive substances such as fatty acids, norharmane, and 4,4'-dihydroxybiphenyl (Abedin & Taha 2008; Catarina Guedes et al. 2011; Volk & Furkert 2006). Cell extracts of *Anabaena flos-aquae* have also demonstrated potent antibacterial effects against the potato brown rot pathogen *R. solanacearum* (Mikhail et al. 2016). Moreover, indigenous rhizospheric cyanobacteria isolated from chili fields have shown promising biocontrol capabilities against chili bacterial wilt caused by *R. syzygii* (Yanti et al. 2019).

Cyanobacteria are also known for their antifungal properties, as they produce secondary metabolites, enzymes, and volatiles that combat phytopathogens like *Fusarium*, *Alternaria*, *Aspergillus*, and *Botrytis* in various crops, including rice, tomato, lupine, and maize. Methanolic extracts of *Nostoc commune*, for example, effectively inhibit the mycelial growth of these fungi (Kim 2006). *Anabaena variabilis* has been found to reduce *Fusarium* wilt in tomatoes by releasing antifungal fatty acids and lipopeptides (Chaudhary et al. 2012). Additionally, cyanobacteria produce chitinase enzymes that suppress fungi like *Fusarium oxysporum* and *Macrophomina phaseolina* (Gupta et al. 2012; Afify & Ashour 2018). They also stimulate plant systemic resistance against foliar fungal pathogens by priming defense enzyme activity (Attia et al. 2017).

Furthermore, cyanobacteria exhibit nematicidal activity through cell-free extracts, effectively targeting plant-parasitic nematodes like *Meloidogyne*, *Heterodera*, and *Rotylenchulus* species by inhibiting mobility, egg hatching, and juvenile mortality (Holajjer et al. 2012; Chandel 2009). They enhance host plant tolerance by triggering systemic resistance pathways mediated by salicylic acid and jasmonic acid signaling (Sharaf et al. 2016).

In terms of pest control, cyanobacterial strains produce insecticidal metabolites toxic to crop pests such as cotton bollworm, Colorado potato beetle, and rice stem borer. Crude extracts of *Nostoc* sp. have demonstrated larvicidal activity against cotton bollworm *Helicoverpa armigera* (Biondi et al. 2004). Toxins derived from *Anabaena variabilis* and *Synechococcus leopoliensis* have been found to inhibit the feeding behavior of the Colorado potato beetle *Leptinotarsa decemlineata* on potato foliage (Gol'din 2012). Additionally, *Anabaena oryzae*, *A. cylindrica*, and *Nostoc muscorum* have shown field control of rice whorl maggot and stem borer by inducing systemic resistance against insects (Yanni & Abdallah 1990).

Lastly, cyanobacterial genes have been employed in plant genetic engineering to create transgenic plants with enhanced resistance to biotic stress. For example, rice lines expressing insecticidal *Bacillus thuringiensis* cry genes, along with promoters and 5'-UTRs from *Anabaena* sp., have exhibited improved resistance against lepidopteran pests (Datta et al. 1998). Similarly, the expression of osmotin, a PR-5 family protein from the halotolerant *Aphanothece halophytica*, has conferred transgenic tobacco with resistance to fungal pathogens such as *Phytophthora parasitica*, *Alternaria alternata*, and *Botrytis cinerea* (Safdar et al., 2013)

8. ANTIMICROBIAL METABOLITES FOR PLANT DISEASE CONTROL

Cyanobacteria produce a diverse array of bioactive metabolites that can inhibit fungal and bacterial phytopathogens (Kulik, 1995). Crude extracts prepared from cyanobacteria using various organic solvents have shown antifungal activity against *Aspergillus*, *Fusarium*, *Sclerotinia*, *Rhizoctonia*, *Pythium* and other pathogens (Righini et al., 2022). Cyanobacterial strains such as *Anabaena*, *Nostoc*, *Hapalosiphon*, *Scytonema*, *Tolypothrix*, and *Fischerella* produce antifungal alkaloids, lipopeptides, polyketides, and other compounds (Demay et al., 2019; Swain et al., 2017; Svirčev et al., 2016).

The antifungal metabolites from cyanobacteria act through mechanisms such as disruption of membrane integrity, inhibition of respiration, interference with cell division, and deprivation of

nutrients. These multiple modes of action can prevent development of resistance in fungal pathogens (Shishido *et al.*, 2015). Cyanobacteria also have antibacterial properties attributed to peptides, fatty acids, and phenolic compounds which disrupt membranes, inhibit enzymes, and interfere with metabolism in bacteria (Alsenani *et al.*, 2020).

Application of live cyanobacterial cells or their extracts can induce systemic resistance against pathogens in plants. *Anabaena* extracts triggered defense enzyme activity in zucchini leaves, leading to reduced powdery mildew severity (Roberti *et al.*, 2015). Foliar sprays of *Nostoc piscinale* and *Anabaena variabilis* suppressed rice sheath blight caused by *Rhizoctonia solani* via induced phytohormones and antifungal metabolites (Zhou *et al.*, 2020). Combining biocontrol traits with N₂-fixing ability gives multifunctional benefits to these bio-inoculants (Bao *et al.*, 2021).

However, cyanobacteria can also produce toxins which may limit their utilization for plant disease control. The cyanotoxins microcystins and nodularin are potential public health hazards if they accumulate in produce or leach into water sources (Nowruzi *et al.*, 2021). Further studies are needed under field conditions along with safety and risk assessments before widespread adoption of cyanobacteria as biofungicides or antibacterials.

9. INFLUENCE ON CEREAL CROP YIELDS

Cyanobacteria have a long history of use in rice paddy agriculture to enhance soil fertility, provide fixed nitrogen, and ultimately increase yields. In early studies, cyanobacterial inoculation was found to increase rice grain weight and the number of productive tillers per plant (Shukla & Gupta, 1967; Singh, 1961). These positive effects result largely from biological nitrogen fixation by heterocystous genera like *Nostoc* and *Anabaena*.

Modern research has focused on integrating cyanobacteria into integrated nutrient management systems for rice. *Anabaena azotica* was able to substitute 30-50% of urea nitrogen without compromising grain yields when applied along with 50% of the recommended mineral fertilizer (Zhang *et al.*, 2021). The cyanobacteria provided between 22-39 kg ha⁻¹ of nitrogen based on the substitution rate.

Cyanobacteria also influence rice yield components like tillers per hill and filled grains per panicle (Begum *et al.*, 2011). Inoculation with *Nostoc muscorum* increased tiller production, grains per panicle, and straw yield of rice over uninoculated controls (Abou Elatta *et al.*, 2019). Combining cyanobacteria with plant growth-promoting bacteria can further improve yield attributes and

productivity (Prasanna *et al.*, 2008). Seed biopriming with cyanobacteria shows potential to enhance germination, seedling vigor and subsequent growth and yields of rice (Sharma *et al.*, 2020). Cyanobacteria supply growth-promoting substances and mobilize nutrients like zinc in the rhizosphere, which translate to better crop performance (Prasanna *et al.*, 2015). However, the effectiveness varies based on the cyanobacterial strain, plant genotype, and environmental conditions (Sharma *et al.*, 2020).

While cyanobacteria contribute to soil fertility and plant nutrition, their ability to decrease incidence of diseases like bacterial leaf blight and sheath blight also contributes to enhanced productivity in rice systems (Bao *et al.*, 2021). Both biofertilization and biocontrol traits make them well-suited to sustainable agriculture approaches. However, maintaining cultures and scaling production remain challenges for widespread application to cereal crops like rice and wheat.

10. TERRESTRIAL CARBON SEQUESTRATION

Cyanobacteria contribute to terrestrial carbon cycling through oxygenic photosynthesis, carbon fixation, and incorporation into soil organic matter. Their natural abundance in agricultural soils and ability to fix CO₂ make cyanobacteria potential organisms for enhancing soil carbon sequestration. The filamentous morphology of many cyanobacteria also aids in soil particle aggregation, which physically protects organic carbon from decomposition (Chen *et al.*, 2014). Incorporation of cyanobacterial biomass directly contributes carbon to the soil, while their oxygenic photosynthesis creates aerobic conditions that slow C mineralization by heterotrophs (Rajeev *et al.*, 2013). Cyanobacteria grown on agricultural waste substrates can provide a carbon-negative source of biofertilizer (Chatterjee *et al.*, 2017). Photosynthetic activity further reduces CO₂ levels in the rhizosphere, thus the cyanobacteria act as a carbon sink (Sheikh *et al.*, 2018).

Biological soil crusts rich in cyanobacteria increase total organic carbon and carbon sequestration rates in arid soils (Li *et al.*, 2022). While non-photosynthetic bacteria dominate the rhizosphere, cyanobacteria occupy soil microsites at the surface where they contribute significantly to C fixation (Zhang *et al.*, 2018). Their Carbon inputs are protected from decomposition by soil aggregates (Darrouzet-Nardi *et al.*, 2015).

Cyanobacteria genetically engineered to overexpress inorganic carbon uptake systems could further optimize CO₂ sequestration in soils (Gupta *et al.*, 2013). However, there are still challenges translating laboratory studies to effective field application for enhancing soil C storage. Maintaining

cyanobacterial inoculants in soils requires adequate light, moisture, temperature, and nutrients. Better understanding synergies between cyanobacteria, plants and heterotrophic microbes that accelerate soil Carbon sequestration is also needed (Gao *et al.*, 2021).

11. PROGRESS AND LIMITATIONS

Algalization refers to the application of algae or cyanobacteria as inoculants to improve soil health and plant growth. Cyanobacteria have a long history of use as algalizers in flooded rice systems to provide biofertilization. Traditional practice in parts of Asia involves inoculating rice paddies with native cyanobacteria from genera such as *Nostoc*, *Anabaena*, *Aulosira*, and *Tolypothrix* (Prasanna & Nayak 2007).

Cyanobacterial inoculation forms algal mats on the water surface that can contribute 25-30 kg N ha⁻¹ and increase rice yields 10-24% (De, 1939; Singh, 1961). Coating rice seeds with cyanobacteria before sowing stimulates germination, plant growth, and grain yield (Taubaev *et al.*, 1970). The exopolysaccharides of cyanobacteria also improve soil structure and fertility (Renuka *et al.*, 2018). However, the efficacy of cyanobacteria-based algalization depends on species selection, rice cultivar, temperature, water, soil nutrients, and other conditions (Yanni, 1991; Vaishampayan *et al.*, 1998). Contamination, limited shelf life of inoculum, and variability in field performance currently constrain more widespread adoption (Herrmann & Lesueur, 2013). Scaling up production of cyanobacteria is challenging compared to fungal and bacterial biofertilizers.

Targeted uses of cyanobacterial algalizers show potential improvements in area such as salt-affected soils, degraded drylands, and cold deserts (Thomas, 1977; Singh & Dhar 2010). Cyanobacteria inoculation was found to increase soil organic carbon, total nitrogen, and aggregation in the desert soils (Muñoz-Rojas *et al.*, 2018; Román *et al.*, 2018). However, field testing is still limited. Cyanobacteria also face competition from other microorganisms in the rhizosphere. Integrating cyanobacteria with plant growth-promoting bacteria or fungi may improve colonization and effectiveness (Nain *et al.*, 2010; Orozco-Mosqueda *et al.*, 2018). Further innovations are needed to make algalization an affordable and reliable means of improving soil health and crop yields.

12. FUTURE PROSPECTS FOR AGRICULTURAL APPLICATIONS

Cyanobacteria have potential to enhance agricultural sustainability and soil resilience through pathways like carbon sequestration, nitrogen fixation, and bioremediation. However, much remains unknown regarding their taxonomy, phylogeny, genomics, and ecology in soil systems (Hirose *et al.*,

2021). Advancing fundamental knowledge should be a priority for directing applied research and biotechnological innovations (Shih *et al.*, 2013). Culture-independent techniques have revealed new cyanobacterial clades and expanded phylogenetic diversity (Di Rienzi *et al.*, 2013; Soo *et al.*, 2017). Further sampling of under-studied environments combined with genomes and metagenomes will likely uncover novel cyanobacteria relevant to agriculture (Lumian *et al.*, 2022). The stressful conditions cyanobacteria endure in soils and their adaptations merit more study (Gr *et al.*, 2021).

Elucidating Cyanobacteria -plant-microbe interactions is also crucial (Rodríguez *et al.*, 2022). Cyanobacteria influence soil microbiomes through organic matter input, oxygenation, nutrient alterations, and bioactive compounds (Gupta *et al.*, 2021; Nowruzi *et al.*, 2021). However, we have limited knowledge of these complex dynamics in the rhizosphere and effects on plant health (Rodríguez *et al.*, 2022). Potential negative impacts like cyanotoxins or competition with crops require investigation (Nowruzi *et al.*, 2021). Advances in cultivation techniques, formulation, stabilization, and delivery systems are essential for translating laboratory research into effective cyanobacterial inoculants. Most agricultural applications have involved commonly studied genera, while bioprospecting novel strains may reveal enhanced traits. Finally, stakeholders like farmers, industries, policymakers, and consumers should be engaged to develop integrated, scalable solutions using cyanobacteria to sustain food production and ecosystem services (Vigani *et al.*, 2015).

13. CYANOBACTERIAL APPLICATIONS IN THE PHYTOREMEDIATION OF CONTAMINATED FIELDS

Cyanobacteria exhibit inherent tolerance mechanisms that enable their survival in environments contaminated with heavy metals and organic pollutants, rendering them promising candidates for phytoremediation processes (Thevarajah *et al.*, 2022). These microorganisms possess the capacity to accumulate heavy metals such as Cd, Cr, Ni, Zn, As, and Pb via extracellular sequestration, efflux systems, and intracellular chelation (Mehta & Gaur, 2005). Noteworthy genera like *Phormidium*, *Microcoleus*, *Nostoc*, *Anabaena*, and *Oscillatoria* have demonstrated resistance to chromium and significant bioremediation potential (Yadav *et al.*, 2021).

In the realm of organic pollutant degradation, specific strains of cyanobacteria have undergone genetic modification to facilitate the breakdown of pollutants. Solvent-tolerant species like *Synechocystis* and *Synechococcus* have been engineered to degrade organic contaminants (Kuritz & Wolk, 1995). A synergistic approach involves integrating metal-resistant cyanobacteria with aquatic

plants in wetland systems, offering a viable strategy for the phytoremediation of metal-contaminated water bodies (Li *et al.*, 2020).

Furthermore, cyanobacteria-derived bio-surfactants, such as microcolin, exhibit promise in solubilizing and degrading petroleum hydrocarbons, thereby serving a crucial role in oil spill bioremediation efforts (Najafi *et al.*, 2010). Despite their diverse detoxification capabilities, comprehensive large-scale field studies are imperative to fully comprehend the efficacy and feasibility of utilizing cyanobacteria for phytoremediation purposes. Ongoing advancements in genetic engineering and synthetic biology hold the potential to further enhance the biodegradation capacities of cyanobacteria.

14. CONCLUSION

Cyanobacteria provide numerous options to increase agricultural sustainability, including biofertilization, bioremediation, disease control, and carbon sequestration. However, information gaps in genetics, plant-microbe interactions, and soil ecology must be addressed before conducting practical research. Developing efficient cyanobacterial inoculants requires advanced cultivation techniques and field delivery strategies. With advancements in biotechnology and soil management, cyanobacteria could minimize pesticide use, improve stress resilience, recover degraded lands, and sustain productivity. However, efficiency varies depending on the strain, plant species, and agroclimatic circumstances. To maximize their potential, cross-disciplinary collaboration and locally tailored solutions are required to improve climate resilience, soil health, and productivity. Further research into genetics, plant relationships, field performance, stress mechanisms, and formulations can help cyanobacteria reach their full potential for sustainable agriculture.

REFERENCES:

- Abbas, H. H., Ali, M. E., Ghazal, F. M., & El-Gaml, N. M. (2015). Impact of cyanobacteria inoculation on rice (*Oryza sativa*) yield cultivated in saline soil. *Journal of American Science*. 11(2), 13-19. <https://api.semanticscholar.org/CorpusID:86111584>.
- Abedin, R. M., & Taha, H. M. (2008). Antibacterial and antifungal activity of cyanobacteria and green microalgae. Evaluation of medium components by Plackett-Burman design for antimicrobial activity of *Spirulina platensis*. *Global Journal of Biotechnology and Biochemistry*. 3(1), 22-31. [https://idosi.org/gjbb/gjbb3\(1\)08/4.pdf](https://idosi.org/gjbb/gjbb3(1)08/4.pdf).
- Abou Elatta, A., Gaballah, M., Afify, A., & Hauka, F. (2019). Effect of inoculation with cyanobacterial strains and nitrogen fertilization on yield and component of rice plant. *Journal of Agricultural Chemistry and Biotechnology*. 10(3), 51-55. <https://doi.org/10.21608/JACB.2019.36826>.
- Afify, A., & Ashour, A. (2018). Use of cyanobacteria for controlling flax seedling blight. *Journal of Agricultural Chemistry and Biotechnology*. 9(11), 259-261. DOI: 10.21608/JACB.2018.36313.

- Ai, Y., Yang, Y., Qiu, B., & Gao, X. (2014). Unique WSPA protein from terrestrial macroscopic cyanobacteria can confer resistance to osmotic stress in transgenic plants. *World Journal of Microbiology and Biotechnology*. 30, 2361-2369. <https://doi.org/10.1007/s11274-014-1661-9>.
- Alsenani, F., Tupally, K. R., Chua, E. T., Eltanahy, E., Alsufyani, H., Parekh, H. S., & Schenk, P. M. (2020). Evaluation of microalgae and cyanobacteria as potential sources of antimicrobial compounds. *Saudi Pharmaceutical Journal*. 28(12), 1834-1841. <https://doi.org/10.1016/j.jsps.2020.11.010>.
- Aminfarzaneh, H., & Duygu, E. (2010). The effect of salicylic acid and triacontanol on biomass production and imidacloprid removal capacity by cyanobacteria. *Communications Faculty of Sciences University of Ankara Series C Biology*. 22(1), 15-31.
- Attia, M. S., Sharaf, A. E. M. M., & Zayed, A. S. (2017). Protective action of some bio-pesticides against early blight disease caused by *Alternaria solani* in tomato plant. *International Journal of Innovative Science, Engineering & Technology*. Vol. 4 Issue 11. https://ijiset.com/vol4/v4s11/IJISSET_V4_I11_08.pdf.
- Ayuso, S., Silva, A., Nelson, C., Barger, N., & Garcia-Pichel, F. (2016). Microbial Nursery Production of High-Quality Biological Soil Crust Biomass for Restoration of Degraded Dryland Soils. *Applied and Environmental Microbiology*. 83. <https://doi.org/10.1128/AEM.02179-16>.
- Bao, J., Zhuo, C., Zhang, D., Li, Y., Hu, F., Li, H. & He, H. (2021). Potential applicability of a cyanobacterium as a biofertilizer and biopesticide in rice fields. *Plant and Soil*. 463, 97-112. <https://doi.org/10.1007/s11104-021-04899-9>.
- Begum, Z. N. T., Mandal, R., & Islam, S. (2011). Effect of cyanobacterial biofertilizer on the growth and yield components of two HYV of rice. *Journal of Algal Biomass Utilization*. 2(4), 1-9. <https://api.semanticscholar.org/CorpusID:54844715>.
- Belnap, J., Weber, B., Büdel, B. (2016). Biological Soil Crusts as an Organizing Principle in Drylands. In: Weber, B., Büdel, B., Belnap, J. (eds) Biological Soil Crusts: An Organizing Principle in Drylands. *Ecological Studies*. vol 226. Springer, Cham. https://doi.org/10.1007/978-3-319-30214-0_1.
- Bhunias, B., Uday, U., Oinam, G., Mondal, A., Bandyopadhyay, T., & Tiwari, O. (2018). Characterization, genetic regulation and production of cyanobacterial exopolysaccharides and its applicability for heavy metal removal. *Carbohydrate polymers*. 179, 228-243. <https://doi.org/10.1016/j.carbpol.2017.09.091>.
- Biondi, N., Piccardi, R., Margheri, M. C., Rodolfi, L., Smith, G. D., & Tredici, M. R. (2004). Evaluation of *Nostoc* strain ATCC 53789 as a potential source of natural pesticides. *Applied and Environmental Microbiology*. 70(6), 3313-3320. <https://doi.org/10.1128/AEM.70.6.3313-3320.2004>.
- Borowitzka, M. A. (1999). Commercial production of microalgae: ponds, tanks, tubes and fermenters. *Journal of Biotechnology*. 70(1-3), 313-321. [https://doi.org/10.1016/S0168-1656\(99\)00083-8](https://doi.org/10.1016/S0168-1656(99)00083-8).
- Boyd, E. S., & Peters, J. W. (2013). New insights into the evolutionary history of biological nitrogen fixation. *Frontiers in Microbiology*. 4, 201. <https://doi.org/10.3389/fmicb.2013.00201>.
- Brito, Â., Rocha, M., Kaštrovský, J., Vieira, J., Vieira, C. P., Ramos, V., ... & Tamagnini, P. (2022). A new cyanobacterial species with a protective effect on lettuce grown under salinity stress: Envisaging sustainable agriculture practices. *Journal of Applied Phycology*. 34(2), 915-928. <https://doi.org/10.1007/s10811-022-02692-4>.
- Büdel, B., Dulić, T., Darienko, T., Rybalka, N., Friedl, T. (2016). Cyanobacteria and Algae of Biological Soil Crusts. In: Weber, B., Büdel, B., Belnap, J. (eds) Biological Soil Crusts: An Organizing Principle in Drylands. *Ecological Studies*. vol 226. Springer, Cham. https://doi.org/10.1007/978-3-319-30214-0_4.
- Caiola, M.G., Billi, D. (2007). *Chroococcidiopsis* from Desert to Mars. In: Seckbach, J. (eds) Algae and Cyanobacteria in Extreme Environments. Cellular Origin, *Life in Extreme Habitats and Astrobiology*. vol 11. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6112-7_30.
- Catarina Guedes, A., Barbosa, C. R., Amaro, H. M., Pereira, C. I., & Xavier Malcata, F. (2011). Microalgal and cyanobacterial cell extracts for use as natural antibacterial additives against food pathogens. *International journal of food science & technology*. 46(4), 862-870. doi:10.1111/j.1365-2621.2011.02567.x.
- Chamizo, S., Adessi, A., Mugnai, G., Simiani, A., & De Philippis, R. (2019). Soil type and cyanobacteria species influence the macromolecular and chemical characteristics of the polysaccharidic matrix in induced biocrusts. *Microbial ecology*. 78(2), 482-493. <https://doi.org/10.1007/s00248-018-1305-y>.
- Chamizo, S., Mugnai, G., Rossi, F., Certini, G., & De Philippis, R. (2018). Cyanobacteria inoculation improves soil stability and fertility on different textured soils: gaining insights for applicability in

- soil restoration. *Frontiers in environmental science*. 6, 49. <https://doi.org/10.3389/fenvs.2018.00049>.
- Chandel, S. T. (2009). Nematicidal activity of the Cyanobacterium, *Aulosira fertilissima* on the hatch of *Meloidogyne triticoryzae* and *Meloidogyne incognita*. *Archives of Phytopathology and Plant Protection*. 42(1), 32-38. <https://doi.org/10.1080/03235400600914363>.
- Chatterjee, A., Singh, S., Agrawal, C., Yadav, S., Rai, R., & Rai, L. C. (2017). Role of algae as a biofertilizer. In *Algal green chemistry*. 189-200. Elsevier. <https://doi.org/10.1016/B978-0-444-63784-0.00010-2>.
- Chaudhary, V., Prasanna, R., Nain, L., Dubey, S. C., Gupta, V., Singh, R. & Bhatnagar, A. K. (2012). Bioefficacy of novel cyanobacteria-amended formulations in suppressing damping off disease in tomato seedlings. *World Journal of Microbiology and Biotechnology*. 28, 3301-3310. <https://doi.org/10.1007/s11274-012-1141-z>.
- Chittora, D., Meena, M., Barupal, T., Swapnil, P., & Sharma, K. (2020). Cyanobacteria as a source of biofertilizers for sustainable agriculture. *Biochemistry and biophysics reports*. 22, 100737. <https://doi.org/10.1016/j.bbrep.2020.100737>.
- Coba de la Pena, T., Redondo, F. J., Manrique, E., Lucas, M. M., & Pueyo, J. J. (2010). Nitrogen fixation persists under conditions of salt stress in transgenic *Medicago truncatula* plants expressing a cyanobacterial flavodoxin. *Plant Biotechnology Journal*. 8(9), 954-965. <https://doi.org/10.1111/j.1467-7652.2010.00519.x>.
- Crouzet, O., Consentino, L., Pétraud, J. P., Marraud, C., Aguer, J.P., Bureau, S., Le Bourvellec, C., Touloumet, L. and Bérard, A. (2019). Soil Photosynthetic Microbial Communities Mediate Aggregate Stability: Influence of Cropping Systems and Herbicide Use in an Agricultural Soil. *Frontiers in microbiology*. 10:1319. <https://doi.org/10.3389/fmicb.2019.01319>.
- Datta, K., Vasquez, A., Tu, J., Torrizo, L., Alam, M. F., Oliva, N. & Datta, S. K. (1998). Constitutive and tissue-specific differential expression of the cryIA (b) gene in transgenic rice plants conferring resistance to rice insect pest. *Theoretical and Applied Genetics*. 97, 20-30. <https://doi.org/10.1007/s001220050862>.
- De, P. K. (1939). The role of blue-green algae in nitrogen fixation in rice-fields. *Proceedings of the Royal Society of London. Series B-Biological Sciences*. 127(846), 121-139. <https://doi.org/10.1098/rspb.1939.0014>.
- Orozco-Mosqueda, M.C., Glick, B. R., & Santoyo, G. (2020). ACC deaminase in plant growth-promoting bacteria (PGPB): An efficient mechanism to counter salt stress in crops. *Microbiological Research*. 235, 126439. <https://doi.org/10.1016/j.micres.2020.126439>.
- Demay, J., Bernard, C., Reinhardt, A., & Marie, B. (2019). Natural products from cyanobacteria: Focus on beneficial activities. *Marine drugs*. 17(6), 320. <https://doi.org/10.3390/md17060320>.
- Di Rienzi, S. C., Sharon, I., Wrighton, K. C., Koren, O., Hug, L. A., Thomas, B. C. & Ley, R. E. (2013). The human gut and groundwater harbor non-photosynthetic bacteria belonging to a new candidate phylum sibling to Cyanobacteria. *Elife*. 2, e01102. <https://doi.org/10.7554/eLife.01102.001>.
- El Sheek, M. M., Zayed, M. A., & Elmossel, F. K. (2018). Effect of cyanobacteria isolates on rice seeds germination in saline soil. *Baghdad Science Journal*. 15(1), 0016-0016. <https://doi.org/10.21123/bsj.2018.15.1.0016>.
- Faisal, M., Hameed, A., & Hasnain, S. (2005). Chromium-resistant bacteria and cyanobacteria: impact on Cr (VI) reduction potential and plant growth. *Journal of Industrial Microbiology and Biotechnology*. 32(11-12), 615-621. <https://doi.org/10.1007/s10295-005-0241-2>.
- Fawley, M. W., & Fawley, K. P. (2020). Identification of eukaryotic microalgal strains. *Journal of applied phycology*. 32, 2699-2709. <https://doi.org/10.1007/s10811-020-02190-5>.
- Gao, E., Kyere-Yeboah, K., Wu, J., & Qiu, H. (2021). Photoautotrophic production of p-Coumaric acid using genetically engineered *Synechocystis* sp. Pasteur Culture Collection 6803. *Algal Research-Biomass Biofuels and Bioproducts*. 54, 102180. <https://doi.org/10.1016/J.ALGAL.2020.102180>.
- Gheda, S. F., & Ahmed, D. A. (2015). Improved soil characteristics and wheat germination as influenced by inoculation of *Nostoc kihlmani* and *Anabaena cylindrica*. *Rendiconti Lincei*, 26, 121-131. <https://doi.org/10.1007/s12210-014-0351-8>.
- Gholamhosseini, A., Sepehr, A., Asgari Lajayer, B., Delangiz, N., Astatkie, T. (2021). Biological Soil Crusts to Keep Soil Alive, Rehabilitate Degraded Soil, and Develop Soil Habitats. In: Vaishnav, A., Choudhary, D.K. (eds) *Microbial Polymers*. Springer, Singapore. https://doi.org/10.1007/978-981-16-0045-6_13.

- Gol'din, E. (2012). Biologically active microalgae and cyanobacteria in nature and marine biotechnology. *Turkish Journal of Fisheries and Aquatic Sciences*. 12(5), 423-427. https://doi.org/10.4194/1303-2712-v12_2_32.
- Gr, S., Yadav, R. K., Chatrath, A., Gerard, M., Tripathi, K., Govindsamy, V., & Abraham, G. (2021). Perspectives on the potential application of cyanobacteria in the alleviation of drought and salinity stress in crop plants. *Journal of Applied Phycology*. 1-18. <https://doi.org/10.1007/s10811-021-02570-5>.
- Gupta, C., Rabani, M. S., Gupta, M. K., Habib, A., Pathak, A., Tripathi, S., & Singh, R. (2021). Cyanobacteria as sustainable microbiome for agricultural industries. *Microbiota and Biofertilizers*. Vol 2: *Ecofriendly Tools for Reclamation of Degraded Soil Environs*. 267-291. https://doi.org/10.1007/978-3-030-61010-4_13.
- Gupta, V., Prasanna, R., Srivastava, A. K., & Sharma, J. (2012). Purification and characterization of a novel antifungal endo-type chitosanase from *Anabaena fertilissima*. *Annals of microbiology*. 62(3), 1089-1098. <https://doi.org/10.1007/s13213-011-0350-2>.
- Harel, Y., Ohad, I., & Kaplan, A. (2004). Activation of photosynthesis and resistance to photoinhibition in cyanobacteria within biological desert crust. *Plant Physiology*, 136(2), 3070-3079. <https://doi.org/10.1104/pp.104.047712>.
- Hashem, M., & Abo-Elyousr, K. A. (2011). Management of the root-knot nematode *Meloidogyne incognita* on tomato with combinations of different biocontrol organisms. *Crop Protection*, 30(3), 285-292. <https://doi.org/10.1016/j.cropro.2010.12.009>.
- Herrmann, L., & Lesueur, D. (2013). Challenges of formulation and quality of biofertilizers for successful inoculation. *Applied microbiology and Biotechnology*. 97(20), 8859-8873. <https://doi.org/10.1007/s00253-013-5228-8>.
- Hirose, Y., Ohtsubo, Y., Misawa, N., Yonekawa, C., Nagao, N., Shimura, Y., & Kawachi, M. (2021). Genome sequencing of the NIES Cyanobacteria collection with a focus on the heterocyst-forming clade. *DNA Research*. 28(6), dsab024. <https://doi.org/10.1093/dnares/dsab024>.
- Hoikkala, L., Tammert, H., Lignell, R., Eronen-Rasimus, E., Spilling, K., & Kisand, V. (2016). Autochthonous dissolved organic matter drives bacterial community composition during a bloom of filamentous cyanobacteria. *Frontiers in Marine Science*. 3, 111. <https://doi.org/10.3389/fmars.2016.00111>.
- Holajjer, P., Kamra, A., Gaur, H. S., & Dhar, D. W. (2012). *In-vitro* nematicidal activity of a terrestrial cyanobacterium, *Synechococcus nidulans*, towards plant-parasitic nematodes. *Nematology*. 14(1), 85-92. <https://doi.org/10.1163/138855411X578879>.
- Ibraheem, I. (2007). Cyanobacteria as alternative biological conditioners for bioremediation of barren soil. *Egyptian Journal of Phycology*. 8(1), 99-117. <https://doi.org/10.21608/egyjs.2007.114548>.
- Jaiswal, P., Dhar, D.W., Sharma, N. et al. (2022). Evaluating the role of endophytic cyanobacterial isolates on growth promotion and N/P status of rice crop. *Vegetos* 35, 244–250. <https://doi.org/10.1007/s42535-021-00299-7>.
- Jaiswal, P., Kashyap, A. K., Prasanna, R., & Singh, P. K. (2010). Evaluating the potential of *N. calcicola* and its bicarbonate resistant mutant as bioameliating agents for 'usar' soil. *Indian journal of microbiology*, 50, 12-18. <https://doi.org/10.1007/s12088-009-0018-9>.
- Jan, Z., Ali, S., Sultan, T., Wasiullah, W., Ahmad, W. (2017). The role of cyanobacteria in availability of major plant nutrients and soil organic matter to Rice crop under saline soil condition. *Sarhad Journal of Agriculture*. 33(4): 566-572. <http://dx.doi.org/10.17582/journal.sja/2017/33.4.566.572>.
- Jones, C. G., Lawton, J. H., & Shachak, M. (1994). Organisms as ecosystem engineers. *Oikos*. 373-386. <https://doi.org/10.2307/3545850>.
- Kaur, R., & Goyal, D. (2018). Heavy metal accumulation from coal fly ash by cyanobacterial biofertilizers. *Particulate Science and Technology*. 36(4), 513-516. <https://doi.org/10.1080/02726351.2017.1398794>.
- Kaushik, B. D., & Subhashini, D. (1985). Amelioration of salt-affected soils with blue-green algae. II. Improvement in soil properties. *Proceedings of the Indian National Science Academy. Part B: Biological sciences*. B-51.386-389.
- Kellar, P. E., & Goldman, C. R. (1979). A comparative study of nitrogen fixation by the *Anabaena-Azolla* symbiosis and free-living populations of *Anabaena* spp. in Lake Ngahawa, New Zealand. *Oecologia*. 43, 269-281. <https://doi.org/10.1007/BF00344954>.
- Kharwar, S., Bhattacharjee, S., & Mishra, A. K. (2022). Deciphering salinity tolerance in the cyanobacterium *Anabaena sphaerica*: an evaluation of physiological and biochemical

- adjustments. *Acta Physiologiae Plantarum*. 44(12), 127. <https://doi.org/10.1007/s11738-022-03465-9>.
- Kheirfam, H., & Roohi, M. (2020). Accelerating the formation of biological soil crusts in the newly dried-up lakebeds using the inoculation-based technique. *Science of the Total Environment*. 706, 136036. <https://doi.org/10.1016/j.scitotenv.2019.136036>.
- Kim, J. D. (2006). Screening of cyanobacteria (blue-green algae) from rice paddy soil for antifungal activity against plant pathogenic fungi. *Mycobiology*. 34(3), 138-142. <https://doi.org/10.4489/MYCO.2006.34.3.138>.
- Kulik, M. M. (1995). The potential for using cyanobacteria (blue-green algae) and algae in the biological control of plant pathogenic bacteria and fungi. *European Journal of Plant Pathology*, 101, 585-599. <https://doi.org/10.1007/BF01874863>.
- Kuritz, T., & Wolk, C. P. (1995). Use of filamentous cyanobacteria for biodegradation of organic pollutants. *Applied and Environmental Microbiology*. 61(1), 234-238. <https://doi.org/10.1128/aem.61.1.234-238.1995>.
- Li, H., Zhao, Q., & Huang, H. (2019). Current states and challenges of salt-affected soil remediation by cyanobacteria. *Science of the Total Environment*. 669, 258-272. <https://doi.org/10.1016/j.scitotenv.2019.03.104>.
- Li, X., Wu, S., Yang, C., & Zeng, G. (2020). Microalgal and duckweed based constructed wetlands for swine wastewater treatment: A review. *Bioresour. Technol.* 318, 123858. <https://doi.org/10.1016/j.biortech.2020.123858>.
- Li, Z., Yuan, S., Jia, H., Gao, F., Zhou, M., Yuan, N. & Luo, H. (2017). Ectopic expression of a cyanobacterial flavodoxin in creeping bentgrass impacts plant development and confers broad abiotic stress tolerance. *Plant Biotechnology Journal*. 15(4), 433-446. <https://doi.org/10.1111/pbi.12638>.
- Lu, Q., Xiao, Y., & Lu, Y. (2022). Employment of algae-based biological soil crust to control desertification for the sustainable development: a mini-review. *Algal Research*. 65, 102747. <https://doi.org/10.1016/j.algal.2022.102747>.
- Lumian, J., Sumner, D., Grettenberger, C., Jungblut, A., Irber, L., Pierce-Ward, N., & Brown, C. (2022). Biogeographic Distribution of Five Antarctic Cyanobacteria Using Large-Scale k-mer searching with sourmash branch water. *bioRxiv*. <https://doi.org/10.1101/2022.10.27.514113>.
- Mazor, G., Kidron, G. J., Vonshak, A., & Abeliovich, A. (1996). The role of cyanobacterial exopolysaccharides in structuring desert microbial crusts. *FEMS Microbiology Ecology*. 21(2), 121-130. [https://doi.org/10.1016/0168-6496\(96\)00050-5](https://doi.org/10.1016/0168-6496(96)00050-5).
- Mehta, S. K., & Gaur, J. P. (2005). Use of algae for removing heavy metal ions from wastewater: progress and prospects. *Critical Reviews in Biotechnology*. 25(3), 113-152. <https://doi.org/10.1080/07388550500248571>.
- Mikhail, M. S., Hussein, B. A., Messiha, N. A., Morsy, K. M. M., & Youssef, M. M. (2016). Using of Cyanobacteria in controlling potato brown rot disease. *International Journal of Scientific & Engineering Research*. 7, 274-281. <https://scholar.cu.edu.eg/?q=maryanmakram/files/using-of-cyanobacteria-in-controlling-potato-brown-rot-disease2.pdf>.
- Muñoz-Rojas, M., Chilton, A., Liyanage, G. S., Erickson, T. E., Merritt, D. J., Neilan, B. A., & Ooi, M. K. J. (2018). Effects of indigenous soil cyanobacteria on seed germination and seedling growth of arid species used in restoration. *Plant and Soil*. 429, 91-100. <https://doi.org/10.1007/s11104-018-3607-8>.
- Muñoz-Rojas, M., Román, J. R., Roncero-Ramos, B., Erickson, T. E., Merritt, D. J., Aguila-Carricondo, P., & Cantón, Y. (2018). Cyanobacteria inoculation enhances carbon sequestration in soil substrates used in dry land restoration. *Science of the Total Environment*. 636, 1149-1154. <https://doi.org/10.1016/j.scitotenv.2018.04.265>.
- Nain, L., Rana, A., Joshi, M., Jadhav, S. D., Kumar, D., Shivay, Y. S., Sangeeta, P. & Prasanna, R. (2010). Evaluation of synergistic effects of bacterial and cyanobacterial strains as biofertilizers for wheat. *Plant and soil*. 331, 217-230. <https://doi.org/10.1007/s11104-009-0247-z>.
- Najafi, A. R., Rahimpour, M. R., Jahanmiri, A. H., Roostaazad, R., Arabian, D., & Ghobadi, Z. (2010). Enhancing biosurfactant production from an indigenous strain of *Bacillus mycoides* by optimizing the growth conditions using a response surface methodology. *Chemical Engineering Journal*. 163(3), 188-194. <https://doi.org/10.1016/j.cej.2010.06.044>.
- Nisha, R., Kiran, B., Kaushik, A., & Kaushik, C. P. (2018). Bioremediation of salt affected soils using cyanobacteria in terms of physical structure, nutrient status and microbial activity. *International Journal of Environmental Science and Technology*. 15, 571-580. <https://doi.org/10.1007/s13762-017-1419-7>.

- Nowruzi, B., Bouaïcha, N., Metcalf, J. S., Porzani, S. J., & Konur, O. (2021). Plant-cyanobacteria interactions: Beneficial and harmful effects of cyanobacterial bioactive compounds on soil-plant systems and subsequent risk to animal and human health. *Phytochemistry*. 192, 112959. <https://doi.org/10.1016/j.phytochem.2021.112959>.
- Osman, M. E. H., Abo-Shady, A. M., & El-Nagar, M. M. (2016). Cyanobacterial *Arthrospira (Spirulina platensis)* as safener against harmful effects of fusilade herbicide on faba bean plant. *Rendiconti Lincei*. 27, 455-462. <https://doi.org/10.1007/s12210-015-0498-y>.
- Pandey, K. D., Shukla, P. N., Giri, D. D., & Kashyap, A. K. (2005). Cyanobacteria in alkaline soil and the effect of cyanobacteria inoculation with pyrite amendments on their reclamation. *Biology and Fertility of Soils*. 41, 451-457. <https://doi.org/10.1007/s00374-005-0846-7>.
- Prasanna, R., & Nayak, S. (2007). Influence of diverse rice soil ecologies on cyanobacterial diversity and abundance. *Wetlands Ecology and Management*. 15, 127-134. <https://doi.org/10.1007/s11273-006-9018-2>.
- Prasanna, R., Adak, A., Verma, S., Bidyarani, N., Babu, S., Pal, M., & Nain, L. (2015). Cyanobacterial inoculation in rice grown under flooded and SRI modes of cultivation elicits differential effects on plant growth and nutrient dynamics. *Ecological Engineering*. 84, 532-541. <https://doi.org/10.1016/j.ecoleng.2015.09.033>.
- Prasanna, R., Bidyarani, N., Babu, S., Hossain, F., Shivay, Y. S., & Nain, L. (2015). Cyanobacterial inoculation elicits plant defense response and enhanced Zn mobilization in maize hybrids. *Cogent Food & Agriculture*, 1(1), 998507. <https://doi.org/10.1080/23311932.2014.998507>.
- Prasanna, R., Joshi, M., Rana, A., Shivay, Y. S., & Nain, L. (2012). Influence of co-inoculation of bacteria-cyanobacteria on crop yield and C-N sequestration in soil under rice crop. *World Journal of Microbiology and Biotechnology*. 28, 1223-1235. <https://doi.org/10.1007/s11274-011-0926-9>.
- Rao, D. L. N., & Burns, R. G. (1991). The influence of blue-green algae on the biological amelioration of alkali soils. *Biology and Fertility of Soils*. 11, 306-312. <https://doi.org/10.1007/BF00335853>.
- Renuka, N., Guldhe, A., Prasanna, R., Singh, P., & Bux, F. (2018). Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges. *Biotechnology Advances*. 36(4), 1255-1273. <https://doi.org/10.1016/j.biotechadv.2018.04.004>.
- Righini, H., Francioso, O., Martel Quintana, A., & Roberti, R. (2022). Cyanobacteria: a natural source for controlling agricultural plant diseases caused by fungi and oomycetes and improving plant growth. *Horticulturae*. 8(1), 58. <https://doi.org/10.3390/horticulturae8010058>.
- Roberti, R., Galletti, S., Burzi, P. L., Righini, H., Cetrullo, S., & Perez, C. J. B. C. (2015). Induction of defence responses in zucchini (*Cucurbita pepo*) by *Anabaena* sp. water extract. *Biological Control*. 82, 61-68. <https://doi.org/10.1016/j.biocontrol.2014.12.006>.
- Rodríguez, A. A., Stella, A. M., Storni, M. M., Zulpa, G., & Zaccaro, M. C. (2006). Effects of cyanobacterial extracellular products and gibberellic acid on salinity tolerance in *Oryza sativa* L. *Saline systems*, 2, 1-4. <https://doi.org/10.1186/1746-1448-2-7>.
- Román, J. R., Roncero-Ramos, B., Chamizo, S., Rodríguez-Caballero, E., & Cantón, Y. (2018). Restoring soil functions by means of cyanobacteria inoculation: importance of soil conditions and species selection. *Land Degradation & Development*. 29(9), 3184-3193. <https://doi.org/10.1002/ldr.3064>.
- Roncero-Ramos, B., Román, J., Rodríguez-Caballero, E., Chamizo, S., Águila-Carricondo, P., Mateo, P., & Cantón, Y. (2019). Assessing the influence of soil abiotic and biotic factors on *Nostoc commune* inoculation success. *Plant and Soil*. 444, 57 - 70. <https://doi.org/10.1007/s11104-019-04239-y>.
- Safdar, N., Mirza, B., & Ullah, N. (2013). Comparative physiological responses of the yeast halotolerance genes expressed in transgenic lines of tomato cv Rio Grande under saline conditions. *Acta Physiologiae Plantarum*. 35, 919-929. <https://doi.org/10.1007/s11738-012-1135-3>.
- Seifikalhor, M., Hassani, S. B., & Aliniaiefard, S. (2020). Seed priming by cyanobacteria (*Spirulina platensis*) and salep gum enhances tolerance of maize plant against cadmium toxicity. *Journal of Plant Growth Regulation*. 39, 1009-1021. <https://doi.org/10.1007/s00344-019-10038-7>.
- Sharaf, A. E. M. M., Kailla, A. M., Attia, M. S., & Nofal, M. M. (2016). Induced resistance in tomato plants against root knot nematode using biotic and abiotic inducers. *International Journal of Advanced Research in Biological Sciences*. 3(11), 31-46. <http://dx.doi.org/10.22192/ijarbs.2016.03.11.004>.

- Sharma, V., Prasanna, R., Hossain, F., Muthusamy, V., Nain, L., Das, S., & Kumar, A. (2020). Priming maize seeds with cyanobacteria enhances seed vigour and plant growth in elite maize inbreds. *3 Biotech.* 10, 1-15. <https://doi.org/10.1007/s13205-020-2141-6>.
- Sheikh, T., Hamid, B., Baba, Z., Iqbal, S., Yattoo, A., Fatima, S., & Sayyed, R. Z. (2022). Extracellular polymeric substances in psychrophilic cyanobacteria: A potential biofloculant and carbon sink to mitigate cold stress. *Biocatalysis and Agricultural Biotechnology*, 42, 102375. <https://doi.org/10.1016/j.bcab.2022.102375>.
- Shih, P. M., Wu, D., Latifi, A., Axen, S. D., Fewer, D. P., Talla, E., & Kerfeld, C. A. (2013). Improving the coverage of the cyanobacterial phylum using diversity-driven genome sequencing. *Proceedings of the National Academy of Sciences*, 110(3), 1053-1058. <https://doi.org/10.1073/pnas.1217107110>.
- Shishido, T., Humisto, A., Jokela, J., Liu, L., Wahlsten, M., Tamrakar, A., Fewer, D., Permi, P., Andreote, A., Fiore, M., & Sivonen, K. (2015). Antifungal Compounds from Cyanobacteria. *Marine Drugs*. 13, 2124 - 2140. <https://doi.org/10.3390/md13042124>.
- Shukla, A. C., & Gupta, A. B. (1967). Influence of algal growth-promoting substances on growth, yield and protein contents of rice plants. *Nature*, 213(5077), 744-744. <https://doi.org/10.1038/213744a0>.
- Singh, N. K., & Dhar, D. W. (2010). Cyanobacterial reclamation of salt-affected soil. Genetic engineering, biofertilisation, soil quality and organic farming, *Sustainable Agriculture Reviews*. 243-275. https://doi.org/10.1007/978-90-481-8741-6_9.
- Singh, R. N. (1961). Role of Blue-Green Algae in Nitrogen Economy of Indian Agriculture. New Delhi: Indian Council of Agricultural Research. I.C.A.R. Monographs on Algae [3].
- Singh, R. P., Yadav, P., Kujur, R., Pandey, K. D., & Gupta, R. K. (2022). Cyanobacteria and salinity stress tolerance. *Cyanobacterial Lifestyle and its Applications in Biotechnology* (pp. 253-280). Academic Press. <https://doi.org/10.1016/B978-0-323-90634-0.00003-2>.
- Smith, W., Dannenberg, M., Dannenberg, M., Yan, D., Herrmann, S., Barnes, M., Barron-Gafford, G., Biederman, J., Ferrenberg, S., Fox, A., Hudson, A., Knowles, J., Knowles, J., MacBean, N., Moore, D., Nagler, P., Reed, S., Rutherford, W., Scott, R., Wang, X., & Yang, J. (2019). Remote sensing of dry land ecosystem structure and function: Progress, challenges, and opportunities. *Remote Sensing of Environment*. <https://doi.org/10.1016/j.rse.2019.111401>.
- Soo, R. M., Hemp, J., Parks, D. H., Fischer, W. W., & Hugenholtz, P. (2017). On the origins of oxygenic photosynthesis and aerobic respiration in Cyanobacteria. *Science*. 355(6332), 1436-1440. <https://doi.org/10.1126/science.aal379>.
- Svirčev, Z., Četojević-Simin, D., Simeunović, J., Karaman, M., & Stojanović, D. (2008). Antibacterial, antifungal and cytotoxic activity of terrestrial cyanobacterial strains from Serbia. *Science in China Series C: Life Sciences*. 51, 941-947. <https://doi.org/10.1007/s11427-008-0115-8>.
- Swain, S. S., Paidasetty, S. K., & Padhy, R. N. (2017). Antibacterial, antifungal and antimycobacterial compounds from cyanobacteria. *Biomedicine & Pharmacotherapy*. 90, 760-776. <https://doi.org/10.1016/j.biopha.2017.04.030>.
- Takabe, T., Uchida, A., Shinagawa, F., Terada, Y., Kajita, H., Tanaka, Y. & Takabe, T. (2008). Overexpression of DnaK from a halotolerant cyanobacterium *Aphanothece halophytica* enhances growth rate as well as abiotic stress tolerance of poplar plants. *Plant growth Regulation*. 56, 265-273. <https://doi.org/10.1007/s10725-008-9306-3>.
- Taubae, T. T., Galkina, N. V., & Vasigov, T. (1970). Some data on stimulating effect of *Chlorella vulgaris* (strain 157) on seeds and seedlings of cotton and rice. *Uzbekskii Biologicheskii Zhurnal*. (4), 60-1. <https://www.cabdirect.org/cabdirect/abstract/19711702469>.
- Thevarajah, B., Nishshanka, G. K. S. H., Premaratne, M., Wasath, W. A. J., Nimarshana, P. H. V., Malik, A., & Ariyadasa, T. U. (2022). Cyanobacterial pigment production in wastewaters treated for heavy metal removal: Current status and perspectives. *Journal of Environmental Chemical Engineering*. 108999. <https://doi.org/10.1016/j.jece.2022.108999>.
- Thomas, J.(1977). Dinitrogen fixation by blue-green algae from paddy fields (INIS-mf--4136). India. https://inis.iaea.org/search/search.aspx?orig_q=RN:9376165.
- Tiwari, B., Chakraborty, S., Srivastava, A. K., & Mishra, A. K. (2017). Biodegradation and rapid removal of methyl parathion by the paddy field cyanobacterium *Fischerella* sp. *Algal research*. 25, 285-296. <https://doi.org/10.1016/j.algal.2017.05.024>.
- Tognetti, V. B., Palatnik, J. F., Fillat, M. F., Melzer, M., Hajirezaei, M. R., Valle, E. M., & Carrillo, N. (2006). Functional replacement of ferredoxin by a cyanobacterial flavodoxin in tobacco confers broad-range stress tolerance. *The Plant Cell*. 18(8), 2035-2050. <https://doi.org/10.1105/tpc.106.042424>.

- Vaishampayan, A., Sinha, R., & Häder, D. (1998). Use of Genetically Improved Nitrogen-Fixing Cyanobacteria in Rice Paddy Fields: Prospects as a Source Material for Engineering Herbicide Sensitivity and Resistance in Plants. *Plant Biology*. 111, 176-190. <https://doi.org/10.1111/J.1438-8677.1998.TB00693.X>.
- Vigani, M., Parisi, C., Rodríguez-Cerezo, E., Barbosa, M. J., Sijtsma, L., Ploeg, M., & Enzing, C. (2015). Food and feed products from micro-algae: Market opportunities and challenges for the EU. *Trends in Food Science & Technology*. 42(1), 81-92. <https://doi.org/10.1016/j.tifs.2014.12.004>.
- Volk, R. B., & Furkert, F. H. (2006). Antialgal, antibacterial and antifungal activity of two metabolites produced and excreted by cyanobacteria during growth. *Microbiological Research*. 161(2), 180-186. <https://doi.org/10.1016/j.micres.2005.08.005>.
- Yadav, A. P. S., Goswami, L., Dwivedi, V., & Kumar, S. (2021). Leveraging the biosorption potential of *Leptolyngbya boryana* for Cr (VI) removal from aqueous solution. *Cleaner Engineering and Technology*. 4, 100198. <https://doi.org/10.1016/j.clet.2021.100198>.
- Yanni, Y. G. (1991). Potential of indigenous cyanobacteria to contribute to rice performance under different schedules of nitrogen application. *World Journal of Microbiology and Biotechnology*. 7, 48-52. <https://doi.org/10.1007/BF02310919>.
- Yanni, Y. G., & Abdallah, F. E. (1990). Role of algalization in rice growth, yield and incidence of infestation with the stem borer *Chilo agamemnon* Bles. and the leaf miner *Hydrellia prosternalis* Deeming in the Nile Delta. *World journal of Microbiology and Biotechnology*. 6, 383-389. <https://doi.org/10.1007/BF01202119>.
- Yanti, Y., Hamid, H., & Syarif, Z. (2019). Screening of indigenous rhizospheric cyanobacteria as potential growth promotor and biocontrol of *Ralstonia syzygii* subsp. *indonesiensis* on chili. *International Journal of Agriculture Environment and Biotechnology*. 4, 1665-1672. <https://doi.org/10.22161/ijeab.46.5>.
- Youssef, M. M. A., & Ali, M. S. (1998). Management of *Meloidogyne incognita* infecting cowpea by using some native blue green algae. *Anzeiger für Schädlingskunde, Pflanzenschutz, Umweltschutz*. 71, 15-16. <https://doi.org/10.1007/BF02770565>.
- Zhang, C., Niu, D., Song, M., Elser, J. J., Okie, J. G., & Fu, H. (2018). Effects of rainfall manipulations on carbon exchange of cyanobacteria and moss-dominated biological soil crusts. *Soil Biology and Biochemistry*. 124, 24-31. <https://doi.org/10.1016/j.soilbio.2018.05.021>.
- Zhang, J., Song, X., Wei, H., Zhou, W., Peng, C., & Li, D. (2021). Effect of substituting nitrogen fertilizer with nitrogen-fixing cyanobacteria on yield in a double-rice cropping system in southern China. *Journal of Applied Phycology*. 33, 2221-2232. <https://doi.org/10.1007/s10811-021-02455-7>.
- Zhou, Y., Bao, J., Zhang, D., Li, Y., Li, H., & He, H. (2020). Effect of heterocystous nitrogen-fixing cyanobacteria against rice sheath blight and the underlying mechanism. *Applied Soil Ecology*. 153, 103580. <https://doi.org/10.1016/j.apsoil.2020.103580>.