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Microalgae in Sustainable Agriculture, Renewable Energy, and Waste Management

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ABSTRACT

Sustainable food and energy supply without posing any threat to the environment is the current call of our society concerning the continuous rise of the global human population and the reduction of natural energy resources. Among terrestrial and aquatic photosynthetic organisms, blue-green algae have recently appeared as potential candidates who can fulfill the demands of the growing population due to their capability to efficiently harvest light and convert it into biomass by utilizing carbon dioxide, water, and nutrients. Cyanobacteria are photosynthetic multi-functional bio-agents for eco-friendly agriculture as they enrich the soil with carbon and nitrogen, enhancing phosphorus's bioavailability. Thus, offer alternatives to chemical fertilizers and are effortlessly integrated into organic farming by improving soil health by forming symbiotic associations with several plants and acting as plant growth enhancers, nutrient improving, and nitrogen fixation agents. Blue-green algae play a vital role in addressing air pollution by capturing & storing CO2 thus mitigating global warming. These bio-agents also play a crucial role in mitigating soil pollution by effectively accumulating, degrading, and removing heavy metals and organic contaminants through phytoremediation thus protecting our environment from various pollutants. Thus, ultimately providing a healthy and sustainable environment. This article will comprehend the direct utilization and challenges of cyanobacteria for the sustainable agricultural sector and environment.

Keywords: Agriculture; Cyanobacteria; environment; global warming; nutrients; sustainability

Introduction:

The burgeoning human population has increased the agricultural output to meet the growing population's ongoing demand, which is raising the impacts of intensified agricultural activity on the environment and uncertain changes in the global climate (Faheed et al., 2008). Consequently, maintaining high agricultural productivity while concurrently alleviating environmental impacts and promoting environmental rejuvenation is an urgent concern. The success of healthy agriculture and the environment heavily depends on the fertility level of the soil. The health of the soil is the basis for organic farming. The development of plants requires vital nutrients from the soil, which in turn supports a multifarious and dynamic biotic population that aids the soil to resist environmental degradation. (Ammar et al., 2022).

In this context, cyanobacteria exhibit a pool of traits such as biofertilizers, organic fertilizers, bio-stimulants, biocontrol agents, and soil conditioners (Abdel-Raouf, 2012; Go´rka et al., 2018) with a unique value for addressing these agricultural and environmental challenges. However, discrete comprehension and insufficient understanding of the effects and mechanisms of cyanobacteria on soil and the environment under a wide range of conditions still curb their utilization in agricultural and environmental sectors. Therefore, this review provides a detailed understanding of the potential and challenges of cyanobacteria in sustainable agriculture and the environment (Carvajal-Muñoz and Carmona-Garcia, 2012).

Cyanobacteria and important traits:

The name cyanobacteria originated from their color (Greek word "kuanos," meaning blue) and is commonly known as blue-green algae. Cyanobacteria evolved during the era of Precambrian around 3.5 billion years ago (Schopf & Packer, 1987) and are characterized as oxygenic photosynthetic organisms that possess photosynthetic pigments such as chlorophyll a, phycobiliprotein, and carotenoid.

Cyanobacteria are thought to be the photosynthetic ancestors of plastids in eukaryotic algae and plants, which were formed by the endosymbiosis of a phototrophic prokaryotic cell. Among all the photosynthetic prokaryotic organisms, cyanobacteria display the utmost diverse and intricate morphologies. Its cell size ranges between 1 mm for unicellular and over 30 mm for multicellular species, which is larger than most bacteria.

The cyanobacteria cells are enclosed within a cell wall (containing an outer peptidoglycan layer surrounded by a mucilaginous sheath), a cell membrane (which separates the cytoplasm from periplasm), thylakoid membranes, carboxysomes, ribosomes, and nucleoids. Cyanobacteria share their thylakoid membrane for photosynthetic and respiratory redox-active protein complexes and do not form grana as it does in algae and plants (Nakamura et al., 2003)

Cyanobacteria are ubiquitous autotrophs with numerous traits, such as fixing atmospheric nitrogen, which is a fundamental metabolic process of cyanobacteria, giving them the simplest nutritional requirements among all living organisms. They use the enzyme nitrogenase complex to convert N_2 into NH_4 (a form through which nitrogen enters the food chain) (e.g., Anabaena, Nostoc) (Veaudor et al., 2020).

Along with a high affinity for nitrogen and phosphorus, cyanobacteria also have high pH optima (Dokulil & Teubner, 2000). In addition, they produce gas vesicles, which are cytoplasmic inclusions with gas-filled and cylindrical structures that regulate buoyancy and enable cyanobacteria to adjust their vertical position in the water column (Walsby, 1987).

Another trait of cyanobacteria is the formation of akinetes, thick-walled, nonmotile cells that differentiate from vegetative cells of cyanobacteria under unfavorable conditions and serve a perennating role as they preserve the ability to recommence morphology and functions of vegetative cells after a long period of dormancy (Sukenik et al., 2019). All these characteristics have enabled cyanobacteria to colonize various niches in the aquatic and terrestrial ecosystems, demonstrating their pioneering ancestral capacities as the earliest earth inhabitants (Moreira et al., 2013). Cyanobacteria are also often associated with other organisms, forming microbial mats, benthic communities, and biofilms. Sometimes these associations are predominant and only life forms in specific extreme habitats. In addition to surviving under different abiotic stresses, cyanobacteria can maintain sustainable agriculture and the environment.

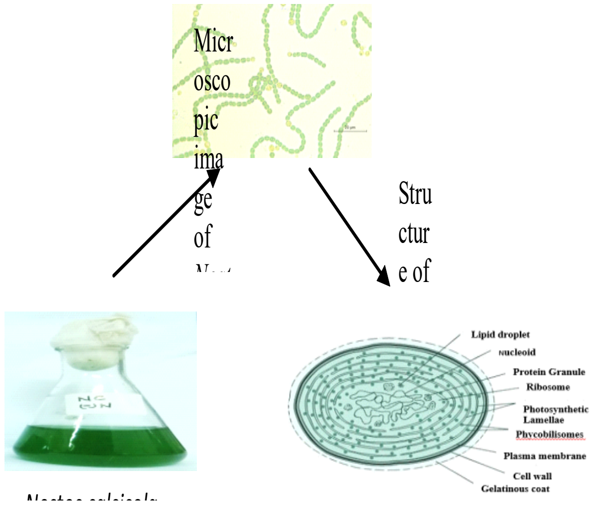

Fig.-1

Application of cyanobacteria in maintaining sustainable agriculture and the environment

Cyanobacteria, one of the largest and multipurpose groups of photosynthetic prokaryotes, are known for their enormous applications (Fig. 2) and have drawn huge attention in the last few decades.

Carbon dioxide sequestration and biofertilizer:

Cyanobacteria have a 10-50 times faster carbon dioxide fixation rate than terrestrial plants, and 20-30% of global primary photosynthetic productivity originates from them. This corresponds to the yearly fixation of about 20-30 Gt of CO_2 into biomass, which can be used for several purposes like biofertilizer and biofuel production, and the release of about 50-80 Gt of O_2 in the atmosphere (Veaudor et al., 2020). Hence, cyanobacteria are considered an effective approach to cutting down the concentration of atmospheric CO_2, thereby helping to mitigate global warming. In addition, many cyanobacteria can fix atmospheric N_2 using heterocysts (modified thick-walled cells), a site for the enzyme complex nitrogenase, which catalyzes the conversion of biological N_2 into a reduced form of ammonia and releases it into the soil either by secretion or by microbial degradation after their death. Apart from heterocystous cyanobacteria, several unicellular and filamentous non-heterocystous cyanobacteria are responsible for fixing atmospheric nitrogen. They contribute 20-30 kg N ha-1 and organic matter to the soil and provide great benefits over chemical nitrogen fertilizers used in agriculture (Issa et al., 2014). Some examples of cyanobacteria that are used as effective biofertilizers are Anabaena variabilis, Nostoc muscorum, Aulosira fertissima, and Tolypothrix tenuis. Along with nitrogen fixation, they can improve the bioavailability of phosphorus in the plants by solubilizing and mobilizing the insoluble organic phosphates present in the soil with the help of phosphatase enzymes (Cameron & Julian, 1988). Hence, improves soil quality by enhancing nutrient solubilization, mobility, soil aggregation, and water permeability, thus improving the overall soil physio-chemical properties and crop production.

Bio-control agents:

Cyanobacteria are also used as bio-control agents producing a wide array of biologically active compounds of antibacterial, antifungal, and antiviral potential (Dahms et al., 2006). These compounds belong to the group of amides, alkaloids, polyketides, lipopeptides, fatty acids, and indoles (Burja et al., 2001). In addition, they also produce anti-algal compounds that constrain the growth of pathogens by disrupting their physiological and metabolic activities (Dahms et al., 2006). The cell extract of cyanobacteria is known to reduce the occurrence of Erysiphe polygoni producing powdery mildew on turnips, Botryti scinerea on strawberries, and damping-off disease in tomato seedlings. Nostoc muscorum produces antifungal compounds against soil fungi, especially those causing damping-off. Nostoc sp., is a known potential cryptophycin producer, a source of natural pesticides against fungi, insects, and nematodes (Biondi et al., 2004). Nostoc muscorum also inhibits the growth of other fungi producing the "wood blue stain," a grayish or bluish discoloration of the sapwood caused by certain dark-color fungi (Alternaria, Aureobasidium, Cladosporium, etc.) on the surface and inside of the wood (Zulpa et al., 2003).

Plant growth promoters:

Cyanobacteria provide a wide scope for the commercial application as plant growth promoters due to their simple nutritional requirements, mainly water, sunlight, and CO2 and fast cell growth (Ruffing, 2011). They produce extracellular growth-promoting substances such as hormones like auxin (Anabaenopsis and Anabaena), Glactothece and Cylindrospermum (Selykh & Semenova, 2000), Nostoc and Plactonema (Sergeeva et al., 2002), gibberellins (Cylindromum and Anabaenopsis), cytokinin (Anabaena, Chlorogloeopsis, and Calothrix) (Selykh & Semenova, 2000); abscisic acids, amino acid, vitamin B, and antibiotics (Selykh & Semenova, 2000). Co-inoculation of cyanobacteria with wheat enhances the root dry weight and chlorophyll content (Obreht et al., 1993).

Bioremediation:

Bioremediation is the treatment of contaminated water, soil, and subsurface material, by using several microorganisms that degrade the target pollutants. One of the emerging bio-remediator is cyanobacteria. Cyanobacteria have several advantages over other microorganisms due to their photosynthetic and nitrogen-fixing nature, which makes them self-sufficient for growth, maintenance, and adaptability to endure in polluted environments. Due to the high multiplication rate and metal sorption capacity, cyanobacteria play a vital role in detoxifying numerous industrial effluents, such as those from breweries and distilleries, sugar mills, oil refineries, paper mills, dye, and pharmaceutical industries. Cyanobacteria help in mitigating metal toxicity and eutrophication problems as they are used for tertiary treatment of urban, agro-industrial effluents. Synechococcu selongatus, Anacystis nidulans, and Microcystis aeruginosa degrade many organo-chlorine and organo-phosphorus insecticides from polluted aquatic systems (Vijayakumar, 2012). Lyngbya sp., Microcystis sp., Anabaena sp., and Nostoc sp., degrade organo-phosphorous herbicide glyphosate, and the mineralized glyphosate is used as a phosphorus source (Forlani et al., 2008).

Source of bio-energy:

The simple cell structure and minimum requirement of nutrients make cyanobacteria a unique group of photosynthetic bio-agents and have the capacity to produce bio-energy, including bio-diesel, bio-hydrogen, and bio- or syngas (Kumar & Singh, 2016). Cyanobacteria convert the carbon dioxide (CO2) taken through photosynthesis to carbon-rich lipids that can be used to produce biofuels.

Cyanobacteria such as Calothrix, Oscillatoria, Anabaena, Nostoc, Cyanothece, Synechococcus, Gloeobacter, Microcystis, Aphanocapsa, Microcoleus, and Chroococcidiopsis, also produce hydrogen an ideal substitute for fossil fuels (Nozzi et al., 2013). Cyanobacteria biomass can also be used for the production of biogas via fermentation or anaerobic digestion. In the cyanobacterial biomass, the organic biopolymers are hydrolyzed, broken down into monomers, and subjected to aerobic digestion to yield biogas.

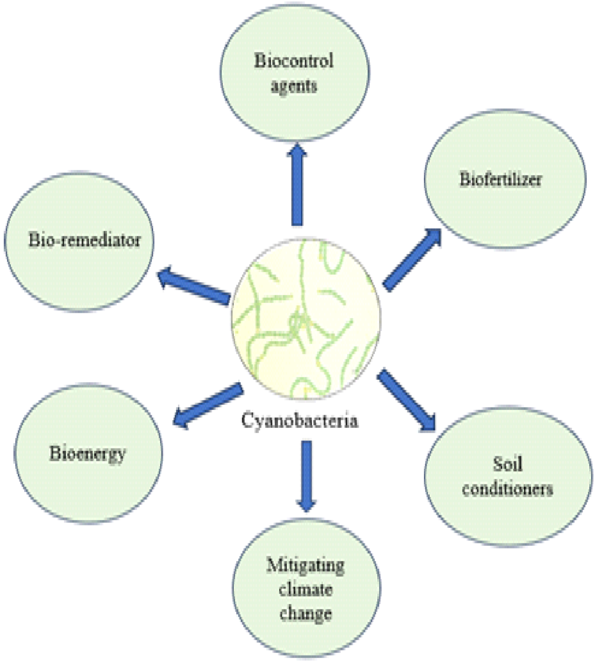

Fig. 2. Application of cyanobacteria in maintaining sustainable agriculture and environment

Challenges in using cyanobacteria for sustainable agriculture and the environment

However, there are several challenges in employing cyanobacteria for sustainable agriculture and the environment. Along with secondary metabolites, cyanobacteria also produce toxic compounds called cyanotoxins that pose a threat to living beings and the environment as well (Ricciardelli et al., 2023). This bioactive compound includes peptides, cyclic amine alkaloids, and non-protein amino acids (Zhang and Whalen, 2019). The nature of toxins is either protein-bound or free, and the ratio of expression of toxins or nontoxic genes depends on various environmental factors (Buratti et al., 2017). The cyanotoxins enter the environment through two routes, the direct route and the indirect route. The cyanotoxins contaminate drinking as well as other water bodies through direct routes, while in the indirect route, either the food items contain cyanobacteria, or the food has bioaccumulated cyanotoxins (Abdallah et al., 2021). The contamination of water bodies with cyanotoxins also contaminates the adjacent soil and plant systems, which further leads to the spread of toxins from water to soil, then to humans and animals. Additionally, water with cyanotoxins (contaminated water) used for irrigation is the root cause of transferring the cyanotoxins in the soil which further may leach out into the groundwater (Melaram et al., 2022).

However, there are various challenges involved in extraction, quantification and identification of cyanotoxins. The utmost challenging tasks in extraction of cyanotoxins is to select a suitable extraction solvent (Schmidt et al., 2014). However, UV degradation and microbial degradation processes are used to remove cyanotoxins from the soil (Bouaïcha and Corbel, 2016). The light-assisted UV degradation is very well studied in microcystins; however, in soil, it is not exactly known (Bouaïcha and Corbel, 2016). There are a variety of techniques and assays used to determine the concentration of cyanotoxins such as cell count, antibody utilized techniques (ELISA), toxin gene determination (PCR, qPCR), different chromatography techniques (HPLC, LC-MS), and toxicity estimation-based techniques (cell and enzymatic) (Gaget et al., 2017). All the techniques mentioned above along with advantages have limitations too. For instance, some of the chromatography-based procedures are expensive and may not detect all the congeners. ELISA and dip-stick, antibody-based techniques are considered highly reliable for the detection of all existing and relevant congeners, however, the assay used in these processes does not contribute a response that is comparative to the quantity of cyanotoxin produced. Additionally, the matrix used in ELISA and dip-stick techniques interfere with the determination of cyanotoxins. Similarly, the toxigenic species with different gene sequences may not be detected using qPCR and PCR, and have low accuracy and interfere with the determination of toxic genes. Likewise, cell and enzymatic-based toxicity determinants also have lesser accuracy with potentially interfering factors . In the view of advantages and disadvantages of each technique, it is imperative to research more on the detection methods and to come up with a reliable and effective approach, as it is likely that one technique may work best for some groups of cyanotoxins, but it might not prove to be effective for another group.

Conclusion:

The ability of blue-green algae to grow in a wide range of environmental conditions provides a sustainable approach to sustainable agriculture and environments. Cyanobacteria, through their nitrogen-fixing capability are used as biofertilizers and thus enhance soil fertility and help to improve the bioavailability of micro and macro-nutrients. By using cyanobacteria as a source of biofertilizer, we can reduce the use of expensive chemical of N sources and benefit the farmer and the earth. The production of various secondary metabolites and phytohormones by blue-green algae helps to regulate plant growth, accompanied by activating defense mechanisms against various biotic and abiotic stressors. As a pioneer species, cyanobacteria can also be utilized for the restoration of degraded land and the production of bioenergy, which will help in mitigating climate change. It is also recommended to develop more accurate and reliable techniques to detect cyanotoxins. Due to social and political barriers, the application of cyanobacteria to fulfill food demands on a major scale might be hindered, hence, these points should also be considered and verified by the authorized organizations.

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