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Mini Review

The Multifaceted Role of Cyanobacteria in Energy, Environment, and Industry

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Abstract

A diversified lineage of oxygen-evolving photosynthetic prokaryotes, cyanobacteria are being used more for industrial innovation, environmental control, and energy production. With an emphasis on their roles in carbon fixation, environmental remediation, biofuel production, and the creation of economically important bio compounds, this study provides a thorough overview of the biological processes and technical uses of cyanobacteria. There is also discussion of their ecological contributions, metabolic pathways, genetic modification methods, and scaling issues. Future developments in cyanobacterial biotechnology are examined to show how important they are to reach sustainable development objectives.

Keywords: Industrial Biotechnology; Synthetic Biology; Photosynthesis; Carbon Sequestration; Bioenergy; Bioremediation; Cyanobacteria

Abbreviations

PSI: Photosystem One; PSII: Photo System Two.

Introduction

Cyanobacteria, often identified as blue-green algae, are considered among the most ancient organisms on Earth, having existed for more than 3.5 billion years. They played a fundamental role in transforming the planet's atmosphere by introducing oxygen through a process known as oxygenic photosynthesis [1]. Owing to their rapid reproduction, ability to adjust to various environmental conditions, and capacity to produce numerous bioactive substances, they are now widely studied for their potential roles in renewable energy, ecological cleanup, agriculture, and global carbon regulation [2]. Cyanobacteria carry out oxygenic photosynthesis, capturing light energy to drive the conversion of carbon dioxide into organic compounds, using water as the electron donor and releasing oxygen in the process.

The mechanism of oxygenic photosynthesis is powered by two distinct photosystems—PSI and PSII— embedded within their internal thylakoid membranes [3]. In addition to this, many cyanobacterial strains contain specialized cells called heterocyst, which are dedicated to nitrogen fixation. These cells facilitate the transformation of atmospheric nitrogen (N_2) into ammonia through the action of the nitrogenase enzyme complex [4]. Moreover, cyanobacteria are known for producing a wide variety of secondary bioactive compounds such as phycobiliproteins—utilized as natural fluorescent markers— alongside carotenoids, terpenoids, and polyunsaturated fatty acids [5].

The bioactive compounds present in the cyanobacteria have various applications in energy, environment, Industry and agriculture sector. Kant., *et al.* has referred cyanobacteria as "wonder microbe for 21st century" due to its various applications in multiple sectors (Figure 1) [6].

Cyanobacteria's autotrophic growth on CO_2 and sunlight has made them viable agents for the manufacture of biofuel. Ethanol, hydrogen, butanol, and biodiesel precursors such alkanes and lipids have all been produced using engineered strains of species like *Synechococcus elongates* PCC 7942 and *Anabaena* sp. (Figure 3 (A-C)) [7,8]. Table 1 describes different applications of Cyanobacteria along with their growth systems and major polysaccharides present. Different product yields have increased because of genetic treatments, such as rerouting carbon flux and overexpressing important enzymes. Cyanobacteria have a smaller ecological footprint than traditional biofuel crops because they don't need fresh water or arable land [9].

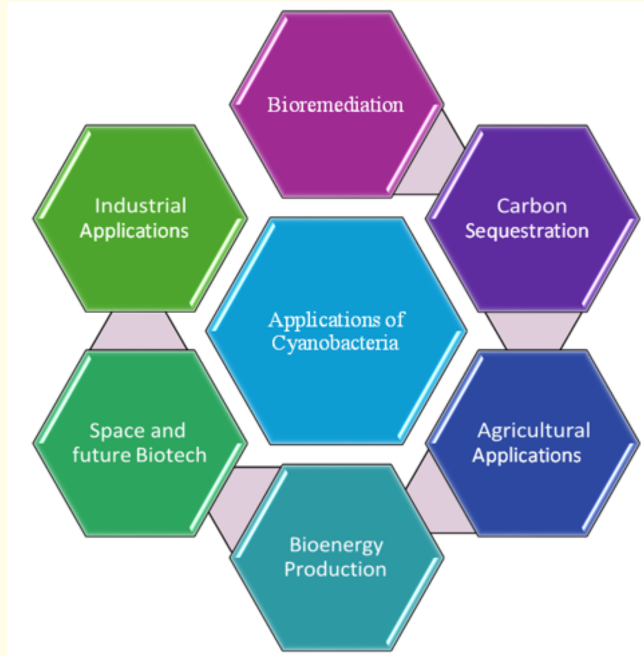

Figure 1: Application of Cyanobacteria.

Cyanobacteria species	Cultural Medium	Growth System	Polysaccharide type	Key Applications
Anabaena sp.	BG-11 Medium	Flask culture	Extracellular Polysaccharide (EPS)	Biofertilizer carrier, soil conditioning
Nostoc commune	BG-11 medium/N-free medium	Batch culture	Sulfated EPS	Wound healing, antioxidant
Gloeocapsa sp.	BG-11 medium	Static culture	Sheath Polysaccharide	UV-Protective coverings
Oscillatoria sp.	BG-11 medium	Batch culture	EPS	Bioremediation and Metal binding
Microcystis sp.	BG-11 medium	Batch culture	Mucilage PS	Flocculation
Calothrix sp.	BG-11 medium	Flask culture	EPS	Soil binding
Lyngbya sp.	BG-11 medium	Batch culture	EPS	Biofilm
Spirulina platensis	Zarrouk medium	Raceway culture	Soluble PS	Nutraceutical

Table 1: Cultivation media, growth systems, and Polysaccharides profile of some species of Cyanobacteria.

Applications in the environment

Bioremediation

Because they can absorb and detoxify a wide range of contaminants, cyanobacteria are useful bioagents for cleaning up contaminated environments. They have carboxyl, hydroxyl, and phosphate functional groups in their cell walls that bind heavy metals like mercury, cadmium, and lead [5]. Certain species, such as *Oscillatoria* (Figure 3 (F-G)) and *Nostoc* (Figure 3 (D)), have shown a great deal of promise in breaking down hydrocarbons and pesticides in contaminated waterways [10].

Sequestration of carbon

Cyanobacteria's effective fixation of carbon dioxide has a major impact on the global carbon budget. According to [11], certain strains have undergone genetic engineering to improve net carbon capture rates by increasing RuBisCO efficiency and carbon concentration mechanisms (CCMs). To reduce industrial greenhouse gas emissions, growing cyanobacteria in photobioreactors for carbon capture has drawn attention [12].

Agricultural applications

Cyanobacteria play a vital role in sustainable agriculture due to their ability to fix atmospheric nitrogen, enhance soil fertility, and improve crop productivity. Several genera such as *Anabaena, Aulosira*, *Cylindrospermum, Nostoc, Scytonema* and *Tolypothrix* (Figure 3) possess specialized cells known as heterocysts that fix atmospheric nitrogen into ammonia, which plants can readily absorb. This process helps reduce the dependency on synthetic fertilizers. In rice cultivation, particularly in India and other Asian countries, the symbiotic association between *Anabaena azollae* and *Azolla fern* is widely exploited as a biofertilizer to enhance soil nitrogen content and crop yield. Cyanobacteria also improve the organic matter content, soil aggregation, and water-holding capacity, thereby maintaining soil health and fertility. Cyanobacteria occur generally in myxotrophic assemblages (Figure 2), providing vital nutrition in the agricultural soils and their regular application in paddy fields increases productivity while promoting eco-friendly and cost-effective farming [5-14].

Bioenergy production

Cyanobacteria have gained attention as renewable energy resources due to their potential in biofuel production. Certain

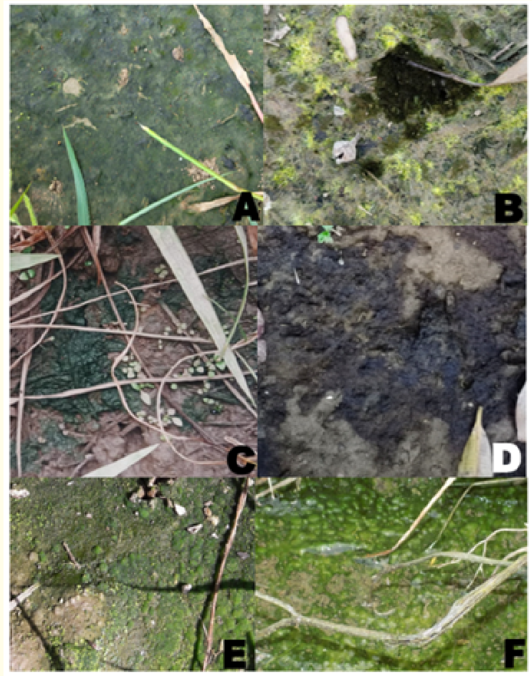

Figure 2: (A-F) Mixotrophic cyanobacterial growth in nature.

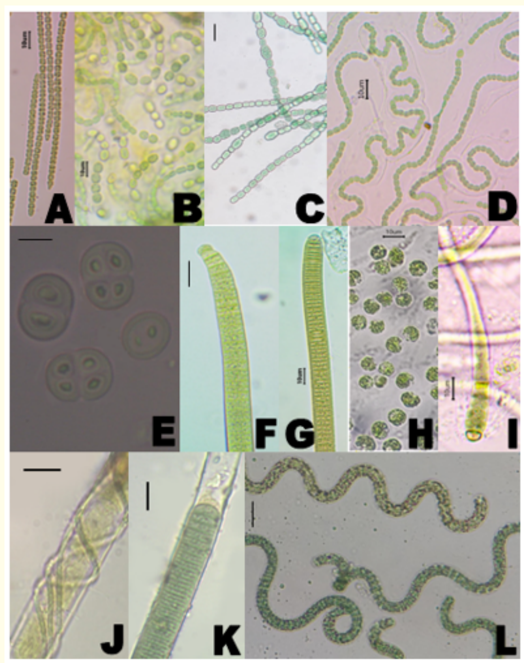

Figure 3: (A-C) *Anabaena* sp. (D) *Nostoc commune* (E) *Gloeocapsa* sp. (F-G) *Oscillatoria* sp. (H) *Microcystis* sp. (I) *Calothrix* sp. (J-K) *Lyngbya* sp. (L) *Spirulina* platensis.

strains can accumulate lipids, carbohydrates, and hydrogen, which serve as raw materials for biodiesel, bioethanol, and biohydrogen production. Their photosynthetic efficiency and ability to utilize sunlight and CO_2 make them suitable for sustainable bioenergy systems. Unlike traditional crops, cyanobacteria can be cultivated in non-arable land and wastewater, thus avoiding competition with food production. Moreover, cyanobacteria genetic engineering has further improved their lipid productivity, making them an emerging platform for green energy technologies [15,16].

Cyanobacteria in space and astrobiology

Cyanobacteria are also studied for astrobiological and space applications. Due to their ability to survive under extreme conditions such as high radiation, desiccation, and salinity, they are considered potential organisms for oxygen and food production in space missions. Their efficient carbon fixation, nitrogen fixation, and oxygen evolution capabilities make them ideal candidates for developing closed-loop life-support systems for future space colonies. Researchers are exploring the use of genetically engineered cyanobacteria to produce essential biomolecules and fuels in extraterrestrial environments [17].

Application in industry

Several commercially valuable chemicals, including pigments (carotenoids phycocyanin, phycoerythrin), enzymes, vitamins (such B12 and E), polysaccharides, proteins and biodegradable plastics like polyhydroxyalkanoates (PHAs), are produced by different cyanobacteria [2,18-26]. The food, cosmetics, pharmaceutical, and environmental industries can all benefit from these items. *Spirulina platensis* (Figure 3 (L)), for example, is a popular nutritional supplement that is high in micronutrients, protein, and antioxidants [27-30]. Additionally, cyanobacterial enzymes are employed in wastewater treatment and detergent compositions.

Synthetic biology and genetic engineering

The study of cyanobacteria has been transformed by the development of synthetic biology technologies. Precise genome editing has been made possible by methods like homologous recombination, CRISPR-Cas, and modular cloning systems [30]. To forecast metabolic fluxes and optimize strain designs for enhanced metabolite synthesis, genome scale metabolic models, or GEMs, are employed. A comprehensive approach to comprehending and modifying biological processes is made possible by the integration of multi-omics data (transcriptomics, proteomics, and metabolomics) [15].

Major obstacles and restrictions

Despite the enormous potential of cyanobacteria, a number of obstacles prevent their widespread use in industry:

- Product titters and productivity are rather low.
- Open systems' susceptibility to contamination
- Restrictions on CO2 availability and light penetration in thick cultures
- Concerns about genetically modified organisms (GMOs) and biosafety.

Improved robustness, the creation of closed photobioreactors, and legislative frameworks that encourage sustainable biotechnologies are all necessary to overcome these obstacles [8].

Conclusion

Cyanobacteria have revolutionary potential to address urgent worldwide issues in industrial production, environmental preservation, and energy sustainability. We can create cleaner and more sustainable substitutes for traditional technology by utilizing their photosynthetic and metabolic capacities. To fully realize and scale their potential, ongoing research and technology integration will be essential.

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Conflict of Interest

Authors declare no conflict of interest in the preparation of this manuscript.

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