HARNESSING THE POWER OF BLUE-GREEN ALGAE FOR SUSTAINABLE AGRICULTURE: A REVIEW

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Abstract: *A long-term source of food and energy that doesn't damage the environment is necessary for the well-being of mankind, as the world's population grows and natural energy resources deplete. Excessive use of chemical fertilizers reduces the quality of the environment and food. Cyanobacteria, also known as blue-green algae, have emerged as essential participants in sustainable agriculture due to their distinct capabilities and diverse contributions to soil fertility, nutrient cycling, and overall ecosystem health. Furthermore, they have been recognized as a rich source of bioactive chemicals with antibacterial, antiviral, and antifungal properties. Cyanobacteria have been the most successful and long-lasting prokaryotic organisms throughout evolution. Utilization of pesticides is very common in agriculture. Nonetheless, reckless use of pesticides has resulted in biomagnification that is detrimental to soil microorganisms, such as cyanobacteria. There is a great deal of potential for cyanobacterial abundance, quick generation, water-holding capacity, mineralizing capability, and nitrogen fixation to reduce the negative effects of pesticides. This paper investigates the varied importance of cyanobacteria in sustainable agriculture, focusing on their involvement in nitrogen fixation, soil stabilization, biofertilizer production, and potential for alleviating environmental concerns.*

Keywords: *Cyanobacteria, Biofertilizer, nitrogen fixation, pesticides, environment.*

INTRODUCTION

Rapid global population expansion necessitates increased food production capacity. To nourish these large populations, agriculture is gradually becoming dependent on chemical fertilizers, pesticides, and insecticides. So, agriculture is becoming a major source of environmental contamination (Savci et al., 2012; Zaring et al., 1996). Chemical fertilizers and frequent irrigation have significantly harmed agricultural land globally, causing erosion, nutrient deficiency in nutrients, and salinity. The inorganic substances used on plants in Canada, United States result in the loss of around 3 billion tons of topsoil. (Singha et al., 2009). Heavy metals, including mercury, cadmium, arsenic, lead, copper, and nickel, that are listed on the US EPA's Harmful and Important Pollutant List and may be present in inorganic fertilizers (Ning et al., 2017; Nagajyoti et al., 2010; USEPA). These substances can create environmental issues such as soil fertility loss, poor nutrient usage, and low agricultural yields. Heavy metals and radioelements gather, introducing them into the food chain and causing health risks to living species. (Bramki et al., 2018; Mathur et al., 2016; Yin et al., 2018). To improve crop yields without harming the environment, alternative fertilizer solutions are necessary (Kantachote et al., 2016). Biological fertilizers, consists of bacteria and mycorrhizal fungi, are a promising option for increasing soil and plant nutrient availability, reducing reliance on chemical fertilizers, and mitigating crop-related diseases such as viroids, viruses, fungi, and pathogen bacteria. (Barragán-Ocaña et al., 2016; Montesinos et al., 2002; Saadatnia and Riahi, 2009). Blue-green algae are gram-negative, oxygen-producing bacteria that have existed for two billion years and continue to thrive on the planet. (Stewart, 1977; Sergeev et al., 2002). The oxygenic environment evolved by cyanobacteria some 2.8 billion years ago, found in fossilized oncolites and stromatolites. (Rastogi and Sinha, 2009). Cyanobacteria also influence plant physiological and biochemical processes, maintaining soil nutrient availability, porosity, pH, and water-holding capacity. They also lower salinity. Fields of rice are an essential ecological niche for cyanobacterial services like N_2-fixation and photosynthesis, which support many physiological activities. (Wilson et al., 2006; Singh, 2014). Cyanobacteria have two types of cells: heterocysts, which fix nitrogen for ammonia synthesis, and vegetative cells, which perform photosynthesis and reproduce normally (Chittora et al., 2020). In paddy fields, cyanobacteria make up a significant portion of the biomass that fixes nitrogen, and they can fix nitrogen at no cost. Because of the fundamental feature of nitrogen fixation, blue-green algae have a unique ability to contribute to increasing production in several agricultural and ecological conditions. (Joshi et al., 2020). In addition to their ecological importance, cyanobacteria synthesize various secondary metabolites that exhibit antimicrobial, antiviral, and antioxidant activities, which are increasingly being explored in pharmaceutical and biotechnological applications. The synthetic fertilizer may be substituted with cyanobacterial biofertilizer (Bhuyan et al., 2023)

Interaction between the plant and the cyanobacteria

Cyanobacteria, or blue-green algae, are photosynthetic prokaryotes that fix nitrogen. Nitrogen-fixing cyanobacteria can be unicellular or multicellular, but their vegetative cells share a basic structure and function. (Stanier, 1977; Stanier and Cohen-Bazire, 1977). Numerous cyanobacteria with many cells create specialized nitrogen-fixing heterocysts. The model bacterium Anabaena (*Nostoc*) sp. strain PCC 7120 maintains a controlled developmental pattern during diazotrophic growth, with single heterocysts spaced apart along filaments by 10-20 photosynthetic vegetative cells. The oxygen-sensitive method for nitrogen fixation is facilitated by the combined action of heterocyst structure and metabolic activity (Kumar et al., 2010). The structural features of Nostoc showing vegetative cells and heterocysts are illustrated in Figure 1.

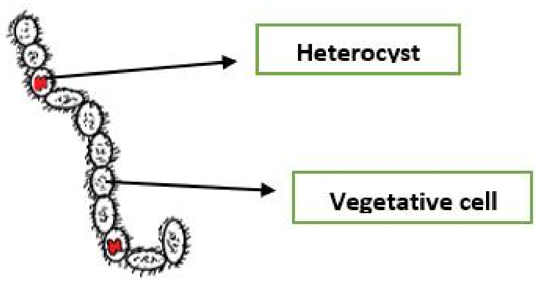

Figure 1. *Nostoc* sp showing vegetative cells and heterocysts.

Diazotrophic cyanobacteria are making headway in their search for sustainable agricultural substitutes (Morrissey et al., 2004; Franks et al., 2006; Piromyou et al., 2011). Numerous Nostoc sp. have been proven by Nilsson et al. (2002) to inhabit rice roots on surfaces and in between cells. It was demonstrated that associative N_2 fixation was more than that of the free-living cyanobacteria. Nutrient exchange occurs between the host plant and cyanobacteria in the following pattern, presented in Figure 2.

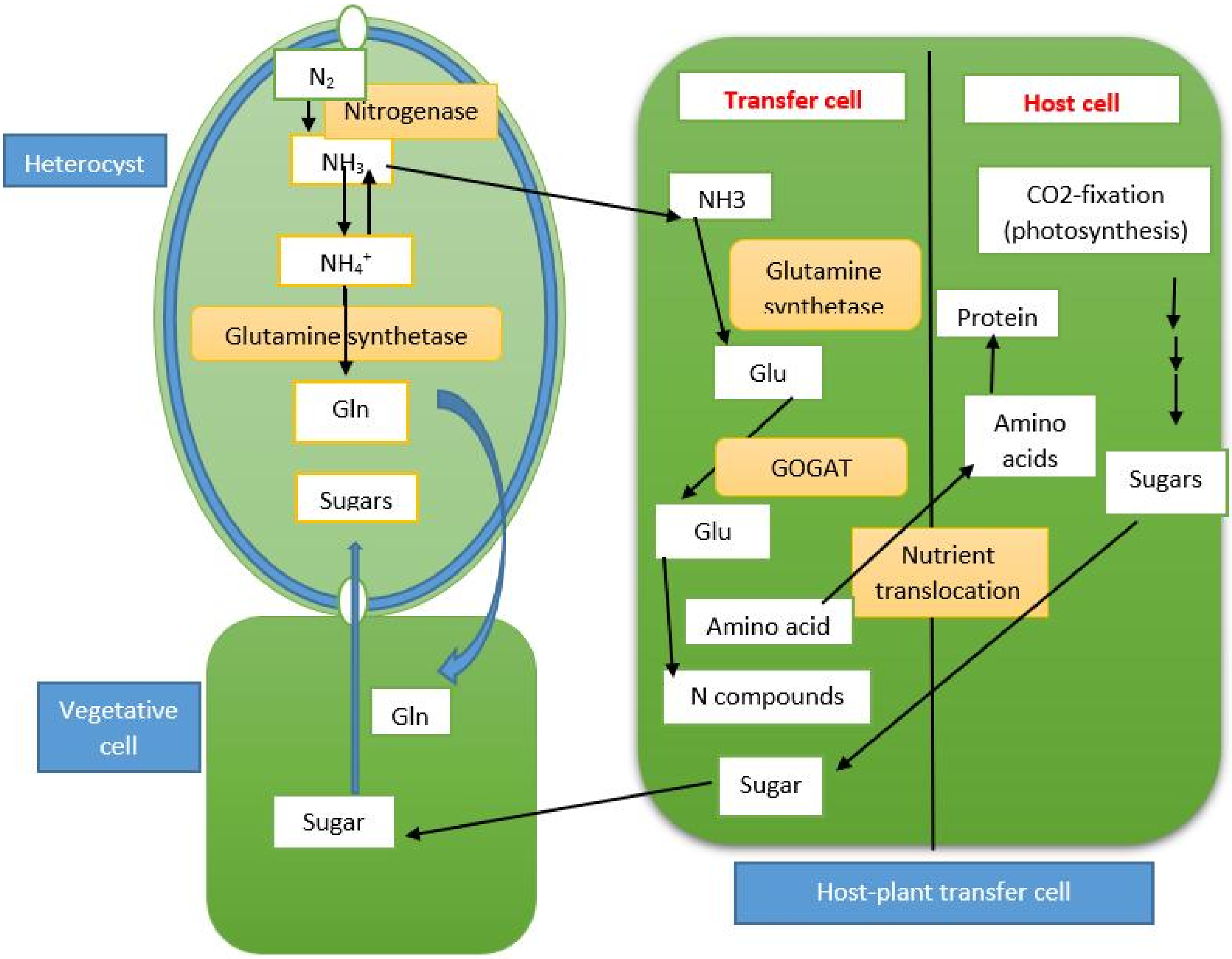

Figure 2. Exchange of nutrients in plant-cyanobacterial symbiosis. (Rai et al., 2019)

Table 1. Impact of Cyanobacterial inoculant on the growth of various vegetables:

Name of vegetables	Scientific name	Bacterial inoculant	Impact on growth	References
Cucumber Tomato	*Cucumis sativus* *S. lycopersicum*	Cyanobacterial inoculant	Positive	Shariatmadari et al., 2013
Rice Wheat	*Oryza sativa* *Triticum aestivum*	new cyanobacterial-based biofilms and cyanobacterial strains	Positive	Prasanna et al., 2009; Triveni et al., 2012a,b

The impact of cyanobacterial inoculants on the growth of different vegetable crops is summarized in Table 1.

Mechanism of action of Cyanobacteria

Cyanobacteria, sometimes known as blue-green algae, are essential to sustainable agriculture because of their special capacities to enhance soil, fix nitrogen, and produce environmentally beneficial biofertilizers.

Nitrogen Fixation

N_2-fixing diazotrophs have been applied in recent years to maintain the soil fertility of the paddy ecosystem. These include cyanobacteria that are photosynthetic, free-living, and symbiotic. photosynthetic, facultative, obligatory anaerobic, free-living aerobic, and diverse associative bacteria. When soil is low in nitrogen and organic carbon, cyanobacteria play a crucial role in preserving soil health. The atmospheric N_2's catalytic conversion to ammonia by nitrogenase in the presence of oxygen is known as biological N_2 fixation (BNF). The nitrogenase complex of enzymes participating in this reaction forms one of the main biochemical elements of microbial metabolism and has been the focus of much work in microbial biochemistry and metabolic control. Nitrogen fixation enhances soil fertility, reduces the use of synthetic fertilizers, and reduces the runoff of nitrogen.

This is a very energy-demanding process that requires eight electrons and almost sixteen equivalents of ATP and is performed by some prokaryotic bacteria and archaea. This may be anaerobic, autotrophic, heterotrophic, aerobic, or microaerobic (Lee et al., 2014).

The ability of a wide range of cyanobacterial species, including filamentous, heterotrichous, non-heterotrichous, and unicellular cyanobacterial species, has been well documented and studied by previous researchers (Fogg et al., 1973; Rippka et al., 1971) to fix nitrogen. Anabaena variabilis, Aulosira fertilisima, Calothrix sp., Tolypothrix sp, and Scytonema sp are the best cyanobacteria to fix nitrogen in the cultivation area of rice crop (Prasad et al., 2021).

Soil Health Improvement

The world food production is also dependent on the soil, which helps sustain the biodiversity who are considered to be a home to various terrestrial species. The aggregation of soils, which is the basic unit of soil structure and pore spaces influence the structure of the soil, which is an indicator of fertility and regulates the capacity of the soil to store water and nutrients to enable crop growth, drainage, and aeration. The contribution of cyanobacteria and the microalgae to soil fertility and soil structure (Ramakrishnan et al., 2023). The cyanobacteria release EPS (high molecular weight) hetero-biopolymers referred to as cyanobacterial extracellular polysaccharides (EPS), which play a critical role in the ecology of natural microbial communities due to their conferring natural resilience to ecological systems and aiding the efficient functioning of the ecosystem. The cyanobacterial extracellular polymers (EPS) are not similar to those of other microorganisms, such as fungi, the eubacteria, and the archaea. They are available in three variations, which are sheath, capsule, and slime. (Nishanth et al., 2021). Cyanobacteria increase the carbon and nitrogen levels of soil through improved colony formation and production of Exopolysaccharides (EPS). Besides, they play a significant role in enhancing soil structure, especially in poor soil, and inhibiting soil erosion (Hosseini et al., 2022).

Biofertilizer Production

Biofertilizers that are eco-friendly can be fabricated using cyanobacteria, which are an excellent alternative to chemical fertilizers. Cyanobacteria are capable of degrading numerous types of contaminants and thus perform numerous functions in the soil ecosystem in order to keep the soil fertile (Subramanian et al., 1996). The diazotrophs are cyanobacteria that assist in the production of cheap, easily accessible biofertilizers, which are environmentally friendly. They can control the lack of nitrogen in plants, improve the availability of air to the ground, promote water retention capacity, and add vitamin B12 (Chittora et al., 2020). The positive effects are facilitated by several biochemical processes that enhance the availability of nutrients and the development of plants.

Biopesticides production

The use of microalgae looks promising because these photosynthetic microorganisms can be utilized for a variety of environmental applications, including the remediation of wastewater and the capture of carbon dioxide. Furthermore, they represent a valuable feedstock that can be used to produce food, feedstock, biodiesel, fertilizers, biopesticides, and biostimulants for the agricultural industry. (Lutzu et al., 2024) Many cyanobacterial metabolites, including peptides, alkaloids, and polysaccharides, possess antimicrobial and antifungal properties that may have potential applications in pharmaceutical and agricultural biotechnology.

Promotion of plant growth by the production of phytohormone

As agents of soil compaction in agriculture and as nutrient supplements, cyanobacteria are major environmental players. Heterocystous type of cyanobacteria predominate across several farming fields in East and North India; Nostoc and Anabaena make up 40% to 90% of the total. This information has been obtained from investigations on diversity and abundance (Roger et al., 1993; Whitton, 2000). These solitary examples demonstrated effectiveness in promoting the germination and development of wheat and rice seeds, as well as an increase in the synthesis of proteins and indole acetic acid (IAA). The cyanobacteria's ability to promote plant development may be due to several chemicals, including auxin hormones, cytokinin, gibberellin, and abscisic acid, in addition to vitamins, specifically vitamin B. These growth-promoting compounds are produced through complex biochemical pathways that regulate plant-microbe interactions at the cellular and molecular level (Rai et al., 2019).

Ecological Benefits and Environmental Sustainability

Cyanobacteria help in both agricultural and environmental or ecological sustainability. In agriculture, they help in soil fertility, reclamation of wetlands, nitrogen fixation and nitrogen fixation, etc. Through these processes, they can produce quality foods and a healthy agro-ecosystem. On the other hand, they also perform bioremediation, CO_2 sequestration, etc. This results in environmental sustainability. Additionally, cyanobacteria play an important role in environmental biotechnology through processes such as pollutant degradation, wastewater treatment, and carbon sequestration (Chittora et al., 2020). The association between cyanobacteria and plants contributing to nitrogen fixation and plant growth promotion is depicted in Figure 3.

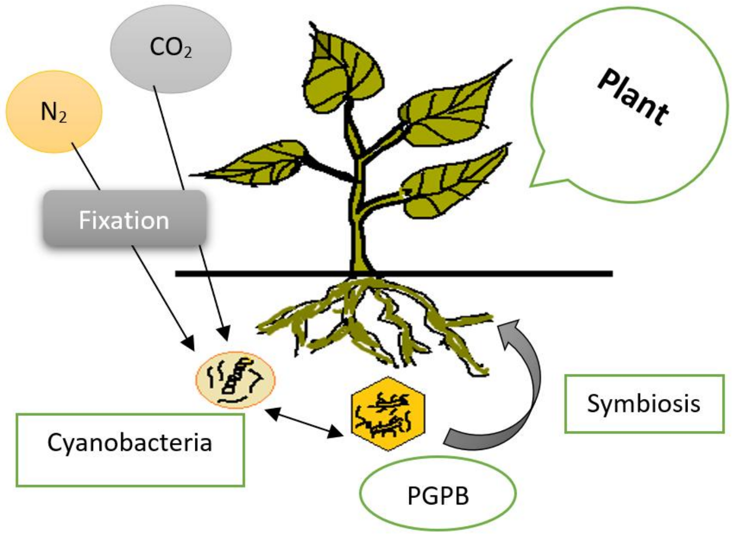

Figure 3. Cyanobacteria and plant association.

Challenges and Future Perspectives

Although cyanobacteria present several exciting prospects for sustainable agriculture, some issues and concerns need to be taken into account. This section outlines current research and possible developments to address these issues while also discussing potential limits, such as fluctuating efficacy under various environmental circumstances. There are also future thoughts on how to best utilize cyanobacteria in agricultural applications.

Conclusion

A useful tool for sustainable agriculture, cyanobacteria can improve soil fertility, lessen reliance on artificial fertilizers, and advance environmental sustainability. In order to develop a more resilient and sustainable food production system, this review paper shows the importance of integrating cyanobacteria into modern agricultural practices, synthesizing existing information and proposing future research directions. Since cyanobacteria are highly adaptive to their environment, the application of cyanobacteria as biofertilizers may prove to be an advantageous practice. Moreover, they still leave a considerable biomass to the topsoil even when they have died. Furthermore, cyanobacteria's biochemical variety and bioactive products point out their possible use in pharmaceutical biotechnology and in environmentally friendly agricultural systems.

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