Chapter

Cyanobacteria: A Futuristic Effective Tool in Sustainable Agriculture

Eman Elagamey, Magdi A.E. Abdellatef and Hassan E. Flefel

Abstract

Cyanobacteria are bioactive photosynthetic prokaryotes that have a superior ability to fix atmospheric nitrogen and are highly competitive in the microflora community. They also improve the physical and chemical properties of the soil and increase its water-holding capacity. Therefore, cyanobacteria are used as biofertilizers in agriculture. Cyanobacteria are able to promote plant growth by providing nutrients and producing many highly effective chemical compounds, such as enzymes and hormones, in the plant rhizosphere, giving the plant a highly competitive ability. In addition to activating plant defense responses against soil-borne pathogens, they have an effective strategy as a biocide against bacteria, fungi, and nematodes that attack plants. With multiple beneficial biological roles, the environmentally friendly cyanobacteria occupied the role of the maestro in sustainable agriculture.

Keywords: cyanobacteria, sustainable agriculture, biofertilizer, nitrogen fixation, abiotic stress, antimicrobial activity

1. Introduction

Given the ongoing increase in the world's population and the depletion of food resources, our society currently needs a sustainable supply of agricultural productivity that poses no environmental risks [1]. Plants are constantly affected by abiotic stresses, such as drought, salinity, cold, heat, and nutrient deficiencies, as well as biotic stress, including pathogens and pests. In addition to climatic changes that greatly affect soil fertility, virulence of pests and diseases, and plant-producing biomass and seeds [2]. In nature, the interaction continues between biotic stress and plants, causing dynamic changes in their activities and composition under changing environmental conditions. Beneficial microorganisms play an effective role in maintaining the balance of this interaction in a way that is in the interest of the plant at the expense of biotic stress. Furthermore, plants can more effectively withstand abiotic stress, enhance nutrient uptake and utilization, and increase photosynthetic activity by virtue of the mechanisms carried out by beneficial microorganisms, which leads to higher yield [3].

Beneficial microorganisms can act as biopesticides by attacking phytopathogens directly and limiting their population by competition for space, nutrients, and the production of antimicrobial compounds [4]. Furthermore, beneficial microorganisms can induce plants to pre-activate the defensive responses controlled by plant hormones in order to combat infections more rapidly and successfully. This is referred to as systemic acquired resistance [5]. Among beneficial microorganisms are cyanobacteria. Cyanobacteria are photosynthetic prokaryotic organisms, extremely varied groups that can be found in practically all of the world's ecosystems.

Cyanobacteria occur in unicellular, colonial, or multicellular filamentous forms. They are considered a subset of the bacterial kingdom. This subset is responsible for a significant amount of N_2 fixation, reduction of the level of CO_2, solubilization of phosphate, and the production of plant growth regulators by releasing phytohormones, polypeptides, amino acids, polysaccharides, and siderophores [6]. Cyanobacteria are composed of numerous organic inclusion units capable of carrying out a wide range of specialized functions, which give cyanobacteria their unique tasks and applications in sustainable agriculture [7]. The components that make up the structure of cyanobacteria are light-harvesting antennae, phycobilisomes, polyphosphate bodies, cyanophycin granules, polyhydroxyalkanoate granules, carboxysomes, lipid bodies, thylakoids, DNA-containing areas, and ribosomes [8] (**Figure 1**). Cyanobacteria have chlorophyll-a, which engages it in oxygenic photosynthesis, carotenoids that protect chlorophyll-a from oxidative degradation, and specific pigments called phycobilins that are bound to water-soluble proteins [9]. Flagella are not present in cyanobacteria [10].

Some kinds of cyanobacteria contain specialized cells called heterocytes and akinetes that are morphologically distinct from vegetative cells. The position, amount, and distribution of heterocytes and akinetes are significant morphological characteristics of cyanobacteria species and genera. Heterocytes are specialized cells that allow nitrogenase to fix atmospheric nitrogen by reducing it to ammonium, a process known as diazotrophy [11]. Akinetes contain granules of glycogen and cyanophycin but no polyphosphate granules and have a multilayered cell wall [9].

2. Characterization of cyanobacteria

Cyanobacteria are distinguished from most other microalgae by their lack of a cell nucleus and other cell organelles. They lack chloroplasts and have instead simple thylakoids, which are the location of the light-dependent processes necessary for photosynthesis. Cyanobacteria exhibit a variety of traits that can be utilized for microscopic analysis and identification, including the size and form of the cells, the presence

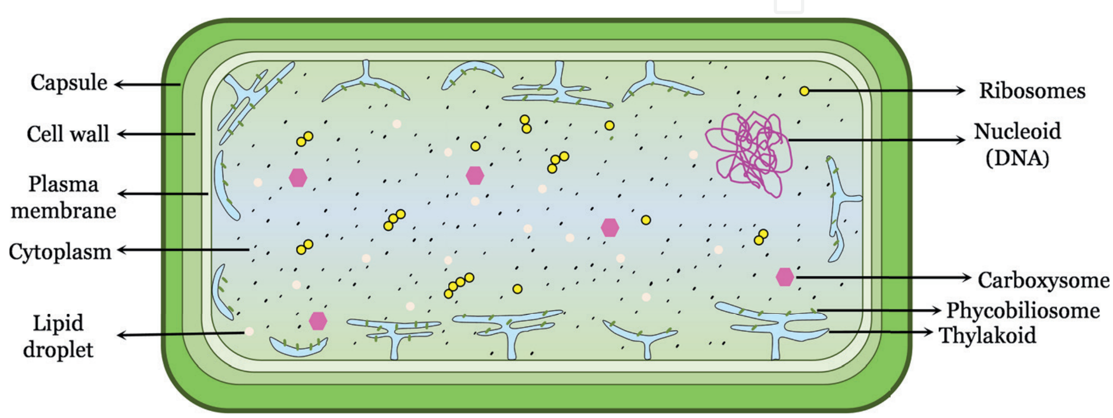

Figure 1.
Cyanobacterial cell structure.

of subcellular structures, and the presence of specialized cells. Flagella, which are present in many other bacterial or phytoplankton taxa, are absent in cyanobacteria. However, many cyanobacteria, especially filamentous varieties, exhibit gliding movement. Cyanobacteria have not been shown to reproduce sexually. The division of vegetative cells is their unique asexual method of reproduction. Cyanobacterial cells can be spherical, cylindrical, barrel-shaped, ellipsoid, conical, or disc-shaped. The critical abiotic parameters that determine the success of cyanobacterial growth are light, pH, temperature, water, CO_2, and nutrient supplements [9, 12].

3. Symbiotic association between plant and cyanobacteria

In a symbiotic relationship, both organisms can benefit from each other in various ways. The filamentous cyanobacteria live in symbiosis with a wide range of eukaryotic hosts, including plants and fungi [13]. The cyanobacteria that will form symbiotic relationships with the plants are called cyanobionts, which can grow inside the host or more or less firmly attach themselves to the host [14]. The plants provide cyanobacteria with carbon sources, for example, sucrose. Cyanobacteria have the ability to fix nitrogen from the air in heterocysts, which benefits plants by supplying them with nitrogen (**Figure 2**). Therefore, the symbiotic cyanobacteria are mostly heterocyst-forming strains. They are virtually entirely associated with the genera Nostoc and Anabaena [15]. Cyanobacteria provide plants with about 88% of the fixed nitrogen in the form of NH_3 and keep only 12% for themselves [16]. In addition to a symbiotic relationship between cyanobacteria and whole plants, there is also a symbiotic relationship between cyanobacteria and plant tissues. Cyanobacteria were found to have colonized different areas of wheat, where they were abundantly present around the root, in the spaces between root epidermal cells and cortex, and as single cells within the stem or on the surface of leaves [17]. Due to the symbiotic relationship between Gunnera and Nostoc, the number of heterocysts formed increased by up to 80%. This is evidence that the symbiotic relationship has different effects on the growth and development of cyanobacteria. Leghemoglobin concentration in chickpea root nodules increases as a result of the simultaneous inoculation of the cyanobacterium *Anabaena laxa* and the rhizobia *Mesorhizobium cicero* [18]. The assimilation of

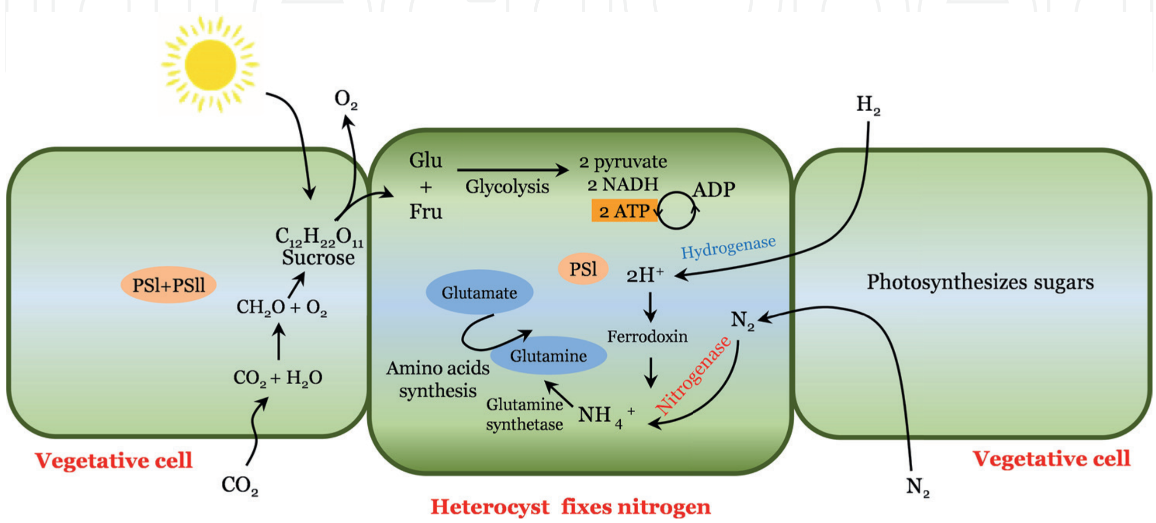

Figure 2.
Nitrogen fixation in cyanobacterial heterocyst cell.

ammonium in cyanobacterial heterocysts is carried out by the enzyme glutamine synthetase. Heterocysts in the *Nostoc-Anthoceros* symbiosis showed a 3- to 4-fold reduction in Glutamine synthetase activity [19]. The reduction of abiotic stress and plant protection against diseases are factors that encourage the development of symbioses from a plant's side. Plants benefit from the general improvement of soil conditions.

4. The role of cyanobacteria in plant improvement

Cyanobacteria play an important role in improving plant growth and crop production. They are good bio-fertilizers, enhance solubilization and mobility of nutrients, and increase essential microelements in soil that are necessary for ion uptake, as well as stimulate plant growth due to their ability to produce bioactive compounds, such as phytohormones and other plant growth regulator substances, such as amino acids and polysaccharides (**Figure 3**).

4.1 Promoting plant growth

Cyanobacteria will actively promote seed germination, plant growth, and development due to their ability to produce some of the plant hormones, such as auxins, cytokinins, and gibberellins, by the genera *Anabaena, Anabaenopsis*, and *Calothrix* [20, 21]. Cyanobacteria have the ability to increase root and stem growth, dry weight, and yield in wheat [8, 20]. The cyanobacteria used in wheat cultivation showed effective results on the appearance of plants in terms of increasing plant height, dry weight, and a number of grains of the wheat crop, in addition to some important positive changes in increasing the bio-carbon content of the beneficial microbial mass [22]. The effects of cyanobacteria on rice crop growth have demonstrated that cyanobacterial inoculation can improve rice seed germination and growth parameters [23]. According to Osman et al. [24], the amount of growth-promoting secondary metabolites varies depending on the cyanobacterial strain. While *Oscillatoria angustissima* had

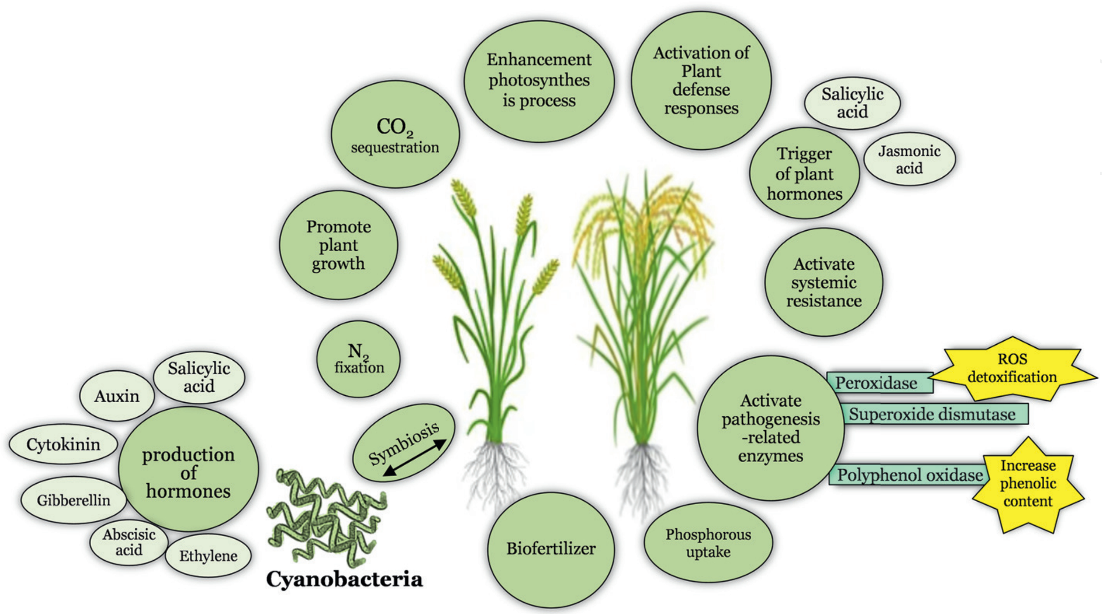

Figure 3.
The role of cyanobacteria in improving plant growth and stimulating the response of defense systems.

higher quantities of gibberellic acid, and *Nostoc entophytum* had higher levels of auxin and cytokinin. Cyanobacterial extracts improved nutrient uptake, and plant development in lettuce, red beet [25], tomato [26], and cucumber [27]. In a broader sense, cyanobacteria are used as commercial bioinoculants to promote plant development because of their greater biodiversity, ability to survive in a variety of conditions, faster growth rate, and simpler nutritional requirements [28].

4.2 Nitrogen fixation

Nitrogen is the most important element needed for plant growth and is a key ingredient for successful cultivation on reclaimed land. Biological atmospheric nitrogen fixation by microorganisms is the main source of soil nitrogen [29]. Cyanobacteria have the ability to fix atmospheric nitrogen through specific cells called heterocysts that possess the nitrogenase enzyme. *Nostoc Linkia*, *Anabaena variabilis*, *Aulosira Fertilissima*, and *Calothrix* SP are the most efficient cyanobacteria in the soil's air nitrogen fixation [30]. Cyanobacteria get established permanently in the field after being applied for three to four subsequent crop seasons [31]. The growth characteristics of *Oryza sativa* were enhanced by the addition of *Nostoc commune* and *Nostoc carneum* as sources of cyanobacteria with chemical fertilizer [32]. Spraying the foliar of *Salix viminalis* L. three times with *Anabaena* sp. and *Microcystis aeruginosa* improved photosynthesis, stomatal conduction, and intracellular CO_2 concentration [33]. The application of *Nostoc entophytum* and *Oscillatoria angustissima* on *Pisum sativum* L. decreased the chemical fertilization to 50% [34]. The addition of cyanobacterium *Phormidium ambiguum* to sandy soil increased nitrate content by 15% more than the untreated soil after 90 days. Furthermore, the use of *Scytonema javanicum* improved the N content in slit loam, sandy loam, loamy sand, and sandy soils by 11, 10, 14, and 55%, respectively, the effect of cyanobacteria in biological crust formation and N supplementation for any sort of soil [35].

4.3 Bio fertility

In modern agriculture, microbes play a vital role in determining fertility and soil structure [36]. Cyanobacteria have potential use in agriculture as biofertilizers. Maintaining soil fertility using renewable bioresources is the main requirement of sustainable agriculture to reduce the need for synthetic fertilizers.

Among such resources, cyanobacteria are the most promising candidates. In the rhizosphere, cyanobacteria can be directly inoculated in the soil or can be used as a coating on seeds, but in both cases, their survival should be guaranteed. Although the use of agricultural chemical nitrogen fertilizers was a solution to all agricultural problems related to food production and increasing agricultural crop production, many environmental problems have arisen as a result of the excessive use of these chemical fertilizers in intensive farming systems. The high prices of chemical fertilizers have led to a decrease in the profit of agricultural crops, and the shortage of chemical fertilizers is a major problem facing farmers in developing countries, which makes researchers try to search for bio-alternatives to expensive chemical fertilizers [37]. Recently, there has been much interest in linking primary field crops in agriculture, especially cereal crops, such as wheat and rice, and organisms as a source of biofertilizers, such as cyanobacteria.

Due to the adaptation of cyanobacteria to most different environmental conditions, it is widely used in increasing soil fertility and improving soil quality and structure, so it has become one of the most important biofertilizers [38]. The effect of cyanobacteria supplementation on growth, productivity, and physical properties of sandy soil under greenhouse conditions was tested. Sood et al. [39] found that there was a lot of ecological and metabolic diversity in cyanobacteria and that their structural-functional flexibility led to even more diversity. The use of cyanobacteria is one of the inexpensive applications in agriculture, which legalizes the use of chemical fertilizers. Cyanobacteria are one of the most important improvers that increase organic matter, amino acids, vitamins, and auxins in the soil, reduce soil salinity and phosphate deposits, and increase productivity in rice crops [40].

Cyanobacteria are emerging microorganisms for sustainable agricultural development. It can contribute about 20–30 kg of N per hectare, as well as soil organic matter, which is quite important for economically weak farmers who cannot invest in expensive chemical nitrogen fertilizers. The diazotroph group is the cyanobacteria most widely used for the development of biofertilizers and is capable of controlling the nitrogen deficiency in plants and improving the aeration of the soil and the water holding capacity. The most efficient nitrogen-fixing cyanobacteria are *Nostoc linkia*, *Anabaena variabilis*, *Aulosira fertilissima*, *Calothrix* sp., *Tolypothrix* sp., and *Scytonema* sp., which are normally present in the rice crop cultivation area.

4.4 Protection against abiotic stress

Abiotic stress on plants can be caused by a variety of factors, such as temperature, droughts, light, and soil-related factors, including salinity, presence of heavy metals, and soil acidity [41, 42]. Cyanobacteria induce diverse changes in response to elevated soil salinity by synthesis and accumulation of protective substances, maintaining low intracellular ion concentrations, and expression of so-called salt stress proteins [43]. *Anabaena torulosa* and *Anabaena* sp., exhibited anti-saline action by suppression of some expressed proteins, enhancement of other proteins, and expression of specialized salt stress proteins [44]. The effect of the extracellular products of *Scytonema hofmanni* on the growth of rice plants under salt stress was clearly demonstrated. These extracellular products made rice plants able to cope with stress caused by high salt concentrations. Comparison with the effects of plant gibberellic acid indicates that *S. hofmanni* produces gibberellin-like plant growth stimuli [45]. Another way to increase the sensitivity of plants to salinity stress is through the expression of cyanobacterial flavodoxin within them. This can induce multiple resistances in plants; it has been shown that it can reduce salt stress in *Medicago truncatula*. Adding cyanobacterium *Aphanothece* sp. and *Arthrospira maxima* led to improve tomato plant growth and increase the content of chlorophyll and nutrients essential content, such as nitrogen, phosphorous, and potassium, under saline stress [46]. Reduce the effects of salt stress on sweet pepper plants increase in growth, as well as in the water content of the plants by using a liquid extract of *Roholtiella* sp. [47].

The reduction of the harmful effect of abiotic stresses on plants was observed by cyanobacteria, which has a direct effect on the soil or an indirect effect through the activation of specific responses in plants [48]. Concerning salinity stress, the mechanisms of cyanobacteria depend on increasing the plant's ability to tolerate salinity through nitrogen fixation; the production of extracellular polysaccharides, compatible solutes, hormones, and antioxidative enzymes; the active export of ions; and the effects on the microbial community [49]. Rice plants showed an effective response to abiotic stress after treatment of rice roots with *Oscillatoria acuta* and *Plectonema boryanum*. That results in regular increases in the activity of peroxidase, phenylalanine ammonia-lyase, and phenylpropanoid [50]. Furthermore, rice plants showed an increase in tolerance to salinity after inoculating roots with strains isolated from saline soils, such as *Nostoc calcicola*, *Nostoc linkia*, and *Anabaena variabilis* [51]. In salt-affected soils, *N. punctiforme* enhanced the physical composition, nutritional status, and microbial activity, leading to noticeably higher growth and yield [52].

Plant germination under drought stress can be enhanced by the use of cyanobacteria [53], moreover, it enhances the growth and development of plants in arid lands [54]. *Microcoleus* sp. and *Nostoc* sp. are capable of increasing germination and seedling growth of *Senna notabilis* and *Acacia hilliana* under drought stress [55]. Similar results were achieved in lettuce plants cultivated in barren soils after the addition of *Spirulina meneghiniana* and *Anabaena oryzae* [56].

Heavy metals can be effectively removed from agricultural soil and water by cyanobacteria [57]. Many cyanobacterial species, including *Anabaena variabilis*, *Nostoc muscorum*, *Aulosira fertilissimia*, and *Tolypothrix tenuis*, may absorb and remove Cr, Cu, Pb, and Zn [58], whereas *Oscillatoria* sp. and *Synechocystis* sp. can remove Cr, this was linked to increasing wheat growth [59]. Applying *Spirulina platensis* can hasten seed germination and boost plant growth by preventing Cd from moving from roots to shoots [60]. *Synechocystis* sp. and *Phormidium* sp. are capable of absorbing and removing systemic insecticide from the soil [61]. The addition of *S. platensis* in the soil can induce the biosynthesis of some amino acids, which can protect plants from the negative effects of the herbicide [62]. Cyanobacteria contribute to stimulating the release of plant hormones, such as salicylic acid or jasmonic acid, which have an effective role in protecting plants from biotic and abiotic stresses by stimulating gene expression of specific proteins [63]. Cyanobacteria lead to increased nitrogen and carbon content, state of soil aggregation, water retention, decrease in pH, exchangeable sodium, and decrease in heavy metals, as well as microbial flora reconstitution which in turn all have an effective role in reducing salt stress [49, 53].

5. The role of cyanobacteria in soil resilience

Soil health is seriously threatened in many parts of the world due to salinization, groundwater pollution from acidification, and excessive use of chemical fertilizers and pesticides. Cyanobacteria are essential for maintaining the health of the soil by enhancing soil physicochemical properties, including aggregation, aeration, and nutrient release patterns [20]. Additionally, cyanobacteria contribute to the fixation of nitrogen, excretion of biologically active compounds, increase soil biomass and organic matter, improve water-holding soil capacity, and improve soil phosphate bioavailability, moreover, cyanobacteria are alternative low-cost and eco-friendly that ensure soil sustainability (**Figure 4**).

5.1 Cyanobacteria improve physical properties of soil

In the upper crust of soil, the growth of cyanobacteria produces exopolysaccharides and extracellular polymers that alter the chemical composition and improve the physical properties of soil, which in turn promote beneficial microbial growth and strengthen soil structure [56]. Some cyanobacteria secrete mucilage or slime, which increases the availability of nutrients, and enhances soil structure that creates an ideal environment for the growth of advantageous microorganisms and plays a part in enhancing soil characteristics. The cyanobacteria *Nostoc muscorum* excrete exopolysaccharides and enhance saline soil stability [64]. Cyanobacteria can contribute to

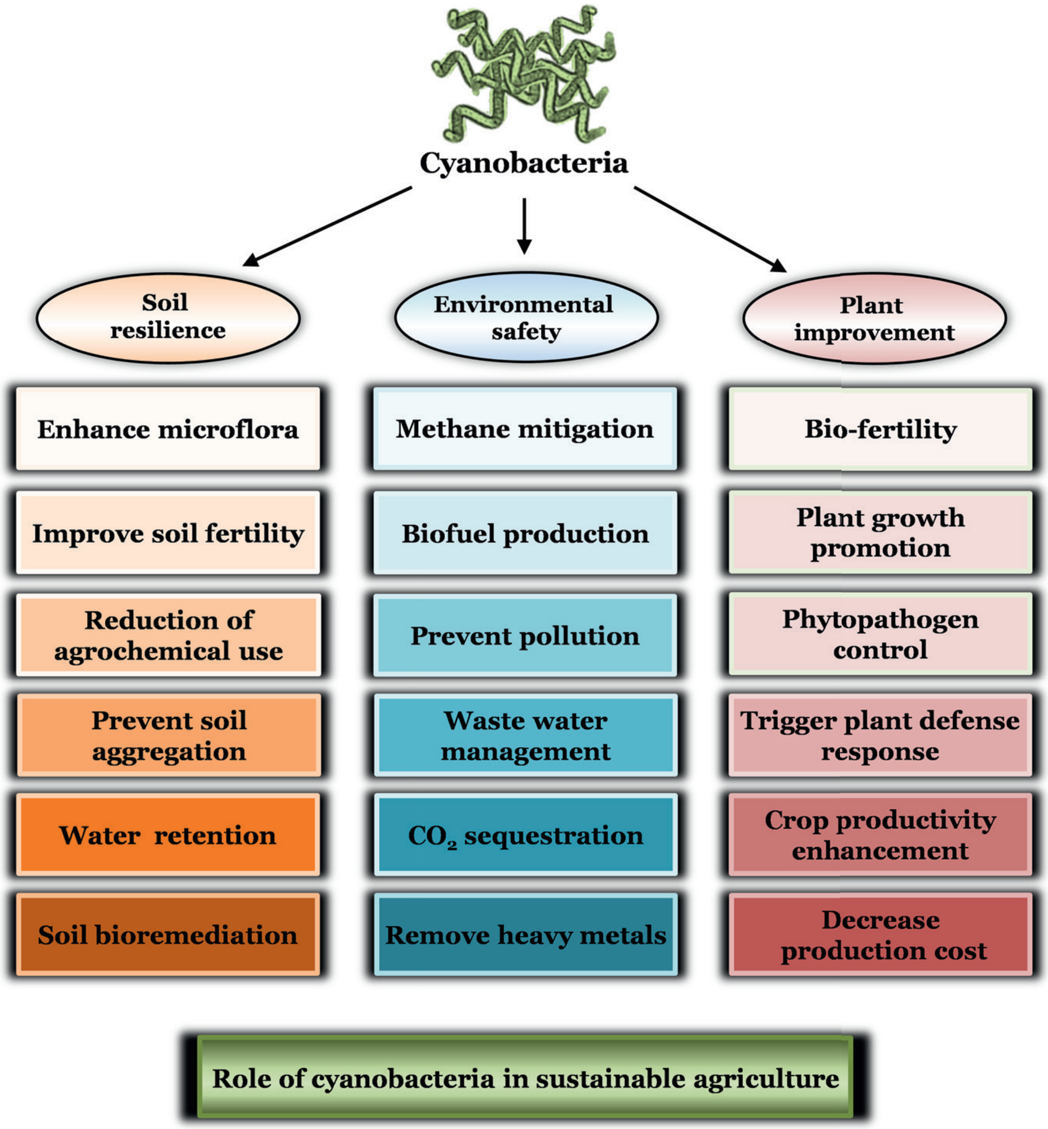

Figure 4.
An overview of the cyanobacterial role in sustainable agriculture and environmental safety.

the improvement and recovery of infertile soils by releasing holding and aggregation of soil particles together, the accumulation of organic content, and an increase in the water-holding capacity of the upper soil layer [65]. Rossi et al. [66] reported that the addition of cyanobacteria to the soil will improve soil properties and texture by adjusting soil stabilization, nutrients, moisture-holding capacity, and crust formation. The micromorphological characteristics of soil were improved after 6 weeks of the application of cyanobacteria combined with polysaccharides [67]. Chamizo et al. [35] demonstrated that the application of cyanobacteria can improve dry land functions through restoration and reestablishment. Cyanobacteria contribute to improving the properties of hard-to-cultivable lands, such as calcareous and saline soils, and making them suitable for cultivation.

5.2 Phosphorus uptake

Phosphorus is the second most important nutrient for plants after nitrogen. It is a crucial mineral for the growth and development of plants. It is one of the essential components of a live cell since it serves as the primary structural support for DNA, RNA, and ATP [68]. Phosphate is frequently supplied to the soil in the form of phosphatic fertilizers. However, plants only use a small portion of this nutrient since a large portion of it is quickly converted to insoluble complexes in the soil that plants cannot utilize. With the help of phosphatase enzymes, cyanobacteria can solubilize and mobilize the insoluble organic phosphates present in the soil, for example, ferric phosphate, aluminum phosphate, tricalcium diphosphate, and hydroxyapatite into soluble forms and improve the bioavailability of phosphorus to the plants [69]. The use of cyanobacteria in crop fields plays a significant role in the mobilization of inorganic phosphates by extracellular phosphates and the excretion of organic acids. Cyanobacteria enhanced the decomposition and mineralization of phosphate and transformed it into readily available soluble organic phosphates.

5.3 Degradation of agrochemicals

Control of agricultural pests and weeds depends on the use of agrochemicals, for example, pesticides, fungicides, bactericides, insecticides, and herbicides. This leads to maintaining global food production by killing agricultural pests, but at the same time, these pesticides pollute the environment. Biological intervention for many beneficial microorganisms, including cyanobacteria, is involved in removing the chemical residues [70]. Cyanobacteria can be used to get rid of various pollutants, such as heavy metals, pesticides, chemical fertilizers, and crude oil [71]. Cyanobacteria are also able to remove heavy metals from water bodies and can reduce the increase in nitrates and phosphates from agricultural fields [72]. Intensive use of pesticides leads to an imbalance in the environmental system, especially in soil, water, and air. Currently, the use of beneficial microorganisms, especially cyanobacteria, is considered the best way to eliminate pesticides and chemicals that pollute agricultural soil. Cyanobacteria have the ability to break down pesticides at a faster rate. This requires some processes, such as adding the necessary nutrients or organic materials, to accelerate the rate of decreasing pollutants by the cyanobacteria, which have growth activities that exceed the chemical roads in addition to being environmentally friendly [73].

Among the different compounds used for agricultural applications the phosphorous-organic pesticide category. The random use of such chemicals causes many environmental problems. It also poses a great danger to other organisms, such as birds, fish, animals, and humans. As a result, it is highly recommended that these hazardous chemicals be removed from the environment in an appropriate manner. Cyanobacteria are one of the best applications of beneficial microorganisms because it breaks down toxic chemicals into nontoxic compounds. The widespread appearance of cyanobacteria in the polluted area is a contributing factor, making them a better candidate for biological decomposition [8].

6. The role of cyanobacteria in controlling phytopathogens

Plants can be attacked by bacteria, fungi, viruses, and nematodes at different stages of growth, causing severe harm to the root system, stem, leaves, and fruits. Chemical pesticides were the best approach to decrease the damage of these diseases, but pesticides have many negative effects over time. The use of biological alternatives, for example, cyanobacteria, has become a necessity to preserve the safety of the environment and the quality of crops. The major strategies used by cyanobacteria to attack plant pathogens are antibiosis, the release of chemical compounds that may have the potential to inhibit a variety of phytopathogens, competition for space, and activation of plant defense responses. Cyanobacteria are distinguished by producing a huge number of bioactive substances (**Figure 5**). Thus, cyanobacteria provide a significant, safe alternative to avoid the harmful effects resulting from chemical control. It is a critical tool in sustainable agriculture [7].

Several plant fungi can be effectively controlled by cyanobacterial extracts, for example, *Fuarium* spp., *Verticillium* spp., *Alternaria* spp., *Penicillium* spp., *Botrytis cinerea*, *Rhizoctonia solani*, and *Sclerotinia sclerotiorum* [6]. Two orders of cyanobacteria, the Nostocales and Oscillatoriales, are very effective against fungal pathogens. Among Nostocales, two species, *Anabaena minutissima* and *Anabaena variabilis* are active in preventing the spread of airborne diseases [74, 75]. Airborne fungal pathogens produce a significant number of spores, which are considered the main source of spread. Therefore, inhibiting spore germination could play an effective role in controlling the disease and preventing secondary infection. Spraying of *A. minutissima* on cucurbit plants can reduce the symptoms of powdery mildew caused by *Podosphera xanthii*; also, infected areas of cucumber leaves and spore production decreased by 31% and 47%, respectively [75], while the disease was inhibited by 25% on zucchini [74]. *A. variabilis* has effective antibiosis against *R. solani* and *F. moniliforme* pathogens that infect tomato seedlings [76]. Also, *A. variabilis*, *N. linckia*, and *N. commune* have the same antibiosis effect on tomato wilt disease caused by *F. oxysporum* f. sp. *lycopersici* [76–78]. *Anabaena* sp. has an antibiosis against *P. xanthii*, which causes powdery mildew in zucchini plants [79]. *N. entophytum* and *N. muscorum* considerably decreased the activity of *R. solani* in soybean by an antibiosis mechanism [24]. Additionally, *Oscillatoria agardhii* has an antibiosis against *F. solani*, *Macrophomina phaseolina*, and *R. solani*, which cause the damping off disease in lupine seedlings [80].

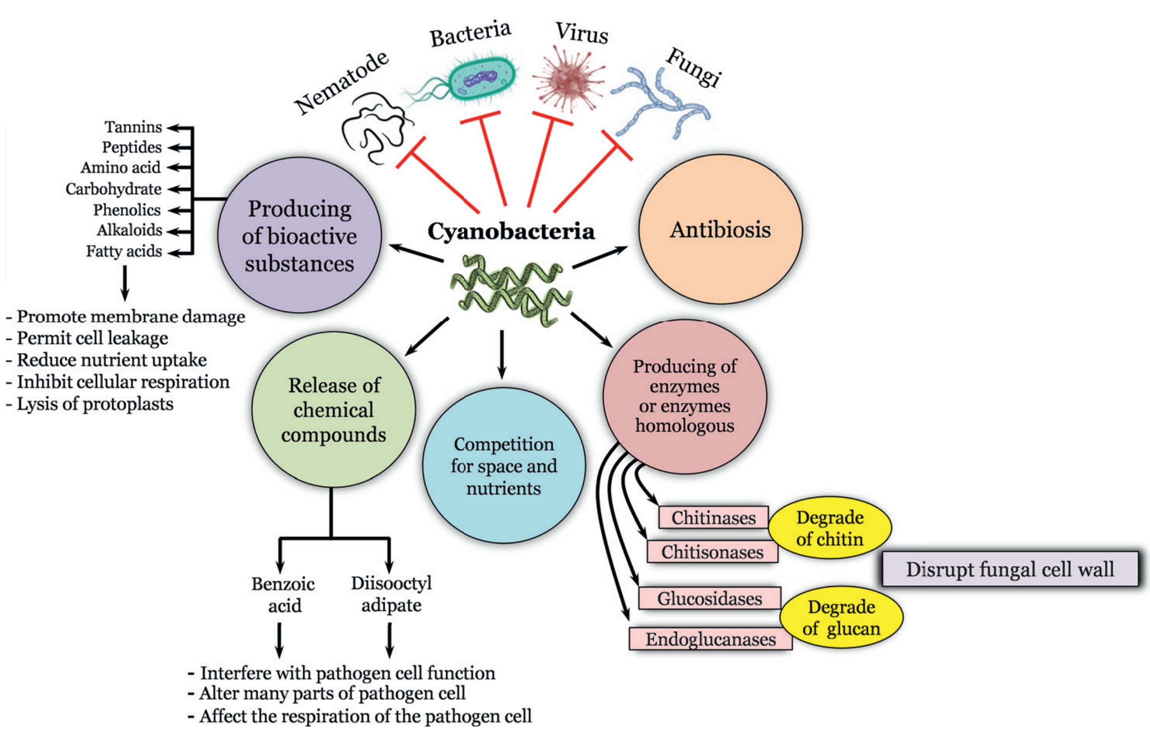

Figure 5.
Mechanisms of antimicrobial activity of cyanobacteria against phytopathogens.

The presence of diisooctyl adipate, extracted from *N. piscinale* and *A. variabilis*, is one strong indication that cyanobacteria contain chemical compounds active against *R. solani*, the causative agent of rice sheath blight, which causes severe damage in rice fields in China [81]. *Anabaena* spp., *Scytonema* spp., and *Nostoc* spp. have antifungal and toxic activity against soil-borne fungi [82]. *Rhizopus stolonifer*, *Phytophthora capsici*, *Pythium ultimum*, *Botrytis cinerea*, *Colletotrichum gloeosporoides*, *Fusarium oxysporum*, and *Alternaria solani* are all considerably inhibited by *Nostoc commune* methanolic extracts [83]. Additionally, methanolic extracts of *Spirulina platensis* effectively prevent the growth of *Helminthosporium* spp., *Alternaria brassicae*, *Aspergillus flavus*, and *Fusarium moniliforme* [84, 85].

Cyanobacteria can produce enzymes that directly act against the pathogen's cell wall. *Anabaena* sp. and *Calothrix elenkinii* can produce chitinases and chitisonases against pathogens, *F. moniliforme*, *F. solani*, *F. oxysporum*, *A. solani*, *M. phaseolina*, and *R. solani* and significantly reduce disease [86, 87]. Endoglucanases and glucosidases are two other enzymes that *Anabaena* sp. and *C. elenkinii* release. These enzymes can disrupt the cell walls of different plant pathogens by degradation of chitin and glucan, respectively [88]. In addition, Gupta et al. [89] reported that the antifungal properties of cyanobacteria are attributed to the production of endoglucanase, chitosanase homologs, and benzoic acid. Benzoic acid has the ability to interfere with fungal cell functioning, alter many parts of the cell, and has an effect on the respiration of the fungal cell [90]. Cyanobacteria can compete for space in the rhizosphere by forming biofilms at the roots and blocking sites of infection for soil pathogens, such as *Anabaena* sp., against *R. solani* in cotton roots [91].

On the other hand, they activate the defensive responses of the plant directly against fungal pathogens, such as *A. variabilis* or *A. laxa*, which enhance the activity of defense and pathogenesis-related enzymes in tomato roots against *F. oxysporum* f. sp. *lycopersici* [92], or by the activation of systemic resistance, such as *N. muscorum* and *A. oryzae,* that increase total phenol content and the activities of peroxidase, superoxide dismutase, and polyphenol oxidase enzymes in tomato leaves against *A. solani* [93].

The ability of cyanobacteria to combat various plant pathogenic bacteria and their ability to release compounds into the environment has been extensively studied [94]. The mechanism underlying the bactericidal action of cyanobacteria is attributed to the presence of tannins, amino acids, phenolics, alkaloids, carbohydrates, and fatty acids, which may cause bacterial membrane deterioration that eventually allows cells to leak, lowers nutrition intake, and prevents cellular respiration [95]. *Pseudomonas aeruginosa* is capable of infecting the roots of *A. thaliana* and *Ocimum basilicum*, causing plant death [96]. Nostoc sp. was effective in controlling *P. aeruginosa* due to the presence of long-chain fatty acids [97]. Additionally, *Anabaena flos-aquae* can completely suppress *Ralstonia solanacearum,* which causes brown rot disease in potatoes due to the production of antibiosis that is released into the environment [98]. Yanti et al. [99] found that cyanobacteria were able to stop *Ralstonia syzygii* subsp. *indonesiensis*, which is the cause of many vascular diseases in different crops.

Cyanobacteria possess antibiosis mechanisms against plant pathogenic nematodes that include paralysis, death, accelerating egg hatching, and inhibiting gall formation against plant harmful nematodes. *Heterodera cajani*, *Heterodera avenae*, *Meloidogyne graminicola*, *Meloidogyne incognita*, and *Rotylenchulus reniformis* can all be immobilized and killed by aqueous extracts of *Synechococcus nidulans* [100]. *Nostoc calcicola*, *Spirulina* sp., and *Anabaena oryzae* can lessen the quantity of nematode galls and egg masses in the cowpea rhizosphere [101]. *M. incognita* and *M. triticoryzae* are nematostatically inhibited by *Aulosira fertilissima* [102]. Additionally, *M. incognita* eggs are inhibited from hatching by the cyanobacteria species *Anacystis nidulans*, *Oscillatoria fremyii*, and *Lyngbya* sp. [103]. Furthermore, *M. incognita* in the tomato rhizosphere can be eliminated by an aqueous extract of *Calothrix parietina* [104]. Additionally, *Microcoleus vaginatus* has the capacity to lower *M. incognita* populations in the tomato rhizosphere and reduce root galling [105]. By coming into touch with plant roots, cyanobacteria can trigger several nematode defense mechanisms in plants. In order to combat *M. incognita*, *S. platensis* increases the catalase activity in the roots of banana plants [106] and stimulates the production of the plant defense compound jasmonic acid in tomato plants [107].

7. Conclusion

The presence of cyanobacteria in the soil is a positive indicator of the availability of organic matter, the support of oxygen, and the synthesis of hormones, amino acids, and vitamins, in addition to increasing the solubility of phosphates and enhancing the efficiency of fertilizers in plants while reducing the soil content of oxidants and salinity. Additionally, it plays a crucial role in nitrogen fixation, which is a major source of plant nutrition. Moreover, cyanobacteria promote the production of plant hormones and play an important role in combating many phytopathogens as antifungal, antibacterial, antinematode, and antiviral. It is clear from the above that cyanobacteria play an integral role in the sustainability of agriculture, as they work to improve the physiology of the plant and protect it against abiotic stress and attack by phytopathogens. Therefore, cyanobacteria should be applied on a larger scale in modern agricultural systems.

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Conflict of interest

The authors declare no conflict of interest.

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