ISSN (E): 2320-3862
ISSN (P): 2394-0530
https://www.plantsjournal.com
JMPS 2024; 12(1): 25-37

Received: 25-10-2023
Accepted: 29-11-2023

Dr. Jainendra Pathak
Pt. Jawaharlal Nehru College, (Affiliated to Bundelkhand University, Jhansi), Banda, Uttar Pradesh, India

Jyoti Jaiswal
Center of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh, India

Dr. Ramesh K Shukla
Pt. Jawaharlal Nehru College, (Affiliated to Bundelkhand University, Jhansi), Banda, Uttar Pradesh, India

Dr. Deepak K Singh
A.N.D Kisan PG College, (Affiliated to Dr RML University, Ayodhya) Babhnan, Gonda, Uttar Pradesh, India

Prof. Rajeshwar P Sinha
1. Center of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh, India
2. University Center for Research and Development (UCRD), Chandigarh University, Chandigarh, India

Corresponding Author:
Dr. Jainendra Pathak
Pt. Jawaharlal Nehru College, (Affiliated to Bundelkhand University, Jhansi), Banda, Uttar Pradesh, India

Cyanobacterial/algal biofertilizers as plant growth stimulants for green sustainable agriculture

Jainendra Pathak, Jyoti Jaiswal, Ramesh K Shukla, Deepak K Singh and Rajeshwar P Sinha

DOI: https://doi.org/10.22271/plants.2024.v12.i1a.1622

Abstract
Population of the Earth has been projected to reach ~9.7 billion by 2050 and Asia and Africa would be the major contributors to this enhanced population. This increased population is directly related with higher demand of food security in very near future. Modern agricultural management is heavily dependent on the fertilizers for increased crop production, but increasing use of chemical-based and inorganic fertilizers may be a serious threat to the environment and human health. Microalgae have biostimulant and biofertilizer properties which are attracting the interest of farmers and agrochemical industries. Application of microbes such as cyanobacteria, microalgae, endo/ecto-mycorrhizal fungi, rhizobacteria, and others serves as an ecofriendly approach for sustainable agriculture practices. Biostimulants are the products derived from organic matter that are applied in small quantities and are able to stimulate the development and growth of several crops under stressed as well as optimal environmental conditions. Plant biostimulants encompass diverse organic and inorganic substances (humic acids and protein hydrolysates) as well as prokaryotes (plant growth promoting bacteria) and eukaryotes such as mycorrhiza and macroalgae (seaweed). Biofertilizers are products containing living microorganisms or natural substances that are able to improve chemical and biological soil properties, stimulating plant growth, and restoring soil fertility. Microalgae and cyanobacteria (blue-green algae), are attracting interest from scientists, extension specialists, private industry and plant growers because of their versatile nature, simple unicellular structure, high photosynthetic efficiency, ability for heterotrophic growth, adaptability to domestic and industrial wastewater, amenability to metabolic engineering, and possibility to yield valuable co-products. This review article focuses on the research achievements on cyanobacteria and microalgae based plant biofertilizers and biostimulants in the agricultural applications. The challenges to commercializing these kinds of biofertilizers are also discussed.

Keywords: Biofertilizer, biostimulants, cyanobacteria, microalgae, soil fertility, sustainable agriculture

1. Introduction

To overcome the challenge of increasing population, the World Health Organization has suggested a doubling of food production by 2050, while the United Nations has suggested a 50% increase in the global food production by 2030. The productivity gains resulted from the "Green Revolution" have essentially reached a plateau, and feeding the increased global population is further challenged by limited availability of agriculture land. Nevertheless, a production system which has a higher productivity but requires a small land area and time for cultivation would be the requirement of the future agriculture [1-2]. In recent years, microalgae and cyanobacteria, have emerged as potential candidates for their application in development of environment friendly and sustainable agricultural practices [3-4]. These oxygen evolving photosynthetic organisms do not compete for arable land for their cultivation. Cyanobacteria, which can be cultivated using seawater, require residual nutrients for high areal productivity and have high protein and reasonable amount of carbohydrate as well as lipid contents per gram of their biomass [5-7]. Globally about 25 Gt a^{-1} of carbon can be fixed into energy-dense biomass by cyanobacteria using atmospheric CO_2 and solar energy [8]. Therefore, generation of microbiological energy through massive solar energy transformation permits harvesting of various forms of eco-friendly energy reserves [9].

The aforementioned characteristics make microalgae and cyanobacteria potential microorganisms for their application as feedstocks for sustainable production of food and non-food commodities, including valuable chemicals and bioenergy [2, 10-12].

2. Cyanobacteria as Biofertilizers

It is very expensive to produce inorganic nitrogen fertilizers due to the requirement of large amount of fossil-fuel energy. This necessitated the development of alternate, sustainable and cost-effective biologically available nitrogen resources which can fulfill the nitrogen demand of agriculture in sustainable manner [13]. For this purpose biological systems have been identified which can fix atmospheric dinitrogen [14]. Biological nitrogen fixation contributes ~2×10^2 Mt of nitrogen annually [15]. According to Metting [16], the total nitrogen fixation can be ~90 kg N ha^{-1} y^{-1}. Symbiotic and free-living eubacteria, including cyanobacteria, are two groups of nitrogen fixing organisms. The free-living cyanobacteria fix <10 kg of N $ha^{-1}y^{-1}$, however, annually ~10-30 kg of N ha^{-1} is fixed by dense mats of cyanobacteria [17-18]. Therefore, cyanobacteria constitute an important component of naturally available biofertilizers [14, 19]. Rice production in tropical countries mainly depends on biological N_2 fixation by cyanobacteria which are a natural component of paddy fields [14]. In these cultivated agriculture systems, annually ~32 Tg of nitrogen is fixed by biological nitrogen fixers [3], and cyanobacteria add about 20-30 kg fixed nitrogen ha^{-1} along with organic matter to the paddy fields [20-21]. Cyanobacteria also make symbiotic associations with different photosynthetic and non-photosynthetic organisms such as algae, fungi, diatoms, bryophytes, hornworts, liverworts, mosses, pteridophytes, gymnosperms, and angiosperms [22-23]. Several heterocystous cyanobacterial genera such as *Anabaena*, *Nostoc*, *Nodularia*, *Scytonema*, *Schytonema topsis*, *Chlorogloea*, *Cylindrospermum*, *Mastigocladus*, *Calothrix*, *Anabaenopsis*, *Aulosira*, *Tolypothrix*, *Haplosiphon*, *Camptylonema*, *Stigonema*, *Fischerella*, *Gloeotrichia*, *Chlorogloeopsis*, *Rivularia*, *Nostochopsis*, *Westiellopsis*, *Wollea* and *Westiella* have been shown to be efficient N_2 fixers [24].

Table 1 contains a list of potential cyanobacteria which can be used as biofertilizers in agricultural fields [14]. For the first time, Fritsch, [25] studied the abundance and importance of cyanobacteria with respect to maintenance of soil fertility of paddy fields through biological nitrogen fixation, which was afterwards recognized by several other workers [26-28]. Generally, for algalization of the rice fields, mixed cyanobacterial cultures of free-living forms are used [29-30]. The water fern *Azolla* harbors *Anabaena azollae* in its fronds and the cyanobacterium releases ammonium into the water when paddy fields are inoculated with foam-immobilized *A. azollae* strains [31]. Significant increase in grain yield, biomass and nutritive value of rice can be achieved by inoculating *Anabaena doliolum* and *A. fertilissima* in paddy fields with or without urea [32]. In addition to rice crop, cyanobacterial biofertilizers can also enhance the yield, shoot/root length, and dry weight of wheat crops [33-35]. Inoculation of soil with various cyanobacterial strains like *Nostoc carneum*, *N. piscinale*, *Anabaena doliolum* and *A. torulosa* results in significantly higher acetylene reducing activity [19]. Additionally, the acetylene reducing activity is highest at harvest stage when wheat fields are inoculated with an *Anabaena*-*Serratia* biofilm along with rock phosphate [36].

Table 1: List of nitrogen-fixing cyanobacteria important for their application in biofertilizer industry (Adapted from Vaishampayan *et al.* [14])

Filamentous
Heterocystous
Anabaena, Anabaenopsis, Aulosira, Calothrix, Camptylonema, Chlorogloea, Chlorogloeopsis, Cylindrospermum, Fischerella, Gloeotrichia, Haplosiphon, Mastigocladus, Nodularia, Nostoc, Nostochopsis, Rivularia, Scytonema, Scytonematopsis, Stigonema, Tolypothrix, Westiella, Westiellopsis, Wollea
Non-heterocystous
Lyngbya, Microcoleus chthonoplastes, Myxosarcina, Oscillatoria, Plectonema Boryanum, Pseudoanabaena, Schizothrix, Trichodesmium
Unicellular
Aphanothece, Chroococcidiopsis, Dermocarpa, Gloeocapsa, Myxosarcina, Pleurocapsa, Synechococcus, Xenococcus

The cyanobacteria based biofertilizers are cost-effective as they cost one third to that of chemical fertilizers [19]. In addition to nitrogen fixation, cyanobacteria also contribute to mobilization of inorganic phosphates through excretion of organic acids and extracellular phosphatases [37-38]. Cyanobacteria solubilize and mobilize the insoluble organic phosphates and improve the availability of phosphorus to the crop [39-40]. The humus content generated after death and decay of cyanobacteria creates strong reducing condition in soil which improve the soil structure and fertility [41]. Different cyanobacterial strains are known to produce plant growth hormones and siderophores, and therefore, cyanobacteria can affect the development and productivity of crops [42-43].

The exo-polysaccharides secreted by cyanobacteria induce aggregation of soil particles which improve the soil structure and fertility by enhancing the accumulation of organic content and water accumulation [2]. These findings collectively support the importance of cyanobacteria as biofertilizers, and methods have been developed for their cultivation and utilization in fertilizer industry [44-46]. In general, biofertilizers are defined as the organic compounds from living microorganisms to promote the growth of seeds, plants, or soil bacterial consortia by essential nutrients such as nitrogen, phosphate, potassium and other ineral nutrients (Figure 1) [47-49].

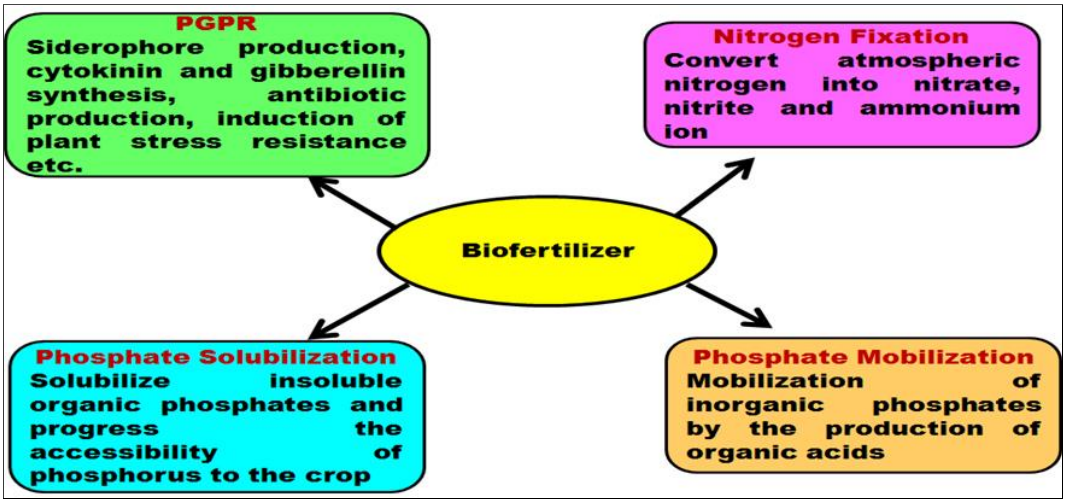

Fig 1: Role of biofertilizers in maintaining soil health

They should be distinguished from the NPK fertilizers, which are based on Nitrogen (N), Phosphorous (P), and Potassium (K), the three main nutrients necessary in high quantities for healthy growth of higher plants. Biofertilizers are classified by the microorganisms and the benefits achieved by their application: nitrogen-fixators; phosphates and potassium solubilizing biofertilizers; phosphorus-mobilizing biofertilizers and biofertilizers for secondary macronutrients, zinc and iron solubilizers, plant-growth-promoting rhizobacteria (PGPR), and compost [47, 50]. The remarkable features of biofertilizers include improved crop productivity per area in a relatively short time; reduced amounts of energy consumption and contamination of soil and water; increased soil fertility; and promoted antagonism and biological control of phyto-pathogenic organisms [51]. Biofertilizers will provide renewable and environmental friendly solutions for modern agriculture, especially in the form of integrated nutrient management (INM) and integrated plant nutrition system (IPNS), which may lead to sustainable economic development [52-53]. However, several challenges are associated with biofertilizers, such as the short period of shelf life (3-4 months) and the conditions required for storage (cool temperatures because of their temperature sensitivity) [54]. Recent studies have indicated that different types of photosynthetic microorganisms such as cyanobacteria and microalgae can be used as biofertilizers and soil conditioners [55-56]. Microalgae are generally divided into Chlorophyta (green algae), Rhodophyta (red algae), Phaeophyta (brown algae), Euglenophyta, Pyrrophyta, and Chrysophyta. Cyanobacteria are the only photosynthetic prokaryotes able to produce oxygen [57]. There are around 30,000 species of both unicellular microalgae and more complex multicellular organisms [58]. Among them, 150 genera and more than 2000 species of microalgae have been listed [59].

Research on industrial applications of algae has been conducted since early 1950s, when productivity and yields were first studied in mass culture [60]. The main industrial benefits of algae are their ability to grow with minimum freshwater inputs and utilize lands that are otherwise agriculturally non-productive. Algae are widely considered to have major influence on essential ecosystem services since they can be cultivated in wastewater and agricultural runoff, recovering excess nutrients and reclaiming water for further use. They can also reduce greenhouse gas emissions by sequestering carbon dioxide and nitrous oxides from industrial sources [61]. Cyanobacteria are considered the simplest, living autotrophic microorganisms. These organisms are capable of building up food materials from inorganic matter and are widely distributed in the aquatic environment [62]. Several unique features of cyanobacteria, such as water-holding capacity, short generation time, ability to fix atmospheric N_2, and adaptation to extreme conditions, make them an effective biofertilizer source to improve soil physico-chemical properties [3, 62]. Cyanobacteria can also secrete plant growth hormones as secondary metabolites, promote the transport of nutrients from soil to plants, cause agglomeration of soil, and improve the chemical properties of the soil [63]. Their diverse morphology and physiological properties enable wide distribution in the ecosystem and tolerance to environmental stresses [64]. This review explores photoautotrophic microorganisms for functions that facilitate the development of biological fertilizers in the agricultural sector. This paper is aimed at reporting developments in the processing of microalgal biostimulants (MBS) and biofertilisers (MBF), summarizing the biologically-active compounds, and examining the researches supporting the use of MBS and MBF for managing productivity and abiotic stresses in crop productions. Microalgae are used in agriculture in different applications, such as amendment, foliar application, and seed priming. MBS and MBF might be applied as an alternative technique, or used in conjunction with synthetic fertilizers, crop protection products and plant growth regulators, generating multiple benefits, such as enhanced rooting, higher crop yields and quality and tolerance to drought and salt. Worldwide, MBS and MBF remain largely unexploited, such that this study highlights some of the current researches and future development priorities. Plant biostimulants (PBs) attract interest in modern agriculture as a tool to enhance crop performance, resilience to environmental stress, and nutrient use efficiency. On the other hand, large-scale biomass production and harvesting still represent a bottleneck for some applications. Although it is long known that microalgae produce several complex macromolecules that are active on higher plants, their targeted applications in crop science is still in its infancy. This paper presents an overview of the main extraction methods from microalgae, their bioactive compounds, and application methods in agriculture. Mechanisms of biostimulation that influence plant performance, physiology, resilience to abiotic stress as well as the plant microbiome are also outlined. Considering current state-of-the-art, perspectives for future research on microalgaebased biostimulants are discussed, ranging from the development of crop-tailored, highly effective products to their application for increasing sustainability in agriculture (Figure 2).

3. Algae-Based Biofertilizers

Algae biotechnology research in the field of biofertilizers has increased in recent years. The majority of the studies published recently used *Chlorella* sp. as the model system (Table 2) [65-74].The most striking potential of algae is that they can survive even in the presence of highly concentrated organic and inorganic chemicals in varying waste streams which are toxic to living organisms. This is important in enabling more sustainable and efficient production in agriculture. Microalgae can be autotrophic or heterotrophic. As solar conversion in some microalgae species is very efficient, the most common procedure for cultivation of this microorganism is presently the autotrophic growth [75]. The basic cultivation system consists of open-ponds used for food supplement and antioxidant production, with highly variable productivity depending on species and environmental conditions [76]. Open system cultivation of microalgae is thus limited to certain robust species, such as *Spirulina* spp., *Dunaliella* spp., and *Chlorella* spp., that are able to grow under extreme conditions. Reduction of growing area and protection against potential contamination can be obtained in closed-ponds, referred to as photobioreactors. This type of cultivation method is often used for the production of high added-value molecules, such as pharmaceutical compounds.

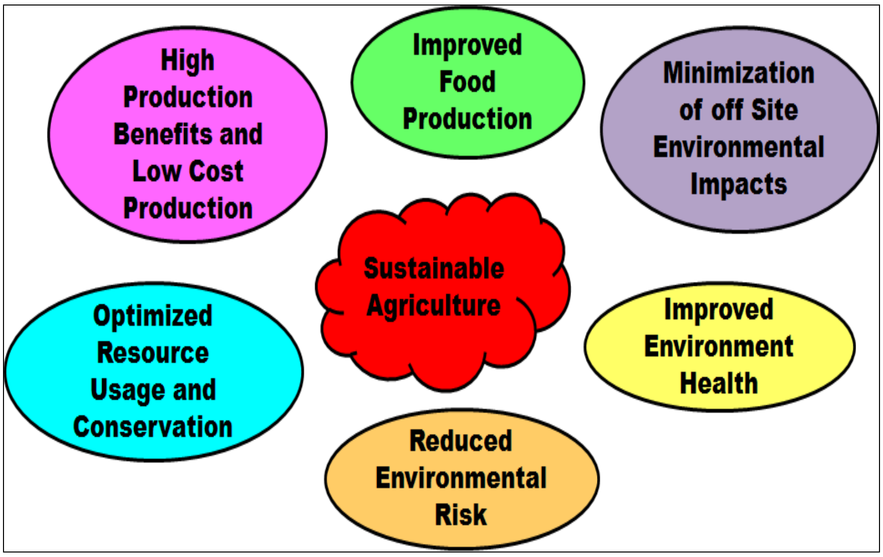

Fig 2: Sustainable agriculture and its various aspects

Table 2: Microbial biofertilizers and their applications

Species	Formulation	Application	Reference
Spirulina platensis	Cyanobacterial biofertilizer -intact cells (Spirufert_bio-fertilizer)	Foliar treatment on eggplant	Dias *et al.* [77]
Spirulina platensis	Cyanobacterial biofertilizer -intact cells after aquaculture wastewater remediation for nitrogen fixation	Spread biomass for leafy vegetables	Wuang *et al.* [78]
Consortium ZOB1	consortium biofertilizer -intact cells as biostimulator for crops	Not mentioned	Zayadan *et al.* [79]
Anabaena sp. *Aulosira* sp. *Cylindrospermum* sp. *Nostoc* sp. *Tolypothrix* sp.	Each one exploitable as cyanobacterial biofertilizer -intact cells for nitrogen fixation and indole acetic acid (IAA) growth promoting substance	Wet land rice cultivation	Chittora *et al.* [80]
Iran native nitrogen-carbon fixing cyanobacteria and bacteria	cyanobacterial biofertilizer/other biofertilizer -intact cells for nitrogen and carbon fixation	Spread to erosion prone soil	Kheirfam *et al.* [63]
Nitrogen-fixing cyanobacteria	cyanobacterial biofertilizer -intact cells for nitrogen fixation	Spread on soil for rice cultivation amended with fly ash	Padhy *et al.* [81]
Frankia Hsli10	cyanobacterial biofertilizer -possible intact cells application for saline soil	Not mentioned	Srivastava and Mishra [53]
Chlorella sp.	Micro algae (MA) biofertilizer - suspensions of microalgae culture and sterile filtrates from wastewater treatment	Spread to agricultural soil	Evan *et al.* [67]
Chlorella vulgaris	MA biofertilizer - cells digestate of anaerobic reactors after growth in wastewater	Not mentioned	Doğa-Subaşi and Demirer [66]
Chlorella vulgaris	MA biofertilizer	dry or liquid microalgae biomass	Ozdemir *et al.* [72]

		Dry and liquid algae widespread to agricultural soil; foliar spray	
Chlorella pyrenoidosa	MA biofertilizer - cellular biomass after im mobilizing for dairy effluent treatment	Spread on rice seeds	Yadavalli and Heggers [74]
Acutodesmus dimorphus	MA biofertilizer - cellular extracts, in distilled water and dry Biomass	Spread to agricultural soil; foliar spray	Garcia-Gonzalez and Sommerfeld [68]
Microcystis aeruginosa MKR 0105 *Anabaena* PCC 7120 *Chlorella* sp.	Blue-green algae (BGA) plus MA biofertilizer - intact cells with limited use of YaraMila Complex synthetic fertilizer	Triple foliar	Grzesik *et al.* [70]
Chlorella vulgaris *Scenedesmus obliquus* ''Consortium C''	Consortium biofertilizer - possible use of cellular bio mass growth in wastewater	Not mentioned	Gouveia *et al.* [69]
Phaeodactylum tricornutum *Pavlova lutheri*	MA biofertilizers - possible use of cellular biomass growth in mineral medium and agro-industrial ultra-filtrate	Not mentioned	Veronesia *et al.* [73]
Consortium of 21 microorganisms	Consortium biofertilizer - possible use based on study of morphological and phylogenetic diversity	Not mentioned	Hernandez Melchor *et al.* [71]
Native microalgae ''Consortia 01'' and ''Consortia 12''	MA biofertilizer - possible readly use of biomass after polishing treatment of municipal waste water	Not mentioned	Beltrán-Rocha *et al.* [65]

However, the main disadvantage of photobioreactors is the high capital cost for designing and operating. A viable alternative for growing microalgae is in heterotrophic conditions exploiting existing industrial bacterial-bioreactors [82-85]. The main advantages of this cultivation system is the high cell concentration, which can reach up to 100 gL^{-1}; in photobioreactors, the maximum density is around 40 gL^{-1}, even lower in open-ponds (c. 10 gL^{-1}). A recent sustainable energy based strategy for growing microalgae relies on using wastewater of industrial, domestic and agricultural origin in bioreactors that allow for the removal of contaminants during the production of microalgal biomass. Therefore, microalgae have the potential to reduce the negative discharges to the environment by, for instance, re-using nutrients and products and valorizing waste from different sources, including those related to agriculture.

3.1 Soil Fertility

Algal biomass formation from wastewater treatment can add value to land use as a biofertilizer, although not much information is available on how it may affect soil nutrient dynamics. Research focused on the indigenous species of *Anabaena* has showed the ability of this strain to promote soil fertility while decreasing soil density [86] even in land with herbicide residuals and limited water supply [87]. Similarly, Marks *et al.* [88] investigated the effects of unicellular green algae on the soil organic carbon using microalga *Chlorella* sp. grown in the liquid slurry. Their results indicated that photoautotrophic growth of *Chlorella* sp. was 3.5 times higher than that grown in dark and culture filtrates without algal cells, and soil respiration was significantly increased [67]. Another interesting research area is the study of algal and bacterial consortia in the biofertilizer application. In fact, it could not only be more efficient in detoxification of pollutants and removal of nutrients from wastewaters compared to the use of individual microorganisms, but such consortia could also allow maximum use of available N, P, and K in the soil. The pollutant abatement between algae and bacteria would lead to the success of consortium engineering [14, 36, 71, 79, 89]. Furthermore, literature suggests that algae/bacteria consortia have great potential for soil amendment of marginal lands, helping to transform them into agricultural soil.

3.2 Nitrogen Fixation

One reason to use cyanobacteria as biofertilizers is based on their nitrogen-fixing ability. Cyanobacteria convert inorganic nitrogen (N_2) from the air into organic nitrogen that can be easily utilized by higher plants [59]. Efforts to use cyanobacteria to promote rice growth have been made both in India and Chile. Local cyanobacterial strains in Chile have shown to increase nitrogen accumulation efficiency in rice paddles. Vaishampayan *et al.* [14] recommended that the *Azolla-Anabaena* (the free-living cyanobacteria *Anabaena* and the water fern *Azolla*) symbiotic N_2-fixing complex be considered self-renewable natural nitrogen resources to reduce inorganic N requirements to the bare minimum. The cyanobacterium *Tolypothrix* sp. was found to produce bioproducts in tropical regions by using low nitrogen containing water sources [90].

According to a comparative study with N^{15}-labelled fertilizer and indigenous cyanobacteria, N_2 recovery by the soil-plant system from cyanobacteria was higher than that from chemical fertilizer [91]. This algal strain was highly capable of increasing the growth of rice plants due to its nitrogen-fixation ability [74]. In another work, following treatment with immobilized *Chlorella pyrenoidosa*, dairy waste water effluent used as a biofertilizer increased rice plants' root and shoot length by 30% [74]. In another work, the inoculants of *Anabaena laxa* and *Anabaena-Rhizobium* consortium were used to formulate biofilm in chickpea cultivation. The *A. laxa* inoculation for the biofilm led to 50% higher grain yield (1,724 kg/ha) compared to the control (847 kg/ha) [74]. In addition, microbial association (21 different microorganisms containing proteobacteria, bacteriodetes, chlorophyta, etc.) was shown to have a high capacity for N_2-fixation (10,294 nmol ethylene/g dry weight/h), when used as a biofertilizer [71]. A more comprehensive description of cyanobacteria use in agriculture as nutrient supplements can be found in several literatures [53, 63,77-79, 81,92] in particular for nitrogen fixation in the wet land rice cultivation.

3.3 Production of Plant Growth Biostimulants

Some algal metabolites have been found to stimulate plant growth directly or indirectly by interacting with soil microbes for biomineralization or plant-microbe symbiosis, thereby increasing nutrient availability [93]. To verify this concept, *Lupinus termis* was grown with plant growth-stimulating substances from cyanobacteria and bacteria. The addition of the cyanobacterial filtrate combined with bacterial suspension significantly increased the average germination compared to seeds untreated or treated by hormones (IAA, GA3, and cytokinins). In particular, the germination rates with such treatments were 53.13, 211.48, 129.04, and 104.18% higher in comparison to

1. Untreated seeds
2. Seeds treated with IAA
3. Seeds treated by GA3 and
4. Seeds treated by cytokinins, respectively [94].

Furthermore, algal species isolated from different rice cultivations in the Iranian region were examined for the production of phytohormones that affect plant growth [95]. Under optimal conditions, the cyanobacterium *Nostoc* could produce 8.66 µg/mL IAA, and sprouting was effectively promoted when the infiltrate was added to taro corn field [92]. In another work by Rodríguez *et al*. it was found that the extracellular products of *Scytonema hofmanni* have produced gibberellin-like plant growth regulators, which enabled the hormone homeostasis of rice seedlings under salt stress [43]. On the other hand, Saadatnia and Riahi isolated four species of *Anabaena* strains and tested them in the germination process of rice seeds. The results showed a significant higher germination rate compared to the control [86]. Similar outcomes were shown in the study of Zaydan *et al*. [79] where the cyanobacteria and *Azotobacter* sp. consortium was established.

3.4 Biopesticidal Substances

Algae can be used as biocontrol agents with nematicidal effect, [96-98] where extracts and exudates of cyanobacteria have been reported to inhibit hatching and to cause immobility and mortality of juvenile plant parasitic nematodes *in vitro*. Antifungal and antibacterial activities were also studied where culture filtrate has hydrolytic activity againt phytopathogens [99-101]. The most economically important fungal pathogen is *Fusarium* sp., and other fungal pathogens have also controlled under above studied. Studies on the biocidal effects of algae have revealed new possibilities to develop novel pest control methods. Future investigations are necessary to validate their spectrum and applications for commercial use.

3.5 Tolerance to Extreme Environmental Conditions

Algae are able tolerate various types of environmental stresses. In regard to pesticide resistance, Ningthoujam *et al*., have found that *Anabaena variabilis* was able to tolerate 100 µg/mL malathion [102]. As an example of salinity tolerance ability, Jha *et al*. demonstrated that cyanobacteria could be negatively affected by Mn and sodium (Na, -30.19%). However, this negative relationship with Na enabled cyanobacteria to be used as an ameliorating agent for salt-affected soil [103]. In another study, the cyanobacterium *Anabaena oryzae* was found to release PO_4^{-3} enzymatically under salt stress conditions, suggesting that it could be used in high salinity and alkaline (calcium (Ca^{2+})-rich) soils [104]. Biosynthesis of UV-absorbing molecules, such as mycosporine-like amino acids (MAAs) and scytonemin, as a defence against continued solar radiation in cyanobacteria has been well documented [105-108] and these compounds aids in survival of cyanobacteria under harsh conditions in soils. Sinha and Häder has discussed about the photoprotective defence mechanisms of cyanobacteria against lethal UV-B, which may play a potential role in utilization of cyanobacteria as biofertilizers for the growth of agricultural crops [108]. The main practical problem of commercialized biofertilizer is related to adaptability of active microorganisms in the environment.

4. Mutation of Algae for Better Biofertilizers

Some studies have suggested possible solutions for the limitations of biotic and abiotic factors on algae and their performances. Therefore, it is appropriate to use novel approaches to produce cyanobacterial mutants in order to explore the potential of cyanobacteria [109-110]. Singh and Datta [111] demonstrated that *A. variabilis* mutant strains exposed to herbicides were able to resist the herbicide and increase rice growth under outdoor conditions in flooded soils. In another work, the plasmid pRL489 was constructed by Ravindran *et al*. and introduced into *Oscillatoria* MKU 277 by electroporation to establish the gene transfer system in the cyanobacteria [112]. This work has improved the mutational techniques for the development of more powerful and viable biofertilizer strains. A chlorate-resistant mutant (Clo-R) of *Nostoc* ANTH for lack of nitrate was studied by Bhattacharya *et al*. It was observed that heterocyst formation and N_2-fixation in the presence of nitrate was able to separate nitrate and nitrite transport systems of the mutant. This mutant is supplementary to chemical nitrate fertilizer as a biofertilizer without N_2-fixation being adversely affected in rice field [113]. Similarly, a nitrogenase derepressed mutant of *Anabaena variabili* has shown potential for developing biofertilizer for rice production, especially when the rice-production systems aim to minimize environmental pollution from inorganic N fertilizers [114]. In more recent study, cyanobacteria mutant induced by the UV-B has showed tolerance to Cu toxicity, provided that the nitrogen fixation ability was suppressed [115]. Singh *et al.* also improved the *A. variabilis* mutant grown in herbicide(s)-stressed agro-ecosystem [115]. Recent advances in synthetic biology can provide a better solution for handling these challenges and have created a new research area in algal biotechnology.

5. Large-Scale Algal Growth

Algal biomass for agricultural applications, in particularly obtained from waste streams, has become an economically attractive investment. Numerous research groups have integrated production of algal biomass with industrial wastewaters bioremediations. For example, Nisha *et al*. and Galhano *et al*. have studied the use of cyanobacteria for both soil fertility and crop protection against residual herbicides. Their potential for improving soil structural stability, nutrient availability and crop productivity has been further exploited under limited water regime which is fundamental for sustainable agricultural management [87, 116]. According to the outcomes of the above studies, indigenous algal strains are more suitable for fertilizer applications. As compared to photobioreactors, open raceways (especially with waste water) are more effective for small capital investments and low power consumption in a large-scale production algal biomass [117]. The important role that algae may play on the elimination of contaminants in various environments is still underestimated [118]. Many studies have pointed out that economically feasible algal production is of critical importance. Algal biomass after harvest can be used as forage, biogas feedstock or biofertilizer. In several review articles, it was shown that algal species were grown with satisfactory results on petrochemical effluent [119], sewage wastewater [120], piggery wastewater [121], municipal wastewater [122], domestic wastewater [123], industrial wastewater [124], aquaculture wastewater [78] and dairy effluent [74]. Barminski *et al*. [125] have provided a media recipes for raceway cultivation of N-fixing cyanobacteria by i) tank method, (ii) pit method, (iii) field method, and (iv) nursery cum algal production method. The former two methods are designed for small-scale and latter two are for bulk production on a commercial scale [55].

6. Formulation of Algal Biofertilizers

Algal biofertilizer formulation has been developed and tested for commercialization. Among them, Dubey and Verma [126] used clay based inoculants for strain inoculation in soil for longer duration. The algae population in soil was about 10-70 times higher than that of the non-inoculated plots, even after four months [126]. Mishra and Pabbi [127] offered technology to farmers after getting a soil-based starter culture, which allowed them to produce the biofertilizer on their own with minimum additional inputs [127]. Tripathi *et al*. [128] used a so-called fly-ash approach, in which the cyanobacteria and nitrogen fertilizer were mixed to improve growth rate and yield of rice plants. This approach reduced nitrogen fertilizers demand [128]. In the study where cyanobacterial-based fertilizers were employed with two carriers (wheat straw and multani mitti-clay), the experiments were compared with traditional soil-based cyanobacterial biofertilizer. It was observed that both the straw-based and soil-based biofertilizer treatments have showed high yields when supplemented with 90 and 120 kg N/ha, respectively. It was thus proven that cyanobacterial biofertilizers can be formulated to maximize crop productivity and reduce inputs of chemical fertilizers in rice cultivation [129]. Paddy straw compost:vermiculite (1:1) as carrier-based formulation was also studied by Prasanna *et al*. [130] and Renuka *et al*., [131] who found that the adaptation rates of some cyanobacteria (*Anabaena torulosa*, *Nostoc carneum*, *Nostoc piscinale*, *Anabaena doliolum*) were higher in the rice field when vermi-compost was used as their carrier [19]. The shelf-life of cyanobacterial biofertilizer can be augmented by selecting translucent packing material, dry mixing, and using paddy straw as a carrier. Dry mixing with a mixing ratio of 50:50 (carrier: cyanobacteria) has given better performance in inoculum loading and shelf-life [132]. Hori *et al*. used phytoextracts of neem (*Azadirachta indica*), bel (*Aegle marmelos*), and tobacco (*Nicotiana tabacum*) in controling cyanobacterial disease during storage duration [133]. They found that tobacco waste was superior to others in disease prevention [132]. Moreover, akinetes were suggested to be used as a biofertilizer after drying processes, as they could be stored for at least several weeks when in a dried state [133]. It was found that algal growth largely depends on temperature and pH [59]. Cyanobacterial preservation can be obtained either by air drying or drying wet blue green algae in oven at 35-40 ºC for 24 h in dark. This method is easy to be applied to ensure a high germination rate [134]. Foliar biofertilization by algae on willow monocultures was studied by Grzesik *et al*. [70] and shown to significantly increase productivity. In particular, studies have indicated that the foliar application of *Acutodesmus dimorphus* aqueous extracts and formulation of growth media have created a positive effect on seed germination and plant growth. It was observed that *A. dimorphus* cellular extract and dry biomass could be used both as a biostimulant and a biofertilizer to trigger faster germination and to enhance plant growth and floral production in Roma tomato plants [68, 135]. Based on the above reports in the literature, we can conclude that the carrier-based formulation is more suitable for N_2 fixing fertilizer and soil conditioning, while foliar-based formulation is more appropriate for germination promoting effects.

7. Challenges and Measures for Commercialization

The commercial utilization of N_2-fixing organisms in agriculture has encountered some difficulties. As Kumar [59] illustrated, factors such as a suitable carrier for individual algal, soil, and climate factors and biotic and abiotic stress in the field are the main constraints for commercial use of algae as biofertilizer. Cyanobacteria-based biofertilizers were widely used in paddy field cultivation due to their habitat and growth requirements. According to several studies, there are some limitations for cyanobacterial biofertilizers in areas possibly contaminated by pesticide residues, herbicides residues, and heavy metals (i.e., nickel and copper), or in land with high salinity. These factors can inhibit algal growth, cellular photosynthesis, and nitrogen fixing activity [136, 137]. He *et al*. [136] reported the inhibition on growth, synthesis of pigments, and photosystem II (PSII) activity of the nitrogen-fixing cyanobacterium *Nostoc* sp. by stress caused by the addition of butachlor. Debnath *et al*. studied the impacts of commonly used pesticide, fungicide, and insecticide on the growth and enzymes production of four cyanobacterial species-*Nostoc ellipsosporum*, *Scytonema simplex*, *Tolypothrix tenuis*, and *Westiellopsis prolifica*. It was observed that both the fungicides and insecticides at EC_{50} concentration would cause an inhibitory effect on the expression of nitrogenase and glutamine synthetase in all four cyanobacterial species studied [138]. These four cyanobacterial strains have been the favored models for deeper understanding of intracellular metabolic processes involved in the production of compounds of medicinal and commercial value [109]. Sharma *et al*. [139] pointed out the need to adopt multidisciplinary approaches with a multiproduct process (biorefinery) strategy to harness the maximum benefit of cyanobacteria.

8. Conclusion

Algae-based biofertilizers have shown significant benefits in the development of green agriculture. Figure 2 illustrates future research areas for algae-based bifertilizers coupled with high energy generation. Beside N_2 fixation, they are able to increase soil fertility and give the PGPR effect to the crops. Some algal fertilizers can be produced as metabolic byproducts during the wastewater treatment processes, making them renewable sources for sustainable agriculture. Carrier systems for maintaining microalgal biomass for long periods of time are readily available from natural (soil, clay) and also renewable sources (paddy straw, multani mitti, etc.). Moreover, handing over the technology to farmers for their needs can create value and build up small-scale biofertilizer production within their individual circumstances. The development of organic farming without requiring a large land for production or even effectively exploiting marginal land are other other advantages of algal fertilizers. In summary, applications of algal biofertilizers will meet the needs of sustainable agriculture with three main objectives: a healthy environment, economic profitability, and a socio-economic equity.

9. Acknowledgment

Dr. Rajeshwar P. Sinha, Senior Professor, Center of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, is greatly acknowledged for providing necessary suggestions and guidance for the paper. Jyoti Jaiswal (926/CSIR-UGC-JRF DEC, 2018) is thankful to the University Grants Commission (UGC), New Delhi, India, for the financial assistance in the form of Senior Research Fellowship (SRF). Incentive grant received from IoE (Scheme no. 6031), Banaras Hindu University, Varanasi, India, to Rajeshwar P. Sinha is highly acknowledged.

10. Author contributions

Jainendra Pathak designed the study and wrote the manuscript, Jyoti Jaiswal, Ramesh K. Shukla, Deepak K. Singh helped in literature review. Rajeshwar P. Sinha reviewed and edited the manuscript.

11. Funding

The authors received no direct funding for this study.

12. Competing interests

The authors declare no competing interest or personal relationships that could have appeared to influence the work reported in this research.

13. References

1. Pathak J, Rajneesh, Pandey A, Singh SP, Sinha RP. World agriculture and impact of biotechnology. In: Current developments in biotechnology and bioengineering: SK Dubey, A Pandey, & RS Sangwan (Eds.): Crop modification, nutrition, and food production. Radarweg; Amsterdam: Elsevier; 2017. 1-22. DOI:10.1016/B978-0-444-63661-4.00001-3
2. Pathak J, Rajneesh, Maurya PK, Singh SP, Häder D-P, Sinha RP. Cyanobacterial farming for environment friendly sustainable agriculture practices: innovations and perspectives. Frontiers in Environmental Science. 2018;6:7. DOI:10.3389/fenvs.2018.0000 7
3. Singh JS, Kumar A, Rai AN, Singh DP. Cyanobacteria: a precious bio-resource in agriculture, ecosystem, and environmental sustainability. Frontiers in Microbiology. 2016;7:529.DOI:10.3389/fmicb.2016.00529
4. Singh R, Parihar P, Singh M, Bajguz A, Kumar J, Singh VP, *et al*. Uncovering potential applications of cyanobacteria and algal metabolites in biology, agriculture, and medicine: current status and future prospects. Frontiers in Microbiology. 2017;8:515. DOI: 10.3389/fmicb.2017.00515
5. Hoekman SK, Broch A, Robbins C, Ceniceros E, Natarajan M. Review of biodiesel composition, properties, and specifications. Renewable and Sustainable Energy Reviews. 2012;16:143-169. DOI: 10.1016/j.rser.2011.07.143
6. Milledge JJ. Commercial application of microalgae other than as biofuels: a brief review. Reviews in Environmental Science and Biotechnology. 2011;10:31-41. DOI: 10.1007/s11157-010-9214-7
7. Williams PJ, Laurens LM. Microalgae as biodiesel and biomass feedstocks: Review and analysis of the biochemistry, energetic and economics. Energy & Environmental Science. 2010:3(5):54-590. DOI: 10.1039/b924978h
8. Pisciotta JM, Zou Y, Baskakov IV. Light-dependent electrogenic activity of cyanobacteria. PLoS ONE. 2010;5(5):e10821. DOI: 10.1371/journal.pone.0010821
9. Paumann M, Regelsberger G, Obinger C, Peschek GA. The bioenergetic role of dioxygen and the terminal oxidase(s) in cyanobacteria. Biochimica et Biophysica Acta (BBA)-Bioenergetics. 2005;1707:231-253. DOI: 10.1016/j.bbabio.2004.12.007
10. Rajneesh, Singh SP, Pathak J, Sinha RP. Cyanobacterial factories for the production of green energy and value-added products: an integrated approach for economic viability. Renewable and Sustainable Energy Reviews. 2017;69:578-595. DOI: 10.1016/j.rser.2016.11.110
11. Sarsekeyeva F, Zayadan BK, Usserbaeva A, Bedbenov VS, Sinetova MA, Los DA. Cyanofuels: biofuels from cyanobacteria. Reality and perspectives. Photosynthesis Research. 2015;125:329-340. DOI: 10.1007/s11120-015-0103-3
12. Wase NV, Wright PC. Systems biology of cyanobacterial secondary metabolite production and its role in drug discovery. Expert Opinion on Drug Discovery. 2008;3(8):903-929. DOI: 10.1517/17460441.3.8.903
13. Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A, *et al*. Biofertilizers: a potential approach for sustainable agriculture development. Environmental Science and Pollution Research. 2017;24:3315-3335. DOI: 10.1007/s11356-016-8104-0
14. Vaishampayan A, Sinha RP, Häder DP, Dey T, Gupta AK, Bhan U, *et al*. Cyanobacterial biofertilizers in rice agriculture. The Botanical Review. 2001;67:453-516. DOI: 10.1007/BF02857893
15. Guerrero MG, Vega JM, Losada M. The assimilatory nitrate reducing system and its regulation. Annual review of plant physiology. 1981;32:168-204. DOI:10.1146/annurev.pp.32.060181.001125
16. Metting B. Microalgae in agriculture. In: Micro-algal biotechnology. MA Borowitzka & LJ Borowitzka (Eds.) Cambridge: Cambridge University Press; c1988. p. 288-304.
17. Aiyer RS, Sulahudean S, Venkataraman GS. Long-term algalization field trial with high yielding rice varieties. The Indian Journal of Agricultural Sciences. 1972;42:380-383.
18. Watanabe I, Espianas CR, Berja NS, Alimagno BV. The utilization of the *Azolla-Anabaena* complex as a nitrogen fertilizer for rice. IRRI Research Paper Series. 1977;11:1-15.
19. Prasanna R, Sharma E, Sharma P, Kumar A, Kumar R, Gupta V, *et al*. Soil fertility and establishment potential of inoculated cyanobacteria in rice crop grown under non-flooded conditions. Paddy and Water Environment. 2013;11:175-183. DOI: 10.1007/s10333-011-0302-2
20. Issa AA, Abd-Alla MH, Ohyama T. Nitrogen-fixing cyanobacteria: future prospect. Advances in Biology and Ecology of Nitrogen Fixation. 2014;2:23-48. DOI: 10.5772/56995

21. Subramanian G, Sundaram SS. Induced ammonia release by the nitrogen-fixing cyanobacterium *Anabaena*. FEMS microbiology letters. 1986;37(2):151-154. DOI: 10.1111/j.1574-6968.1986.tb01784.x
22. Adams DG, Duggan PS. Cyanobacteria-bryophyte symbioses. Journal of Experimental Botany. 2008;59(5):1047-1058. DOI: 10.1093/jxb/ern005
23. Sarma MK, Kaushik S, Goswami P. Cyanobacteria: a metabolic power house for harvesting solar energy to produce bio-electricity and biofuels. Biomass and Bioenergy. 2016;90:187-201. DOI: 10.1016/j.biombioe.2016.03.043
24. Venkataraman GS. Blue-green algae (Cyanobacteria). In: SN Tata, AM Wadhwani, MS Mehdi (Eds.): Biological nitrogen fixation. New Delhi: Indian Council of Agriculture. Research; c1993. p. 45-76.
25. Fritsch FE. The subaerial and freshwater algal flora of the tropics. Annals of Botany. 1907;30:235-275. DOI: 10.1093/oxfordjournals.aob.a089132
26. Fogg GE, Stewart WDP. *In situ* determinations of biological nitrogen fixation in Antarctica. British Antarctic Survey Bulletins. 1968;15:39-46.
27. Holm-Hansen O. Ecology, physiology, and biochemistry of blue-green algae. Annual Reviews in Microbiology. 1968 Oct;22(1):47-70. DOI: 10.1146/annurev.mi.22.100168.000403
28. Singh RN. Reclamation of usar soils in India through blue-green algae. Nature. 1950;165:325-326. DOI: 10.1038/165325b0
29. Roger PA, Kulasooriya SA. Blue-green algae and Rice. Manila: The International Rice Research Institute; c1980.
30. Venkataraman GS. Algal biofertilizer and rice cultivation. New Delhi: Today and tomorrow's Printers and Publishers; c1972.
31. Kannaiyan S, Aruna SJ, Kumari SMP, Hall DO. Immobilized cyanobacteria as a biofertilizer for rice crops. Journal of Applied Phycology. 1997;9:167-174. DOI: 10.1023/A:1007962025662
32. Dubey AK, Rai AK. Application of algal biofertilizers (*Aulosira fertilissimatenuis* and *Anabaena doliolum* Bhardwaja) for sustained paddy cultivation in Northern India. Israel Journal of Plant Sciences. 1995;43:41-51. DOI: 10.1080/07929978.1995.10676589
33. Karthikeyan N, Prasanna R, Sood A, Jaiswal P, Nayak S, Kaushik BD. Physiological characterization and electron microscopic investigations of cyanobacteria associated with wheat rhizosphere. Folia Microbiologica. 2009;54:43-51. DOI: 10.1007/s12223-009-0007-8
34. Obreht Z, Kerby NW, Gantar M, Rowell P. Effects of root-associated N_2-fixing cyanobacteria on the growth and nitrogen content of wheat (*Triticum vulgare* L.) seedlings. Biology and Fertility of Soils. 1993;15:68-72. DOI: 10.1007/BF00336292
35. Spiller H, Gunasekaran M. Ammonia-excreting mutant strain of the cyanobacterium *Anabaena variabilis* supports the growth of wheat. Applied Microbiology and Biotechnology. 1990;33:477-480. DOI: 10.1007/BF00176670
36. Swarnalakshmi K, Prasanna R, Kumar A, Pattnaik S, Chakravarty K, Shivay YS, *et al*. Evaluating the influence of novel cyanobacterial biofilmed biofertilizers on soil fertility and plant nutrition in wheat. European Journal of Soil Biology. 2013;55,107-116. DOI: 10.1016/j.ejsobi.2012.12.008
37. Bose P, Nagpal US. Solubilization of tricalcium phosphate by blue-green algae. Current Science. 1971;40:165-166.
38. Rai AK, Sharma NK. Phosphate metabolism in the cyanobacterium *Anabaena doliolum* under salt stress. Current Microbiology. 2006;52:6-12. DOI: 10.1007/s00284-005-0043-9
39. Cameron HJ, Julian GR. Utilization of hydroxyapatite by cyanobacteria as their sole source of phosphate and calcium. Plant and Soil. 1988;109:123-124. DOI: 10.1007/BF02197589
40. Dorich RA, Nelson DW, Sommers LE. Estimating algal available phosphorus in suspended sediments by chemical extraction. Journal of Environmental Quality. 1985;14:400-405. DOI:10.2134/jeq1985.00472425001400030018x
41. Abdel-Raouf N, Al-Homaidan AA, Ibraheem, I. B. Agricultural importance of algae. African Journal of Biotechnology. 2012;11:11648-11658. DOI: 10.5897/AJB11.3983
42. Rastogi RP, Sinha RP. Biotechnological and industrial significance of cyanobacterial secondary metabolites. Biotechnology Advances. 2009;27(4):521-539. DOI: 10.1016/j.biotechadv.2009.04.009
43. Rodriguez AA, Stella AM, Storni MM, Zulpa G, Zaccaro MC. Effects of cyanobacterial extracellular products and gibberellic acid on salinity tolerance in *Oryza sativa* L. Saline Systems. 2006;2:7. DOI: 10.1186/1746-1448-2-7
44. Brouers M, De Jong H, Shi DJ, Rao KK, Hall DO. Sustained ammonia production by immobilized cyanobacteria. Progress in Photosynthesis Research. 1987;2:645-647. DOI: 10.1007/978-94-009-3535-8_153
45. Shi DJ, Hall DO. The *Azolla-Anabaena* association: historical perspective, symbiosis, and energy metabolism. The Botanical Review. 1988;54:253-386. DOI: 10.1007/BF02858416
46. Vaishampayan A, Sinha RP, Gupta AK, Häder DP. A cyanobacterial recombination study, involving an efficient N_2-fixing non-heterocystous partner. Microbiological Research. 2000;155:1-5. DOI: 10.1016/S0944-5013(00)80026-9
47. Bhattacharjee R, Dey U. Biofertilizer, a way towards organic agriculture: A review. African Journal of Microbiology Research. 2014;8(24):2332-2343.
48. Reddy CA, Saravanan RS. Polymicrobial multi-functional approach for enhancement of crop productivity. Advances in applied microbiology. 2013;82:53-113.
49. Singh TSSP, Agrobios I. Biofertilizers Technology. Agrobios India; c2011.
50. Vessey JK. Plant growth-promoting rhizobacteria as biofertilizers. Plant and Soil. 2003;255(2):571-586. DOI:10.1023/A:1026037216893
51. Carvajal-Muñoz J, Carmona-Garcia C. Benefits and limitations of biofertilization in agricultural practices. *Livestock* Research for Rural Development. 2012;24(3):1-8.
52. Richardson AE. Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. Functional Plant Biology. 2001;28(9):897-906.
53. Srivastava A, Mishra AK. Regulation of nitrogen metabolism in salt-tolerant and salt-sensitive *Frankia* strains. Indian Journal of Experimental Biology. 2014;52:352-358.

54. Verma M, Sharma S, Prasad R. Liquid biofertilizers: Advantages over carrier-based biofertilizers for sustainable crop production. International Society of Environmental Botanists; c2011, 17(2).
55. Priyadarshani I, Rath B. Commercial and industrial applications of microalgae-A review. Journal of Algal Biomass Utilization. 2012;3(4):89-100.
56. Sharma R, Khokhar MK, Jat RL, Khandelwal SK. Role of algae and cyanobacteria in sustainable agriculture system. Wudpecker Journal of Agricultural Research. 2012;1(9):381-388.
57. Singh B, Bauddh K, Bux F. Algae and environmental sustainability. New Delhi, Springer, New Delhi, India; c2015, 7.
58. Rath B. Microalgal bioremediation: Current practices and perspectives. Journal of Biochemical Technology. 2012;3(3):299-304.
59. Kumar N. Effect of algal bio-fertilizer on the *Vigna radiata*: A critical review. International Journal of Engineering Research and Applications. 2016;6(2):85-94.
60. Burlew JS. Algal culture from laboratory to pilot plant. Washington, Publication 600, Carnegie Institution of Washington; c1953. p. 37-54.
61. Wang R, Peng B, Huang K. The research progress of CO_2 sequestration by algal bio-fertilizer in China. Journal of CO_2 Utilization. 2015;11:67-70. DOI:10.1016/j.jcou.2015.01.007
62. Abdelgani ME, Hassan IA. The use of biofertilizers for increasing food production in Africa. Africa, Khartoum: International University of Africa, Sudan. 2006;1-201.
63. Kheirfam H, Hamidreza SS, Homaee M, Darki BZ. Quality improvement of an erosion-prone soil through microbial enrichment. Soil and Tillage Research. 2017;165:230-238. DOI: 10.1016/j.still.2016.08.021
64. De Marsac NT, Houmard J. Adaptation of cyanobacteria to environmental stimuli: new steps towards molecular mechanisms. FEMS Microbiol Lett. 1993;104(1-2):119-189. DOI: 10.1111/j.1574-6968.1993.tb05866.x
65. Beltrán-Rocha JC, Barceló-Quintal ID, García-Martínez M, Osornio-Berthet L, Saavedra-Villarreal N, Villarreal-Chiu J, *et al*. Polishing of municipal secondary effluent using native microalgae consortia. Water Sci Technology. 2017;75(7-8):1693-1701. DOI: 10.2166/wst.2017.046.
66. Doğa-Subaşi E, Demirer GN. Anaerobic digestion of microalgal (*Chlorella vulgaris*) biomass as a source of biogas and biofertilizer. Environmental Progress & Sustainable Energy. 2016;35(4):936-941. DOI: 10.1002/ep.12294
67. Evans PA, Cenko SB, Kennea JA, Emery SW, Kuin NP, Korobkin O, *et al*. Swift and NuSTAR observations of GW170817: detection of a blue kilonova. Science. 2017 Dec 22;358(6370):1565-70.
68. Garcia-Gonzalez J, Sommerfeld M. Biofertilizer and biostimulant properties of the microalga *Acutodesmus dimorphus*. Journal of applied phycology. 2016;28(2):1051-1061. DOI:10.1007/s10811-015-0625-2
69. Gouveia L, Graca S, Sousa C, Lucas Ambrosano, Belina Ribeiro, Elberis PB, *et al*. Microalgae biomass production using wastewater: treatment and costs: Scale-up considerations. Algal Research. 2016;16:167-176. DOI:10.1016/j.algal.2016.03.010
70. Grzesik M, Romanowska-Duda Z, Kalaji H. Effectiveness of cyanobacteria and green algae in enhancing the photosynthetic performance and growth of willow (*Salix viminalis* L.) plants under limited synthetic fertilizers application. Photosynthetica. 2017;55(3):510-521. DOI :10.1007/s11099-017-0716-1
71. Hernandez Melchor DJ, Carmona Jimenez J, Hidalgo Lara ME, Dendooven L, Marsch Moreno R, Canizares Villanueva RO. Phylogenetic and morphological identification of a photosynthetic microbial consortium of potential biotechnological interest. Hidrobiológica. 2016 Aug;26(2):311-21.
72. Ozdemir S, Sukatar A, Oztekin GB. Production of *Chlorella vulgaris* and its effects on plant growth, yield, and fruit quality of organic tomato grown in the greenhouse as biofertilizer. Tarim Bilimleri Dergisi-Journal of Agricultural Sciences. 2016;22(4):596-605.
73. Veronesi D, Idà A, D'Imporzano G, Adani F. Microalgae cultivation: nutrient recovery from digestate for producing algae biomass. Chemical engineering transactions. 2015;43:1201-1206. DOI: 10.3303/CET1543201
74. Yadavalli R, Heggers GRVN. Two-stage treatment of dairy effluent using immobilized *Chlorella pyrenoidosa*. Journal of Environmental Health Science and Engineering. 2013;11(1):11-36. DOI: 10.1186/2052-336X-11-36
75. Renuka N, Guldhe A, Prasanna R, Singh P, Bux F. Microalgae as multi-functional options in modern agriculture: current trends, prospects and challenges. Biotechnology advances. 2018;36(4):1255-73. DOI: 10.1016/j.biotechadv.2018.04. 004
76. Chiaiese P, Corrado G, Colla G, Kyriacou MC, Rouphael Y. Renewable sources of plant biostimulation: microalgae as a sustainable means to improve crop performance. Frontiers in plant science. 2018;9:1782. DOI: 10.3389/fpls.2018.01782
77. Dias GA, Rocha RHC, Araújo JL, Lima JF, Guedes WA. Growth, yield, and post-harvest quality in eggplant produced under different foliar fertilizer (*Spirulina platensis*) treatments. Water Science Technology. 2017;37(6):1693-1701. DOI: http://dx.doi.org/10.5433/1679-0359.2016v37n6p3893
78. Wuang SC, Mar CK, Chua QD, YD Luo. Use of *Spirulina* biomass produced from treatment of aquaculture wastewater as agricultural fertilizers. Algal Research. 2016;15:59-64. DOI:10.1016/j.algal.2016.02.009
79. Zayadan BK, Matorin DN, Baimakhanova GBK. Bolathan, Oraz GD, Sadanov AK. Promising microbial consortia for producing biofertilizers for rice fields. Microbiology. 2014;83:391-397. DOI:10.1134/S0026261714040171
80. Chittora D, Meena M, Barupal T, Swapnil P. Cyanobacteria as a source of biofertilizers for sustainable agriculture. Biochemistry and Biophysics Reports. 2020;22:100737. DOI: 10.1016/j.bbrep.2020.10073
81. Padhy RN, Nabakishore N, Dash-Mohini RR, Rath S, Sahu RK. Growth, metabolism, and yield of rice cultivated in soils amended with fly ash and cyanobacteria and metal loads in plant parts. Rice Science. 2016;23(1):22-32. DOI: 10.1016/j.rsci.2016.01.003
82. Hu J, Nagarajan D, Zhang Q, Chang JS, Lee DJ. Heterotrophic cultivation of microalgae for pigment

production: A review. Biotechnology Advances. 2018;36(1):54-67. DOI: 10.1016/j.biotechadv.2017.09.009
83. Kim S, Park JE, Cho YB, Hwang SJ. Growth rate, organic carbon, and nutrient removal rates of *Chlorella sorokiniana* in autotrophic, heterotrophic, and mixotrophic conditions. Bioresource Technology. 2013;144:8-13. DOI: 10.1016/j.biortech.2013.06.068
84. Kovar K, Pˇribyl P, Wyss M. Microalgae grown under heterotrophic and mixotrophic conditions. In: HP Meyer & DR Schmidhalter (Eds.): Industrial scale suspension culture of living cells. Hoboken, NJ: Wiley; c2014. p. 164-185. DOI: 10.1002/9783527683321.ch04
85. Venkata Mohan S, Rohit MV, Chiranjeevi P, Chandra R, Navaneeth B. Heterotrophic microalgae cultivation to synergize biodiesel production with waste remediation: progress and perspectives. Bioresource Technology. 2015;184: 169-178. DOI: 10.1016/j.biortech.2014.10.056
86. Saadatnia H, Riahi H. Cyanobacteria from paddy fields in Iran as a biofertilizer in rice plants. Plant Soil Environment. 2009;55(5):207-212.
87. Galhano V, Peixoto F, Gomes-Laranjo J, Fernández-Valiente E. Differential Effects of bentazon and molinate on *Anabaena cylindrica*, an autochthonous cyanobacterium of Portuguese rice field agro-ecosystems. Water, air, and soil pollution. 2009;197:211-222. DOI: 10.1007/s11270-008-9804-y
88. Marks EAN, Miñón J, Pascual A, Montero O, Navas LM, Rad C. Application of a microalgal slurry to soil stimulates heterotrophic activity and promotes bacterial growth. Science of the Total Environment. 2017;605:610-617. DOI:10.1016/j.scitotenv.2017.06.169
89. Subashchandrabose SR, Ramakrishnan B, Megharaj M, Venkateswarlu K, Naidu R. Consortia of cyanobacteria/microalgae and bacteria: Biotechnological potential. *Biotechnology advances*. 2011;29(6):896-907. DOI:10.1016/j.biotechadv.2011.07.009
90. Velu C, Cirés S, Alvarez-Roa C, Heimann K. First outdoor cultivation of the N_2-fixing cyanobacterium *Tolypothrix* sp. in low-cost suspension and biofilm systems in tropical Australia. Journal of Applied Phycology. 2015;27(5):1743-1753. DOI: 10.1007/s10811-014-0509-x
91. Valiente EF, Ucha A, Quesada A, Leganés F, Carreres R. Contribution of N_2-fixing cyanobacteria to rice production: Availability of nitrogen from ^{15}N-labelled cyanobacteria and ammonium sulfate to rice. Plant and Soil. 2000;221(1):107-112. DOI:10.1023/A:1004737422842
92. Ashok AK, Ravi V, Saravanan R. Influence of cyanobacterial auxin on sprouting of taro (*Colocasia esculenta* var. *antiquorum*) and corm yield. The Indian Journal of Agricultural Sciences. 2017;87(11):1437-1444.
93. Sangha JS, Kelloway S, Critchley AT, Prithiviraj B. Seaweeds (macroalgae) and their extracts as contributors of plant productivity and quality. In: N Bourgougnon (Ed.): The current status of our understanding. Elsevier Ltd; c2014. p. 125-159. DOI: 10.1016/B978-0-12-408062-1.00007-X
94. Tantawy ST, Atef NM. Growth responses of *Lupinus termis* to some plant growth-promoting cyanobacteria and bacteria as biofertilizers. Journal of Food, Agriculture & Environment. 2010;8(3/4 part 2):1178-1183.
95. Shariatmadari Z, Riahi H, Seyed Hashtroudi M, Ghassempour A, Aghashariatmadary Z. Plant growth promoting cyanobacteria and their distribution in terrestrial habitats of Iran. Soil Science and Plant Nutrition. 2013;59(4):535-547. DOI: 10.1080/00380768.2013.782253
96. Youssef MM, Ali MS. Management of *Meloidogyne incognita* infecting cowpea by using some native blue green algae. Anzeiger für Schädlingskunde, Pflanzenschutz, Umweltschutz. 1998 Jan;71:15-6.
97. Hashem M, Abo-Elyousr KA. Management of the root-knot nematode *Meloidogyne incognita* on tomato with combinations of different biocontrol organisms. Crop Protection. 2011;30(3):285-292. DOI:10.1016/j.cropro.2010.12.009
98. Holajjer P, Kamra A, Gaur HS, Manjunath M. Potential of cyanobacteria for biorational management of plant parasitic nematodes: A review. Crop Protection. 2013;53:147-151. DOI:10.1016/j.cropro.2013.07.005
99. Alwathnani HA, Perveen K. Biological control of Fusarium wilt of tomato by antagonist fungi and cyanobacteria. African Journal of Biotechnology. 2012;11(5):1100-1105. DOI : 10.5897/AJB11.3361
100. Kulik MM. 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. 1995;101(6):585-599. DOI:10.1007/BF01874863
101. Prasanna R, Nain L, Tripathi R, Vishal G, Vidhi Chaudhary, Sheetal M, *et al*. Evaluation of fungicidal activity of extracellular filtrates of cyanobacteria-Possible role of hydrolytic enzymes. Journal of Basic Microbiology. 2008;48(3):186-194. DOI: 10.1002/jobm.200700199
102. Ningthoujam M, Habib K, Bano F, Zutshi S, Fatma T. Exogenous osmolytes suppress the toxic effects of malathion on *Anabaena variabilis*. Ecotoxicology and Environmental Safety. 2013;94:21-27. DOI:10.1016/j.ecoenv.2013.04.022
103. Jha M, Chaurasia S, Bharti R. Effect of integrated nutrient management on rice yield, soil nutrient profile, and cyanobacterial nitrogenase activity under rice-wheat cropping system. Communications in Soil Science and Plant Analysis. 2013;44(13):1961-1975. DOI:10.1080/00103624.2013.794821
104. Singh S, Singh S, Pandey V, Mishra AK. Factors modulating alkaline phosphatase activity in the diazotrophic rice-field cyanobacterium, *Anabaena oryzae*. World Journal of Microbiology and Biotechnology. 2006;22:927-935. DOI:10.1007/s11274-006-9137-1
105. Pathak J, Pandey A, Maurya PK, Rajneesh, Sinha RP, Singh SP. Cyanobacterial secondary metabolite scytonemin: A potential photoprotective and pharmaceutical compound. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences. 2020;90:467-481. DOI:10.1007/s40011-019-01134-5
106. Singh DK, Pathak J, Pandey A, Rajneesh, Singh V, Sinha RP. Purification, characterization and assessment of stability, reactive oxygen species scavenging and antioxidative potentials of mycosporine-like amino acids (MAAs) isolated from cyanobacteria. Journal of Applied

Phycology. 2022;34,3157-3175. DOI: 10.1007/s10811-022-02832-w

107. Singh PR, Singh AP, Rajneesh, Gupta A, Sinha RP, Pathak J. In: VK Kannaujiya, RP Sinha, Md. A Rahman & S Sundaram: Photoprotective Green Pharmacology: Challenges, Sources and Future Applications: Bioprospection of photoprotective compounds from cyanobacteria. Springer Singapore; c2023. p. 65-82. DOI:10.1007/978-981-99-0749-6_3
108. Sinha RP, Häder DP. Impact of UV radiation on rice-field cyanobacteria: Role of photoprotective compounds. In: F Ghetti, G Checcucci, JF Bornman (Eds.): Environmental UV Radiation: Impact on Ecosystems and Human Health and Predictive Models. Springer; c2006. p. 217-230.
109. Gupta V, Ratha SK, Sood A, Chaudhary V, Prasanna R. New insights into the biodiversity and applications of cyanobacteria (blue-green algae) prospects and challenges. Algal Research. 2013;2(2):79-97. DOI:10.1016/j.algal.2013.01.006
110. Singh S, Datta P. Screening and selection of the most potent diazotrophic cyanobacterial isolate exhibiting natural tolerance to rice field herbicides for exploitation as biofertilizer. Journal of basic microbiology. 2006;46(3):219-225. DOI: 10.1002/jobm.200510074.
111. Singh S, Datta P. Outdoor evaluation of herbicide-resistant strains of *Anabaena variabilis* as biofertilizer for rice plants. Plant and Soil. 2007;296:95-102. DOI:10.1007/s11104-007-9293-6
112. Ravindran CM, Suguna S, Shanmugasundaram S. Electroporation as a tool to transfer the plasmid pRL489 in *Oscillatoria* MKU 277. Journal of microbiological methods. 2006;66(1):174-176.
113. Bhattacharya J, Singh AK, Rai AN. Isolation and characterization of a chlorate resistant mutant (Clo-R) of the symbiotic cyanobacterium *Nostoc* ANTH: Heterocyst formation and N_2-fixation in the presence of nitrate, and evidence for separate nitrate and nitrite transport systems. Current microbiology. 2002;45(2):99-104. DOI: 10.1007/s00284-001-0098-1
114. Kamuru F, Albrecht SL, Allen Jr LH, Shanmugam KT. Dry matter and nitrogen accumulation in rice inoculated with a nitrogenase-derepressed mutant of *Anabaena variabilis*. Agronomy Journal. 1998;90(4):529-535. DOI:10.2134/agronj1998.00021962009000040015x
115. Singh VP, Srivastava PK, Prasad SM. UV-B induced differential effect on growth and nitrogen metabolism in two cyanobacteria under copper toxicity. Cellular and Molecular Biology. 2012;58(1):85-95.
116. Nisha R, Kaushik A, Kaushik C. Effect of indigenous cyanobacterial application on structural stability and productivity of an organically poor semi-arid soil. Geoderma. 2007;138(1):49-56. DOI:10.1016/j.geoderma.2006.10.007
117. Acién FG, Molina E, Reis A, Torzillo G, Zittelli GC, Sepúlveda, *et al*. Photobioreactors for the production of microalgae. In: C Gonzalez-Fernandez & R Muñoz (Eds.): Microalgae-based biofuels and bioproducts. Woodhead Publisher; 2017. p. 1-44. DOI:10.1016/C2015-0-05935-4
118. Koller M, Muhr A, Braunegg G. Microalgae as versatile cellular factories for valued products. Algal Research. 2014;6:52-63. DOI: 10.1016/j.algal.2014.09.002
119. Satpal KA, Khambete AK. Waste water treatment using micro-algae-A review Paper. International Engineering Management & Applied Science. 2016;4(2):188-192.
120. Ajayan KV, Selvaraju M, Thirugnanamoorthy K. Growth and heavy metals accumulation potential of microalgae grown in sewage wastewater and petrochemical effluents. Pakistan Journal of Biological Sciences. 2011;14(16):805-811. DOI: 10.3923/pjbs.2011.805.811
121. Abou-Shanab RA, Ji MK, Kim H-C, Paeng K-J, Byong-Hun, Jeon BH. Microalgal species growing on piggery wastewater as a valuable candidate for nutrient removal and biodiesel production. Journal of Environmental Management. 2013;115:257-264. DOI:10.1016/j.jenvman.2012.11.022
122. Woertz I, Lundquist T, Nelson Y. Algae grown on dairy and municipal wastewater for simultaneous nutrient removal and lipid production for biofuel feedstock. Journal of Environmental Engineering. 2009;135(11):1115-1122. DOI :10.1061/(ASCE)EE.1943-7870.0000129
123. Rawat I, Kumar RR, Mutanda T, Bux F. Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Applied Energy. 2011;88(10):3411-3424.
124. Wu LF, Chen PC, Huang AP, Lee CM. The feasibility of biodiesel production by microalgae using industrial wastewater. Bioresource Technology. 2012;113:14-18. DOI:10.1016/j.biortech.2011.12.128
125. Barminski R, Storteboom H, Davis JG. Development and evaluation of an organically certifiable growth medium for cultivation of cyanobacteria. Journal of Applied Phycology. 2016;28(5):2623-2630.
126. Dubey V, Verma R. Shelf life and colonization of soil by clay-based cyanobacterial inocula. Indian Journal of Experimental Biology. 2009;47:222-224.
127. Mishra U, Pabbi S. Cyanobacteria: A potential biofertilizer for rice. Resonance. 2004;9(6):6-10. DOI:10.1007/BF02839213
128. Tripathi RD, Dwivedi S, Shukla MK, Mishra S, Srivastava S, Singh R, *et al*. Role of blue-green algae biofertilizer in ameliorating the nitrogen demand and fly-ash stress to the growth and yield of rice (*Oryza sativa* L.) plants. Chemosphere 2008;70(10):1919-1929. DOI:10.1016/j.chemosphere.2007.07.038
129. Dhar DW, Prasanna R, Singh BV. Comparative performance of three carrier based blue green algal biofertilizers for sustainable rice cultivation. Journal of Sustainable Agriculture. 2007;30(2):41-50. DOI:10.1300/J064v30n02_06
130. Prasanna R, Triveni S, Bidyarani N, Babu S, Yadav K, Adak A, *et al*. Evaluating the efficacy of cyanobacterial formulations and biofilmed inoculants for leguminous crops. Archives of Agronomy and Soil Science. 2014;60(3):349-366. DOI: 10.1080/03650340.2013.792407
131. Renuka N, Prasanna R, Sood A, Ahluwalia AS, Bansal R, Babu S, *et al*. Exploring the efficacy of waste water grown microalgal biomass as a biofertilizer for wheat. Environmental Science and Pollution Research. 2016;23(7):6608-6620.
132. Jha M, Prasad AN. Efficacy of new inexpensive cyanobacterial biofertilizer including its shelf-life. World Journal of Microbiology and Biotechnology. 2006;22(1):73-79. DOI :10.1007/s11274-005-7024-9
133. Hori K, Okamoto J, Tanji Y, Unno H. Formation,

sedimentation, and germination properties of *Anabaena* akinetes. Biochemical Engineering Journal. 2003;14(1):67-73. DOI: 10.1016/S1369-703X(02)00136-5.

134. Silva PG, Ferrari SG, Silva HJ. Preservation methods of *Tolypothrix tenuis* for use as a cyanobacterial fertilizer. Journal of Applied Phycology 2007;19(3):239-246. DOI.org/10.1007/s10811-006-9129-4
135. Stirk W, Van Staden J. Screening of some South African seaweeds for cytokinin-like activity. South African Journal of Botany. 1997;63(3):161-164. DOI: 10.1016/S0254-6299(15)30730-4
136. He H, Li Y, Chen T, Huang X, Guo Q, Li S, *et al*. Butachlor induces some physiological and biochemical changes in a rice field biofertilizer cyanobacterium. Pesticide Biochemistry and Physiology. 2013;105(3):224-230. DOI:10.1016/j.pestbp.2013.02.009
137. Yadav RK, Tripathi K, Ramteke PW, Varghese E, Abraham G. Salinity induced physiological and biochemical changes in the freshly separated cyanobionts of *Azolla microphylla* and *Azolla caroliniana*. Plant Physiology and Biochemistry. 2016;106:39-45. DOI: 10.1016/j.plaphy.2016.04.031
138. Debnath M, Mandal NC, Ray S. Effect of fungicides and insecticides on growth and enzyme activity of four cyanobacteria. Indian journal of microbiology. 2012;52(2):275-280. DOI: 10.1007/s12088-011-0212-4
139. Sharma NK, Tiwari SP, Tripathi K, Rai AK. Sustainability and cyanobacteria (blue-green algae): Facts and challenges. Journal of Applied Phycology. 2011;23(6):1059-1081