REVIEW ARTICLE

A Review on Diversity and Potential Applications of BGA in India

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Abstract

Cyanobacteria, also called blue-green algae, are the probable ancestors of the chloroplast. They are the microbes behind the origin and oxygenation of the ancient earth's atmosphere. Their unbeaten evolutionary capability to mitigate harsh conditions is through the production of adaptation proteins and metabolites that have made them survive and transcend from the ancient atmosphere to the present condition. They are the organisms that fulfill the basic needs of mankind to a certain level by providing resources like food, feed, medicine, biofertilizers and energy sources in the form of hydrogen without compromising environmental health. This review is the compilation of the research of cyanobacterial applications in different fields to assess their diversity and effect on plant growth in India. It provides prospects and valuable information in the field of cyanobacterial microbiology through its use in the form of liquid trees.

Keywords: Cyanobacteria, Secondary metabolites, Eco-friendly, Environment sustainability, Cyanoremediation.

Highlights

- Cyanobacteria represent an incredibly diverse group of photosynthetic, prokaryotic microorganisms that can be found thriving in a variety of ecosystems around the world.
- Cyanobacteria are the oldest organisms on earth that are capable of tolerating various environmental stress.
- Cyanobacteria play an important role in improving soil health and maintaining environmental sustainability.
- Cyanobacteria are used as food and nutritional supplements, bioplastics, cosmetics and other beauty products.
- It has a future prospect of being used as nanoparticles and liquid trees.

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Introduction

Blue-green alga or cyanobacteria is a primitive group of organisms that share characteristics of both bacteria and plants. They are the only photosynthetic prokaryotes that contain pigments chlorophyll a, carotenes, xanthophylls, phycobiliproteins, and produce oxygen. BGA are economically important in the form of nutritional supplements as well as in improving physical, chemical and biological properties of soil, enhancing fertility, especially in rice fields. These organisms are producers of a variety of biostimulants like, cytokinins, auxins, betaines, vitamins, amino acids and polyamines that help to regulate abiotic stress and promote growth in plants (Ronga *et al.,* 2019). BGA has been suggested as one of the solutions to compensate the adverse effects of the use of chemical fertilizers in soil. Various researches have been conducted to assess the cyanobacterial diversity in different parts of India and to characterize the novel species in soil and water (Nikam *et al.,* 2013; Ramanathan *et al.,* 2013, Singh *et al.,* 2014; Kensa, 2017; Subudhi *et al.,* 2017; Singh *et al.,* 2022; Silambarasan and Kathiresan, 2023). This compilation focuses on the diversity of BGA in India and summarizes its potential in different areas of science and development (Fig. 1).

This review is based on a rigorous analysis of different research papers available in libraries and the internet.

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Applications

Improving soil health and growth of plants

Plant growth is dependent on the productivity of soil and is determined by the availability of nutrients, soil structure and microflora. BGA as part of microflora, adds nutrients to the soil by fixing atmospheric nitrogen and adding organic matter. Its metabolic activities add additional nutrients like phosphate, potassium and iron to the soil. It also increases the water retention capacity of soil by forming biofilms. Various experiments have been carried out on different plants using cyanobacterial inoculums to investigate their response in terms of productivity, vegetative growth, seed yield, etc. The experimental plants treated with BGA showed improved plant growth and other attributes along with the increase in soil fertility (Ibraheem, 2007; Bidyarani *et al.*, 2016; Rai *et al.*, 2019; Purwani *et al.,* 2021; Ramakrishnan *et al.,* 2023).

Applying cyanobacteria as compared to using chemical methods or excessive irrigation for ameliorating salt-affected soil is not only environment friendly but cost-effective. Cyanobacteria adopt various mechanisms to mitigate salt stress. Thus, it has been used in reclamation of salt-affected soils (Rao and Burns, 1991; Pandey *et al.,* 2005). Salinity stress is the condition in which variation in ion concentration inside

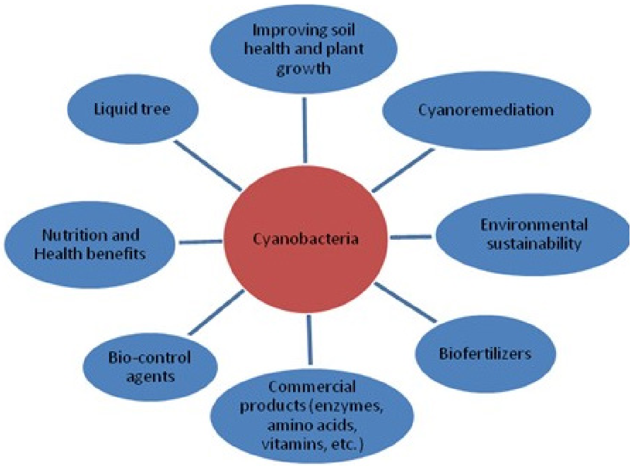

Fig. 1: Cyanobacterial Applications

and outside the cell changes water potential and causes loss of water from the cell. Mechanisms adopted by cyanobacteria to mitigate salt stress are active efflux of sodium from the cell through the sodium proton antiporter system in the plasma membrane, antioxidant defense system and production of stress proteins (Molitor *et al.,* 1986; Babele *et al*., 2010). The role of cytokinin produced by cyanobacteria has also been shown to enhance the salt stress tolerance capacity and productivity of plants (Uniyal *et al*., 2022).

Cyanoremediation

Microorganisms clean the environment by degrading complex toxic substances into less toxic forms. Cyanobacteria are the preferred microbes for this process. These organisms can degrade a variety of obnoxious pollutants, like pesticides, heavy metals, hydrocarbons, oil spills, domestic wastewater as well as industrial effluents in soil and water (Cohen, 2002; Sood *et al*., 2015; Safari *et al*., 2016; Gahlout *et al*., 2017; Badr *et al*., 2019; Sultana *et al*., 2022; Kalita and Baruah, 2023). Cyanoremediation of radioactive pollutants from the environment has also been proven (Sasaki *et al*., 2013). Sewage and effluent treatment plants require land and energy consumption. Integration of such methods with cyanoremediation is cost-effective, sustainable, efficient, and eco-friendly and could be used for the production of bio-fertilizers and biofuels (Chi *et al*., 2011). Besides the above factors, it is easy to grow cyanobacteria as compared to other heterotrophs, as these photoautotrophic organisms do not require complex organic nutrients. Cyanobacteria fulfill their carbon need from CO_2 and capture energy from sunlight.

Environmental Sustainability

The CO_2 level has continuously increased in the atmosphere since the Industrial Revolution and has reached the current level of 424 ppm. Cyanobacteria are the agents that not only improve soil and water environment but also act as sinks for greenhouse gases. These microbes are the voracious consumers of carbon. The carbon concentrating mechanism at the site of photosynthetic carboxylation in cyanobacteria is a cheap way to reduce the danger of this increasing greenhouse gas in the air (Kaplan *et al*., 1994). The alga uses free CO_2 and bicarbonate ions as a source of inorganic carbon during photosynthesis (Badger and Price, 2003). Since cyanobacteria grow at a much faster rate than conventional crops, they can fix more CO_2 within the same time frame.

The detrimental effect of the extensive use of fossil fuel on the environment and human health has instigated the use of biofuel produced from the fats and carbohydrates of plants as an alternative energy source. However, using terrestrial plants for biofuel production led to an increase in competition for agricultural lands and enhanced food prices. In these dearth conditions, cyanobacteria is a promising alternative for fuel as these organisms have comparatively higher photosynthetic efficiency, lower sulfur emission and better combustion (Sitther *et al*., 2020; Agarwal *et al*., 2022, Singh *et al*., 2023).

Another environmental hazard is petrochemical-derived plastics that take many years to degrade. Polyhydroxybutyrate (PHB), a form of microbial processed biopolymer plastics belonging to the polyhydroxyalkanoate (PHA) family, have attracted the attention in the present scenario as they are not only biodegradable and non-toxic but also cost-effective as cyanobacteria itself meet the requirement of carbon source for the production of plastics (Kamravamanesh *et al*., 2018; McAdam *et al*., 2020). *Nostoc muscorum*, *Phormidium, Arthrospira, Aulosira*, *Synechocystis, Synechococcus*, etc. are some of the cyanobacteria used in the production of bioplastics (Sartori *et al*., 2021). Bioplastics can also solve other problems caused by conventional plastics, like, water logging, harm to animal and human body and pollution. PHB is produced as inclusion bodies in bacteria and serves as a carbon source. Fermentation is the common method for the production of PHB in cyanobacteria. It is synthesized from acetyl coenzyme A by the sequential action of three enzymes: β-keto thiolase (phbA gene), acetoacetyl-CoA-reductase (phbB gene) and PHB synthase (phbC gene). This PHB has various applications in pharmaceuticals, packaging products, electrical devices, construction and other materials (Sharma, 2019).

Biodegradation of polyethylene by using microbes is another eco-friendly way to degrade non-biodegradable plastics. The researchers demonstrated that the microalgal consortium (the mixture of Cyanobacteria and *Chlorella* sp.) successfully colonized the polyethylene sheets and degraded the polymers into monomers through secretion of exoenzymes and polysaccharides without adding any chemicals or capping agents (Govindan *et al*., 2021). Although cyanobacteria provide a great solution to the environmental problems caused by fossil plastics, the high cost of producing PHAs compared to conventional types is still one of the significant economic barriers to commercialization.

As a source of Nutrition and health benefits

Continuous decrease in cultivable land due to the increase in population, urbanization and industrialization has increased the demand for alternative food sources. Engineering cyanobacteria for food and feed production could be a better alternative as it is nutrient-rich and does not demand large agricultural area or expensive inputs besides having therapeutic benefits as athero-protective, anti-inflammatory, antitumoral, anticancerous, antioxidant and wound healer (Ku *et al*., 2013, Demay *et al*., 2020). Cyanobacteria have been consumed since ancient times for food and nutritional supplements, like vitamins, essential fatty acids, minerals, enzymes and exopolysaccharides. BGA, like *Spirulina* is used as a food supplement on a large scale as its protein content is even more than fish, soybeans, dried milk, eggs and peanuts (AlFadhly *et al*., 2022). Some of the other BGA that have nutritional benefits are *Aphanizomenon, Nostoc, Anabaena* and *Merismopedia* (Issa *et al*., 2020). Amer *et al*. (2014) proved the efficacy of *Nostoc* sp. isolated from the Egyptian rice field to prevent hepatitis C virus (HCV) replication and named the species as *Nostoc EGY*. The findings of the research with *Spirulina* supplementation in patients having type 2 diabetes mellitus showed its role in improving blood glucose levels and lipid profile (Parikh *et al.,* 2001).

Other Commercial products

Natural pigments produced by cyanobacteria are commercially valuable and finds use in many industries. Chlorophyll a is used in pharmaceuticals and phycobiliproteins in immunofluorescence techniques. Phycocyanin produced from *Spirulina platensis, Aphanizomenon flos-aquae* and *Anabaena* are used as colorants, in cosmetics and other beauty products (Nowruzi *et al*., 2020). BGA like *Anabaena flos-aquae, Chroococcus minutus, Oscillatoria jasorvensis, Spirulina platensis*, and *Nostoc* sp., produce industrially important enzymes (protease, amylase, lipase, cellulase, chitinase, urease, lactamase and phosphatases), amino acids (aspartic acid, serine, glycine, glutamic acid, lysine, phenylalanine and methionine) and vitamins (A, B_1, B_2, B_5, B_{12}, and C) (Toribio, 2020; Beltagy and Elkomy, 2021).

Use of nanoparticles is becoming popular in present time as it makes the material smaller, lighter, stronger and more durable. Nanoparticles range in size from 10 to 500 nm and had potential applications in space, medicine, agriculture, textile, electronics and sports equipment. Biological synthesis of nanoparticles by employing bioresources such as bacteria, fungi, diatoms and cyanobacteria has been given priority over physical and chemical methods as there is no use of radiation or chemical substances that are toxic for the environment and human health (Hamouda *et al.,* 2021). Nanoparticles derived from cyanobacteria have antifungal, antialgal, antibacterial and anticancer activities. Silver (Ag), platinum (Pt), gold (Au), palladium (Pd) and selenium (Se) nanoparticles are formed from cyanobacteria such as *Anabaena*, *Calothrix*, *Leptolyngbya* and *Oscillatoria limnetica* (Brayner *et al.,* 2007; Afzal *et al.,* 2019; Hamouda *et al.,* 2019).

Some of the companies involved in the commercial production of cyanobacteria in India are: Ballarpur Industries, EID Parry and Zydus Cadila (Ahmedabad); Cosmic Nutracos Solutions Pvt Ltd. and Sanat Products Ltd. (New Delhi); Hash Biotech Ltd. (Chandigarh); Parry Neutraceuticals (Oonaiyur); Hydrolina Biotech Pvt Ltd. (Chennai); Ecotech Technologies India Pvt Ltd. and Mapra Laboratories Pvt Ltd. (Mumbai) (Chittora *et al*., 2020).

Cyanobacteria as a biofertilizer

Nitrogen fertilizers not only contribute towards greenhouse gas emissions, but their production requires the combustion of fossil fuel. Amid the growing demand for healthy food and long-term sustainability, biofertilizers has emerged as the best alternative. *Nostoc*, *Anabaena*, *Tolypothrix* and *Aulosira* are some of the algal species that are used as fertilizers, mostly in the paddy fields. These BGA improve soil characteristics and increase crop yield as they have the capability to fix atmospheric nitrogen, provide minerals, enhance soil porosity, improve soil aggregation quality, solubilize phosphate, produce plant growth-promoting substances and remediate saline soil. Species of *Oscillatoria, Nostoc, Anabaena, Scytonema, Microcoleus, Spirulina* and *Leptolyngbya* are some of the cyanobacteria known to improve soil fertility (Ammar *et al.,* 2022). Application of BGA reduces the application of urea in the field, enhances the bioavailability of soil nutrients, controls weed growth, and increases the yield of plants and income of farmers (Saadatnia and Riahi, 2009; Manjunath *et al.,* 2016). In order to popularize the applicability of BGA biofertilizer application, more scientific researches are needed to reduce the cost of production, convince the farmers about the increase in yield, provide area specific strain based inoculums to the farmers at low cost and train the farmers so that they can produce the biofertilizers in their own fields at low cost.

Cyanobacteria as bio-control agents

Bioactive secondary metabolites like phytols, free fatty acids, exopolysaccharides, phenolics, terpenoids, phytoene, sterols, carotenoids, tannins, scytonemin, phytohormones, cyanotoxins, produced by cyanobacterial species like *Oscillatoria, Calothrix, Lyngbya* and *Synechocystis* have strong antifungal, antibacterial, antimalarial, antiviral and antiprotozoal effect that make them natural biocontrol agents. Although cyanotoxins produced by cyanobacterial sp., such as, *Microcystis, Aphanizomenon, Nodularia* and *Anabaena* form toxic blooms, they can be exploited in agricultural fields as pesticides. As they are short-lived, they have less adverse effect on the health of ecosystem (Berry *et al*., 2008; Raghini *et al.,* 2022).

Liquid tree

Microalgae in the form of liquid trees has been considered as a sustainable and innovative solution for reducing greenhouse gas emissions and improving air quality in cities where there is a lack of free space for planting trees. The concept of liquid tree/liquid 3 was given in 2021 by Dr. Ivan Spasojevic of the Institute for Multidisciplinary Research, University of Belgrade, Department of Life Sciences (Castim, 2021). The liquid tree is a photobioreactor, in which microalgae are poured into an aquarium of six hundred liters of water and are kept in public places. It is designed in the form of a bench that has mobile chargers and solar panels and produces light at night. The project has been recognized as the climate-smart solution under the Climate Smart Urban Development project, created by the UNDP and the Ministry of Environmental Protection and sponsored by the Global Environment Facility (GEF) for its useful and unique design (Dhar *et al*., 2023).

Supporting Space Misson

An experiment on *Nostoc* sp., isolated from dry desert macrobiotic crusts, was found to have survivability in Mars-like environments of low temperature, desiccation and high UV radiation (Ye *et al*., 2021). This experiment is conducive with the report given by the team of experts after examination of photographs of Gale Crater (Martian lake) from NASA's rover Curiosity as part of NASA's Mars Science Laboratory mission. According to this specimens resembling calcium-carbonate encrusted cyanobacteria were observed and tentatively identified. The report summarized that algae colonized Mars early and may contribute to oxygen production on Mars (Joseph *et al.,* 2020). The survivability of cyanobacteria in mars like environment provides clues to explore the possibility of life on extraterrestrial bodies.

Diversity of Cyanobacteria in India

Petkar *et al.* (2008) identified *Nostoc, Anabeana, Oscillatoria, Microcystis* and *Lyngbya* as the dominating genera from the paddy field areas of Chandrapur district of Maharashtra. Khadatare and Suryavanshi (2016) pioneered the isolation and purification of four different strains of Cyanobacteria, viz, *Gloecapsa, Nostoc, Oscillatoria* and *Phormidium* from maize fields in Solapur city of Maharashtra. Gaikwad (2022) documented algal flora from rice fields of Bhor and Velhe Talukas of Pune district, Maharashtra State. These are *Chrococcus, Cylindrospermum, Gloeocapsa, Gloeotrichia, Aphanocapsa, Oscillatoria, Nostoc, Anabaena, Aulosira, Scytonema, Synechococcus* and *Spirulina*.

Faldu *et al.,* (2014) identified eight cyanobacterial isolates from Gujarat on the basis of morphology and 16s rDNA sequence analysis and emphasized the importance of both morphology and genetic methods in the study of cyanobacterial diversity.

Rajasekaran and Raja (2021) studied the non-heterocystous BGA from the paddy fields of Chennai and found *Lyngbya, Oscillatoria, Phormidium* and *Chrococcus* as the most dominant types.

Silambarasan and Kathiresan (2023) studied the diversity of cyanobacteria collected from island mangroves of the Gulf of Munnar marine biosphere reserve. They found a maximum number of species belonging to the family Oscillatoriaceae, with *Anabaena iyengarii, Lyngbya majuscula, Oscillatoria cortiana, Phormidium fragile* and *Trichodesmium erythraeum* as common types in all the islands.

Srinivas and Aruna (2016) collected soil samples from paddy fields of Telangana State and identified *Scytonema, Oscillatoria, Nostoc* and *Lyngbya* as the commonly occurring alga.

The findings of Mohan and Kumar (2019) suggested that the agriculturally fertile soil of Patna is favorable for the growth of several cyanobacterial species. Species of *Oscillatoria*, *Lyngbya*, *Micrococcus*, *Schizothrix*, *Phormidium*, *Stigonema, Arthrospora, Aphanocapsa*, *Nostoc*, *Anabaena*, *Gloeocapsa,* etc. were found cosmopolitan in distribution. They also studied the seasonal dominance of different BGA in the agricultural soil of Patna.

Saha *et al*., (2007) studied the cyanobacterial diversity from the freshwater stream of the Kakoijana reserve forest of Assam and identified three species *Chlorogloea purpurea*, *Leptolyngbya boryana* and *Leptolyngbya calotrichoides* as new records from India. The investigation on N_2-fixing cyanobacterial diversity in soil of Kamrup district, Assam, revealed *Nostoc* and *Anabaena* as the most dominant type in forests and rice field areas. In contrast, *Oscillatoria* was abundant in coalfield areas (Adhikari and Baruah, 2015).

Nostoc was the most dominantly observed cyanobacteria in different ecological conditions of Meghalaya. Other types were *Anabaena, Calothrix, Cylindrospermum, Gloeocapsa,* etc. The study also revealed that cyanobacterial strains that can withstand acidic pH (Syiem *et al*., 2010).

Pal *et al.,* (2022) collected new species of soil-dwelling cyanobacterial strain (KLS-BP-3A_PS) from the Unakoti district of Tripura on the basis of 16S rRNA gene phylogenetic analysis. Das (2017) identified a novel species of cyanobacteria *Scytonema (Myochrotes) adhikarii* from the Sikkim Himalayas. The species was distinguished from other similar looking taxa through morphological characterization of trichomes and the sheath.

Research work focused on the diversity of *Nostoc* was carried out at Meerut district, Uttar Pradesh (Kumar and Rama Kant, 2023).

Srivastava *et al.* (2009) correlated salinity with the diversity of cyanobacteria in the rice fields of Eastern Uttar Pradesh, India and found that very high salinity supported the growth of non-heterocystous genera, while low salinity favored the presence of heterocystous cyanobacteria.

Conclusion and Future Prospects

Cyanobacteria, a wonder organism in terms of their ubiquity, adaptability and metabolism, must be searched for a variety of novel genes having promising effects that can be utilized in the welfare of mankind. In this prospect, the herbicide-tolerant gene, when transferred from *Gloeocapsa* strain to *Nostoc muscorum* it developed herbicide resistance. The introduction of the isoprene synthase (*IspS*) gene of *Pueraria montana* (kudzu vine) in the cyanobacterium *Synechocystis* enabled the production of isoprene (C_5H_8) hydrocarbons in these cyanobacteria through photosynthesis using sunlight, water and CO_2. These isoprenes could serve as a renewable biofuel without environmental degradation.

Genetic engineering is commonly deployed to increase the yield of bioplastic raw material PHB compared to wild types. The cyanobacterium *Synechocystis* sp. PCC 6714 can produce up to 37% dry cell weight of PHB with CO_2 as the only carbon source. Cyanobacteria could also be genetically engineered to enhance the production of growth hormones like cytokinin to utilize its properties of enhancing stress tolerance, growth and productivity in plants. Harnessing cyanobacterial potential as a degrader of different kinds of environmental pollutants, including metal ions and pesticides and in reclamation of the saline soil is the need of the hour. The utilization of cyanobacterial nanoparticles for therapeutic use also seems to have a great future as it is a greener route without the deployment of any hazardous chemicals.

The research on the impact of BGA technology on farmers showed a positive and significant change in terms of yield, cost of production and income of farmers. Biocontrol properties of cyanobacteria can solve the problem of biomagnification.

Several proteomics investigations in different cyanobacterial species reveal that its acclimatization capability to varied stress conditions of UV radiation, light quality, temperature, salt, nutrient deficiency, etc., is regulated by its ability of significant gene expression that leads to the production of different proteins and metabolites in different stress conditions. Thus, cyanobacterial proteomics and metabolomics require serious investigations in search of adaptation proteins and metabolites to identify and harness the novel gene products in neutraceuticals, cosmetics, medicines and other industrial biotechnology.

Cyanobacteria are non-polluting, environment-friendly organisms, providing solutions to various contemporary problems, like pollution by chemical fertilizers and plastics, shortage of food and feed, greenhouse gases and heavy metal stress. It opens the possibility of extraterrestrial habitation by man as it is the only organism that can survive in Mars conditions. Its proteomics and metabolomics studies are still required to harness the potential of bioactive natural compounds that they synthesize under varied stress conditions. Though a variety of cyanobacterial compounds are exploited for their therapeutic potential, still more scientific exploration is needed to find novel compounds of unexploited strains from unexplored extreme habitats. Utilization of cyanobacterial-derived nanoparticles in the development of drugs also requires specific attention.

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Authors Contribution

Dr Swati Chaurasia has compiled and edited the review work.

Conflict of Interest

None

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