Chapter 18
Cyanobacteria as Biofertilizer and Their Effect Under Biotic Stress

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Contents

1 Introduction

Cyanobacteria, also known as blue-green algae, were the first organisms that created molecular oxygen and transformed the biosphere from anaerobic to largely aerobic. Many cyanobacteria have a very wide distribution. Thanks to these features, they are considered as a model organism that enables us to learn about microbial biogeography and evolution (Gupta et al. 2013; Prasanna et al. 2009; Ahmed et al. 2010).

Cyanobacteria have been identified as important inhabitants of many agricultural soils that potentially contribute to biological nitrogen fixation, phosphate dissolution, mineral release to increase soil fertility, and crop productivity (Singh 2014). They produce and secrete a variety of biologically active substances, such as proteins, vitamins, carbohydrates, amino acids, polysaccharides, and phytohormones, which act as signal molecules to support plant growth. So, they protect plants against environmental stress. It is determined that the related bacteria are also found

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in cultivated fields. Identification of dominant strains effective in plant growth was found important for plant production (Osman et al. 2010; Prasanna et al. 2009).

Cyanobacteria show antagonistic activity against many plant pathogenic fungi. The application of cyanobacteria as biological fertilizers reduced the disease severity caused by the pathogen in many plants (Küçük and Sezen 2019).

2 General Features of Cyanobacteria

Cyanobacteria members are the oldest oxygen-producing photoautotrophs on earth. Plant chloroplasts evolved from cyanobacteria through the process of endosymbiosis. Cyanobacteria are known as blue-green algae, which is commonly confused with algae because it shares traits with algae and bacteria, because of the C-fucocyanin, a blue-green pigment they contain (Yadav et al. 2017) (Table 18.1).

Their cell structures are simple, and individual cells can also exist as spheres, courses, or flat colonies. The most common form of the colonies is a filament. The colonies can contain several cells or several thousands of cells in a mucilage sheath. Threads of cyanobacteria are called "trichomes." There is no organization or division of labor between cells in the threads. However, it is seen that some cells grow and take a homogeneous appearance, and structures called "heterocyst" occur. A thick wall, enriched with nutrients, surrounds some of the cells, and structures resistant to unfavorable conditions called "akinetes" are formed. In some cells, real branching is seen, while in other cells, false branching is also observed. In some species, it is seen that the trichome thinners from the bottom to the end and there is a heterocyclic at the bottom (Mishra et al. 2013).

Since cyanobacteria cells have a prokaryotic organization, they do not have any membrane organelles. The cell wall is similar in structure and function to Gram-negative bacteria (Whitton and Potts 2012; Mishra et al. 2013). The cytoplasm structure consists of two different layers, namely, chromoplasm and centroplasm.

Table 18.1 General characteristics of algae (on the left) and bacteria (on the right). Cyanobacteria have combination characteristics that come from algae and bacteria (middle column) (adapted from https://www.deq.ok.gov, DEQ n.d.)

Algae	*Cyanobacteria*	*Bacteria*
• Eukaryote • Photosynthetic • Unicellular and multicellular • Can be filamentous • Found only in aquatic environments • Does not produce toxins • Can form visible colonies in water	• Prokaryote • Photosynthetic • Unicellular and multicellular • Can be filamentous • Found in many diverse habitats • Capable of producing toxins • Can form visible colonies in water	• Prokaryote • Non-photosynthetic • Unicellular • Found in many diverse habitats • Capable of producing toxins • Can cause increased turbidity, not visible colonies

Chromoplasm is a colorful and networked structure with uncertain boundaries around the centroplasm. Generally, it does not have a vacuole and is immobile. As a chemical structure, RNA is dispersed, and assimilation pigments have a lamellar structure. However, they are not homogeneously disperplastics as plastids surrounded by a real membrane. Centroplasm is colourless and located in the centre. Its chemical structure consists of DNA; it contains elements in the form of a stick, reticular, or thread. All of these correspond to the nucleus and are called chromatin devices. There is no real nucleus (Shevela et al. 2013).

There is only chlorophyll-a from chlorophylls in cyanobacteria. Among the carotenoids, they contain β-carotene and E-carotene. Cyanobacteria often have all the types of xanthophylls and lutein. They contain C-fucocyanin and allophycocyanin, which are phycobilins. The color of *Cyanophyta* is mostly bluish green, olive green, and yellow brown. Cyanobacteria take the blue-green color from fucocyanin. There is also a small amount of phycoerythrin (Takaichi et al. 2009; Singh 2014).

Food storage substances in chromoplasma are glycogen, cyanophilin from proteins, and volutin. Nitrogen constitutes 8% of the dry weight of blue-green algae.

Reproduction in cyanobacteria occurs by dividing the cells into two, as in bacteria. Colony-forming species are seen cell division, and asexual reproduction occurs in a type of fragmentation. In some of the filamentous species, with the death of the cells in between, the thread breaks down into several cells. These parts are called "hormogonium." Hormogoniums occur in abnormal conditions and develop and form the thread when the conditions are favorable (Cohen and Meeks 1997).

2.1 Ecology and Phylogeny of Cyanobacteria

Cyanobacteria have spread to all parts of the earth. They live in freshwaters and seas. Some of their species are planktonic. Some species are benthic; they live on the grounds of streams, lakes, pond waters, and marshes. In suitable conditions and seasons, some of the planktonic species can over-proliferate and cause the death of fish and other aquatic organisms due to the toxic substances that appear. Some species of cyanobacteria are found in moist soils and on rocks that leak water as a blackish-mucilage cover. They also live on bare rocks on the shores of the seas, bark, and arctic regions (Nagarajan et al. 2011). In addition to their association with plants, they can develop epiphytically on bark, leaves, roots, and stems of submerged areas (Aguiar et al. 2008; Boopathi et al. 2013). They are the most abundant algae after diatoms on the soil surface and below. There are also species living in the dark cave walls as they show chromatic adaptation according to the light intensity. Some species live at 75–85 °C in hot water sources. There are also species living in deserts, poles, snow, rarely in salt waters, and oceans.

Cyanobacteria provide nitrogen for the growth of the plant partner. It has been explained that cyanobacteria can convert atmospheric nitrogen to ammonium form with nitrogenase enzyme, and ATP is used in this conversion (Magnuson 2019):

$$N_2 + 8H^+ + 8e^- + 16MgATP \rightarrow 2NH_3 + H_2 + 16MgADP + 16Pi$$

Species belonging to some blue-green algae genus (*Chroococcus*, *Gloeocapsa*, etc.) live symbiotically with fungi and form "lichens." Some species of *Anabaena* and *Nostoc* also live symbiotically with some species of ferns, Gymnosperm and Angiosperms. Cyanobacteria are known to affect tallus morphogenesis in lichens (Singh et al. 2016; Singh 2014). It is known that cyanobacteria, especially those that form symbiotic relationships with plants, secrete protein from carbohydrate-rich arabinogalactan. It has been found that these proteins act as signaling molecules which do not play an important role in the regulation of plant growth and development (Abdel-Raouf et al. 2012). The secretion of phytohormones by cyanobacteria begins with the formation of a symbiotic relationship (Singh et al. 2016).

Nitrogen fixation is an important feature of cyanobacteria. Various species can physiologically detect the free nitrogen of the air. Cyanobacteria are similar to bacteria in these aspects. Apart from cyanobacteria, no other algae group has this feature. The nitrogen-binding species in the structure of lichens give nitrogen they detected to the fungus (Zehr 2011; Stal 2013).

Base compositions of DNA molecules belonging to different cyanobacteria have been determined. GC rates of cyanobacteria with unicellular form vary between 35 and 71%. This ratio indicates that this group includes a very large group of organisms that have very few genetically related relationships. On the other hand, DNA ratios of DNA molecules of the cyanobacteria group that form the heterocysts very much less (between 38 and 46%). Cyanobacteria are grouped with their morphological lines as well as phylogenetic features. Unicellular cyanobacteria are very broad phylogenetic, and different representatives show phylogenetic relationship with different morphological groups (Yadav et al. 2017; Chittora et al. 2020).

3 Biofertilizers

Agricultural systems that use more inputs for high yields cause environmental problems and depletion of natural resources. The rapid production increase caused by the application of chemicals decreases gradually, and a healthy agriculture system becomes inevitable. The production of clean foods without agricultural chemicals is compulsory for the future of humanity and natural resources. Plant nutrients are essential for crop and healthy food production, given the growing population of the world. Today, agricultural strategies are mainly carried out on inorganic chemical-based fertilizers, which pose a serious threat to the environment and human health (Itelima et al. 2018). Biofertilizer is used as an alternative way to increase soil fertility and crop production in sustainable agriculture. The use of beneficial microorganisms as biofertilizers is crucial for the agricultural sector, given their potential in food safety and sustainable crop production (Vessey 2003). Research is ongoing to make biofertilizers an important component of nutritional management. According to a report by the FAO published in 2006, biofertilizer is a substance used for products containing microorganisms that fix atmospheric N or secrete growth-promoting substances that help dissolve soil nutrients (FAO 2006).

Nitrogen fixers (N-fixer), potassium and phosphorus solubilizers, plant growth-promoting rhizobacteria (PGPRs), endo- and ectomycorrhizal fungi, and cyanobacteria are commonly used as biofertilizer components (Fig. 18.1) (Ansari and Mahmood 2017; Zakeel and Safeena 2019). The use of biofertilizers provides improved nutrients and water intake, plant growth, and enhanced plant defense against abiotic and biotic stresses. These properties of biofertilizers play a very important role in soil fertility and environmental protection. Also, their low cost will benefit farmers economically (Itelima et al. 2018).

Biofertilizer is an alive, pure, or mixed microorganism formulation that, when applied to seed, plant surface, or soil, colonizes in the rhizosphere or enters the plant tissues, fixes atmospheric nitrogen, and increases soil uptake and plant nutrient uptake and vegetative growth (Chatterjee et al. 2017) (Fig. 18.2). Biofertilizers are cheaper than chemical fertilizers, do not show toxic effects to plants, do not pollute groundwater, do not increase soil acidity, and do not adversely affect plant development. The most prominent features of biofertilizers related to plant development are nitrogen fixation, making plant nutrients available, biological control of diseases, and secretion of plant growth stimulants. While a significant amount of fossil energy is used in chemical fertilizer production, energy is free in biological fertilization. The species that are active among the bacteria generally isolated from the rhizosphere are chosen by considering their adaptability to activity and environmental conditions and are stored for use in single or multiple species containing biological fertilizers. Reducing the use of excessive chemical fertilizers, potential nitrogen fixation and the use of phosphate-dissolving bacteria as biological fertilizers increases productivity in agricultural products. However, it is necessary to develop special plant-microorganism combinations that will show high efficiency in wide environmental conditions (Vessey 2003; Adesemoye and Kloepper 2009; Sinha et al. 2010; Khosro and Yosef 2012; Santos et al. 2012; Raja 2013; Youssef and Eissa 2014; Chun-Li et al. 2014).

As biofertilizers are living content and product content, quality of life and shelf life directly affect the availability or efficiency of biofertilizer.

Biofertilizer:

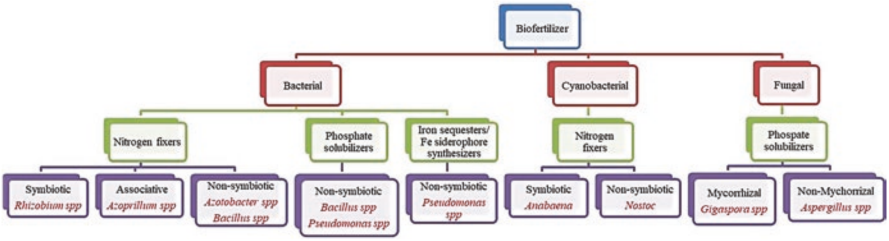

Fig. 18.1 Classification of biofertilizers. (Adapted from Zakeel and Safeena 2019)

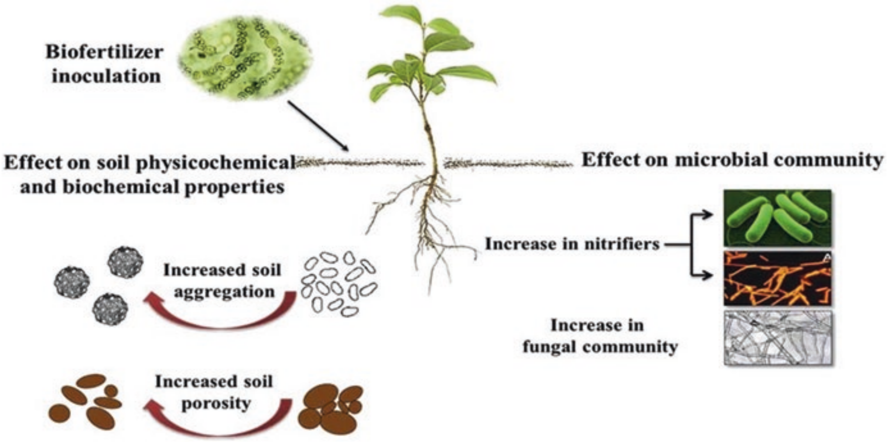

Fig. 18.2 Effects of biofertilizers on physiological and biochemical properties of soil

- Colonized in the rhizosphere when entering seed, plant surface, or soil or entering plant tissues.
- Fixing atmospheric nitrogen.
- A living, pure, or mixed microorganism formulation that increases soil.

These:

- Cheap cost.
- Do not show toxic effects to plants.
- Do not pollute groundwater.
- Do not increase soil acidity.
- Biologically controlling soil-borne diseases and secreting substances that stimulate plant growth (increase tolerance to environmental stresses) phosphorus, and uptake of plant nutrients and plant growth (Çakmakçı 2014).

Effective work of microorganisms occurs only when there are favorable and optimal conditions for them to metabolize their substrates. Some of these conditions are adequate water and oxygen (varies depending on whether microorganisms are aerobic or anaerobic), pH, and ambient temperature.

3.1 Types of Biofertilizers

According to the general classification in the FAO's report entitled "Plant Nutrition for Food Security" published in 2006, biofertilizers can be divided into four main categories:

1. **N-fixing biofertilizers**: These include *Rhizobium*, *Azotobacter*, *Azospirillum*, *Clostridium*, and *Acetobacter* bacteria; cyanobacteria; and fern *Azolla* (collaborating with cyanobacteria).
2. **P-solubilizer/activating biofertilizers:** Phosphate-solubilizing bacteria (PSB) and phosphate-solubilizing microorganisms (PSMs), for example, *Bacillus*, *Pseudomonas*, and *Aspergillus*. Mycorrhiza is a nutrient-activating fungus.
3. **Composting accelerators:** Cellulosic (*Trichoderma*) and ligninolytic (Humicola).
4. **Plant growth-promoting rhizobacteria (PGPRs)**: *Pseudomonas* species. PGPRs increase plant growth and performance.

Different types of biological fertilizers and related microorganisms are given in Table 18.2 (Itelima et al. 2018).

Among these, the groups of N-fixing organisms are the most important biological fertilizers used in plant growing. Another important biofertilizer is those containing P-dissolving organism cultures. Unlike industrial nitrogen fixation, biological nitrogen fixation involves the conversion of nitrogen (N2) to ammonia via microorganisms. Many microorganisms (e.g., *Rhizobium*, *Azotobacter*, and *Cyanobacteria*) reduce the atmospheric N_2 to ammonia (NH_3) using molecular N_2 with the help of nitrogen enzyme:

$$N_2 + 6H^+ + 6e^- \rightarrow 2NH_3$$

Biological nitrogen fixation is an important nitrogen source for plant life. Biological nitrogen fixation estimates range from 100 to 290 million tons N/year. It is estimated that 40–48 million tons of this total is biologically fixed in agricultural

Table 18.2 Types of biofertilizers and related microorganisms (Itelima et al. 2018)

Groups	Examples
	Nitrogen-fixing biofertilizers
Free-living	*Azotobacter*, *Beijerinckia*, *Clostridium*, *Klebsiella*, *Anabaena*, *Nostoc*
Symbiotic	*Rhizobium*, *Frankia*, *Anabaena*, *Azolla*
Associative symbiotic	*Azospirillum*
	Phosphate-solubilizing biofertilizers
Bacteria	*Bacillus megaterium* var. *phosphaticum*, *Bacillus subtilis*, *Bacillus circulans*
Fungi	*Penicillium* spp., *Aspergillus awamori*
	Phosphate-mobilizing biofertilizers
Arbuscular mycorrhiza	*Glomus* spp., *Gigaspora* spp., *Acaulospora* spp., *Scutellospora* spp., *Sclerocystis* spp.
Ectomycorrhiza	*Laccaria* spp., *Pisolithus* spp., *Boletus* spp., *Amanita* spp.
Ericoid mycorrhiza	*Pezizella ericae*
Orchid mycorrhiza	*Rhizoctonia solani*
	Plant growth-promoting rhizobacteria (PGPRs)
Pseudomonas	*Pseudomonas fluorescens*

crops and fields. Only nitrogen-fixing microorganisms supply an additional nutrient (N) to the soil plant system. Other biological fertilizers dissolve or activate the nutrients already in the soil. *Azolla* is an almost unique species when evaluated as a green fertilizer among nitrogen-fixing cyanobacteria. In this process, it does not only add the nitrogen it fixes biologically but also other nutrients it receives from the soil. While *Rhizobium* is specific to legumes, *Cyanobacteria* and *Azolla* are useful in increasing N supplies during flooded rice cultivation as they are abundant in wetlands (FAO 2006).

Some of the biofertilizers promote plant growth through the production of plant hormones. The production of hormones such as auxins, cytokinins, and giberellins has an effect on plant development and quality via direct and/or indirect mechanisms (Eşitken et al. 2003a, b; Elsheikh and Elzidany 1997).

Direct mechanisms:

- Biological nitrogen fixation.
- Reducing environmental stress.
- Harmony in a bacteria-plant relationship.
- Increasing the inorganic phosphorus solubility.
- Mineralization of organic phosphorus compounds.
- Increasing iron intake and increasing the ratio of some trace elements.
- Vitamin synthesis.
- Increasing root permeability.

Indirect mechanisms:

- Taking a role as biocontrol agents, reducing diseases with antibiotic production.
- In soils contaminated with various organic compounds, it is counted as protecting plants by breaking down barrier xenobiotics.

The main idea in biological fertilization is to reduce the use of chemicals to support agricultural sustainability, to protect natural resources and the environment, and to improve the quality. In its current state, biofertilizers cannot replace agricultural chemicals alone, but they reduce their usage rates and support ecological agriculture (Eşitken et al. 2003a, b; Elsheikh and Elzidany 1997).

4 Biotic Stress

Stress in plants is defined as all external factors that adversely affect the growth, development, or productivity. Plants are constantly subjected to environmental stresses due to their immobile structure. Stresses in plants cause a wide variety of events such as cellular metabolism, gene expression, changes in growth rates, crop yields, etc. Plants developed effective strategies and mechanisms to deal with environmental stresses. Stress response mechanisms contribute to stress resistance or stress tolerance at different morphological, biochemical, and molecular levels (Bakır 2020). The stresses to which plants are exposed are gathered under two

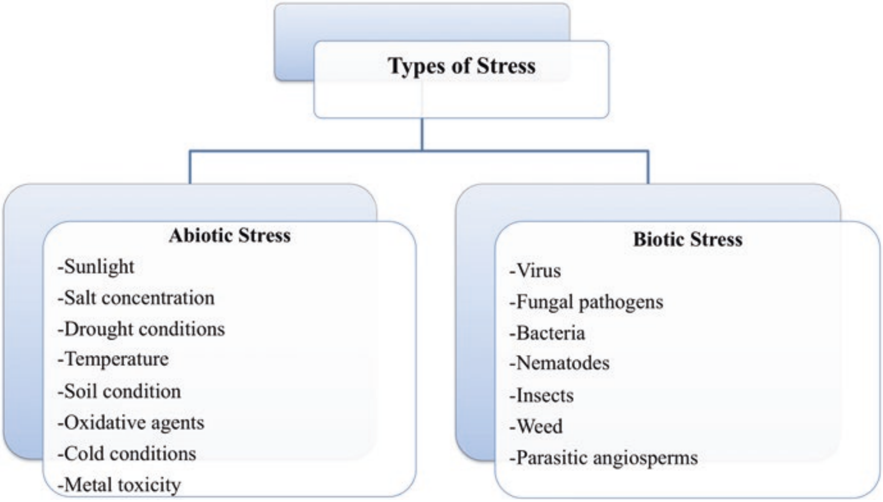

Fig. 18.3 Types of stress in plants

important topics. These are “abiotic” and “biotic” stresses (Fig. 18.3). Biotic factors are stresses caused by infection of microorganisms (fungi, bacteria, and virus) and attacks of harmful animals (Lichtenhaler 1996; Büyük et al. 2012). Abiotic stress factors are environmental factors including drought, cold, hot, salt, and nutritional deficiencies and are among the factors that decrease productivity in agricultural production. Biotic and abiotic stresses have been shown to reduce the average crop productivity by 65–87% depending on the crop type (Verma et al. 2013).

Viruses, bacteria, fungi, nematodes, insects, arachnids, and weeds are known as living organisms that cause biotic stress in plants. The organisms that cause biotic stress can lead to the death of plants by depriving their hosts of nutrients directly. Biotic stresses are very important for agriculture due to pre- and postharvest losses. Generally biotic stresses affect photosynthesis, because of chewing insects and virus infections, and reduce the rate of photosynthesis (Gull et al. 2019). The increase in the amount of pests and pathogens in nature can be caused by climate changes. For example, it is known that an increase in temperatures facilitates pathogen spread. At the same time, many abiotic stress conditions weaken the defense mechanisms of plants and thereby increase their susceptibility to pathogen infection (Suzuki et al. 2014).

Three different pathogen attack strategies have been defined (Koeck et al. 2011; Elad et al. 2011):

1. Necrotrophy: Plant cells are killed by pathogen infection (gray mold, *Botrytis cinerea*).
2. Biotrophy: In biotrophy the plant cells remain alive (powdery mildew, *Podosphaera aphanis*).

3. Semibiotrophy: The pathogen does not immediately kill the cells, causing them to die later in the infection, in this type (anthracnose, *Colletotrichum acutatum*).

Some pathogens that cause biotic stress in plants and their effects on the area they infect are given in the table below (Table 18.3) (Kanwar and Jha 2019).

Plants use highly complex defense systems against pathogen attacks. The defense mechanism has two types: innate and systemic plant response. However, the plant in two ways exhibits a natural defense: specific (specific to species/pathogen race) and nonspecific (non-host or general resistance). Nonspecific resistance is based on both structural barriers and inducible responses, including numerous proteins and other organic molecules produced before infection or during a pathogen attack. Structural defenses include morphological and structural barriers, chemical compounds, proteins, and enzymes. These compounds not only protect the plant from invasion but also give the plant strength and hardness, giving it tolerance or resistance to biotic factors (Onaga and Wydra 2016).

5 Usage of Cyanobacteria as Biofertilizer for Biotic Stress

Different microorganism groups associated with plants have been described to produce metabolites with beneficial effects on plants (Berendsen et al. 2012; Mendes et al. 2013). The harmful effects of pathogens on plants have been known for a long time. Studies reveal signals related to microorganisms promoting plant growth (PGPR = plant growth-promoting rhizobacteria), and plant communications have accelerated in recent years. PGPRs have been reported to release signaling compounds that can bind to receptor sites on the plasma membrane and cause activation of genes, leading to the synthesis of proteins and enzymes or secondary metabolites (Hussain et al. 2013). Many of the signaling compounds included in the phytochemical reaction belonging to the carbohydrate, lipid, glycolipid, or glycoprotein group have been identified (Yamaguchi and Huffaker 2011). Some of these compounds have been found to cause an increase in the accumulation of glucosinolates, alkaloids, polyphenols, flavonoids, flavonoid glycosides, saponins, terpenes, and phytoalexins, when applied to plants as spray or root treatments (Hussain et al. 2013; Rodriguez et al. 2006). These phytochemicals protect plants from biotic and abiotic stress and help plants develop resistance to these stresses (Shan et al. 2012; Sokolova et al. 2011).

When studies on microorganisms that support plant growth are examined, it has been determined that the most researched studies are rhizobacteria, symbiotic rhizobia, and mycorrhizal fungi. In recent studies, it is seen that another group of microorganisms that encourage plant development is cyanobacteria (Mendes et al. 2013; Willis et al. 2013). In recent studies, data affecting the gene expression of host plants have been obtained with the signals produced by cyanobacteria; thus it has been determined that various changes occur in the phytochemical structures of plants (Manjunath et al. 2010; Singh et al. 2016; Yadav et al. 2017). The

Table 18.3 Some biotic stresses and their effect in plants (Kanwar and Jha 2019)

Pathogen	Plant	Effect	References
Bacteria			
Pseudomonas syringae	Soybean	Reduced photosynthesis	Zou et al. (2005)
Xanthomonas campestris pv. vesicatoria	Tomato	Reduced photosynthesis	Kocal et al. (2008)
Pseudomonas syringae	Arabidopsis	Reduced photosynthetic rate at the infection site	Bonfig et al. (2006), Berger et al. (2007), de Torres Zabala et al. (2015)
Viruses			
Tobacco mosaic virus	Tobacco	Photo inhibition and photo oxidation of chlorophyll in infected cells	Balachandran et al. (1994)
Cucumber mosaic virus	*Cucurbita pepo*	Reduced photosynthesis, starch mobilization, and alteration in metabolism	Tecsi et al. (1996)
Potato virus Y	Tobacco	Accumulation of soluble sugars	Herbers et al. (2000)
Abutilon mosaic virus	*Abutilon striatum*	Carbohydrate accumulation in leaves during early symptom development	Lohaus et al. (2000)
Pepper mild mottle virus (PMMoV)-I	*Nicotiana benthamiana*	Increase in NPQ values of the areas invaded by the pathogen	Pérez-Bueno et al. (2006)
Rice stripe virus	Rice	Repression of genes related to photosynthesis	Cho et al. (2015)
Strawberry vein banding virus (SVBV)	*Fragaria vesca*	Altered photosynthesis	Chen et al. (2016)
Grapevine leafroll-associated virus 3 (GLRaV-3)	*Vitis vinifera*	Reduced photosynthesis and altered expression of genes related to sugar metabolism	Vega et al. (2011), Montero et al. (2016)
Bean common mosaic virus (BCMV)	*Phaseolus vulgaris*	Repression of genes related to photosynthesis and carbohydrate metabolism	Martin et al. (2016)
Herbivores attack or wounding			
Caterpillar	Wild parsnip	Reduced CO_2 assimilation in the attacked leaf is proportionally greater than the leaf area that is actually damaged	Zangerl et al. (2002)

(continued)

Table 18.3 (continued)

Pathogen	Plant	Effect	References
Manduca sexta	*Nicotiana attenuata*	Repression of genes related to photosynthesis, while induction of genes related to carbohydrate metabolism	Hui et al. (2003)
Mechanical wounding or (*Choristoneura occidentalis* or *Pissodes strobi*)	*Picea sitchensis*	Repression of genes related to photosynthesis	Ralph et al. (2006)
Trichoplusia ni	Arabidopsis	Reduced maximum quantum efficiency of photosystem II and increased dark respiration rates	Tang et al. (2006)
Mirid bug (*Tupiocoris notatus*)	*Nicotiana attenuata*	Increased photosynthesis	Halitschke et al. (2011)
Meloidogyne incognita	Tomato	Altered expression of genes related to primary metabolism	Shukla et al. (2017), Zhao et al. (2018)

development of phytochemicals has opened a new field of research that may have significant economic benefits for the agricultural industry. Studies on resistance induced to control plant diseases in laboratory, greenhouse, and field conditions enabled the commercialization of R&D products, thereby providing new-generation microbial fertilizers or product preservatives.

Bioactive compounds produced by cyanobacteria have been found to increase phytohormone levels, which are responsible for triggering the development of the subsoil and aboveground parts of the plant. It is also known that phytohormones regulate the enzymatic activities and metabolic changes that occur during plant growth. Therefore, the increase in the activity of peroxidase and phenylalanine ammonia-lyase enzymes from defense enzymes has also been linked to phytohormone levels (Tvorogova et al. 2013). The presence of jasmonic acid (JA) has been detected in cyanobacteria (Singh 2014). These bacteria have been reported to trigger the accumulation of abscisic acid (ABA), which ensures plant survival in stress conditions such as wilt, water stress, osmotic stress, and salt stress (Khan et al. 2012). Jasmonic acid and its various metabolites are known to be responsible for regulating plant development as well as plant reactions to abiotic and biotic stress (Khan et al. 2012). In addition, members of *Synechococcus*, *Anabaena*, *Nostoc*, *Calothrix*, *Scytonema*, and *Cylindrospermum* can produce ethylene (Singh et al. 2016). Flavonoids and phytohormones have been reported to aid plant-microorganism interactions (Jaiswal et al. 2018); these compounds increased root colonization of microorganisms (Kehr et al. 2011), providing an allelochemical effect on the population of other organisms (Khan et al. 2012). These also served as signal molecules (Kehr et al. 2011; Khan et al. 2012).

Cyanobacteria are used as biological fertilization of some rice cultures. It is known that over a hundred of cyanobacteria species fix N. Common cyanobacteria, *Nostoc*, *Anabaena*, *Aulosira*, *Tolypothrix*, and *Calothrix*, are used as biological fertilizers for rice (Chittora et al. 2020). Cyanobacteria also release plant growth substances such as IAA (indoleacetic acid) and GA (gibberellic acid) and improve polysaccharides that help bind soil particles (improving soil structure). These are also used as a soil conditioner and to protect the soil against erosion by entangled bulk formation (FAO 2006). The optimum temperature for cyanobacteria is about 30–35 °C. The pH of the soil is the most important factor in the growth of cyanobacteria and N fixation. The optimal pH for growth of cyanobacteria in the culture medium is 7.5–10, and the lower limit is around 6.5–7. The growth of cyanobacteria is better in neutral to alkaline soils under natural conditions. Cyanobacteria need all plant nutrients to grow and fix nitrogen (N). N-containing fertilizers often inhibit the growth and N fixation of cyanobacteria. Since phosphorus (P) increases the growth and N fixation of cyanobacteria, sufficient phosphorus must be present in irrigation water. Consequently, P deficiency causes a marked decrease in the growth of cyanobacteria and thus N fixation. Cyanobacteria vaccine can be prepared in the laboratory or open areas. The open-air soil culture method is simple, is less expensive, and can be easily adapted by farmers (FAO 2006).

Some cyanobacteria have been found to reduce the occurrence of a disease caused by plant pathogens in plants (Table 18.4), for example, culture filter and ethyl acetate extract of *Calothrix elenkinii* Kossinskaja; in pot experiments, it has been found that it decreases disease severity on *Pythium aphanidermatum* (Edson) Fitzp-infected soybean, tomato, and pepper seeds (Manjunath et al. 2010). It was investigated that damping-off disease in tomato seedlings inoculated with a group of fungal pathogens containing *Pythium debaryanum* R. Hesse, *Fusarium oxysporum* f. sp. *lycopersici* W.C. Snyder & H.N. Hansen, *Gibberella fujikuroi* (Sawada) Wollenw, and *Rhizoctonia solani* J.G. Kühn decreases with *Trichormus variabilis* (Kützing ex Bornet & Flahault) Komarek & Anagnostidis and *Anabaena oscillarioides* Bory ex Bornet & Flahault applications (Chaudhary et al. 2012). *Trichormus variabilis* and *A. laxa* A. Braun were found to produce a systemic defense response in tomato plants struggling with *Fusarium* sp. wilt. Some enzyme activities, phenylalanine ammonia-lyase, polyphenol oxidase, chitosanase, and β-1,3-glucanase, were found high in the tomato roots treated with cyanobacterial formulations. This situation revealed the importance of cyanobacterial interaction with tomato seedlings (Prasanna et al. 2013).

The use of bacteria that promote plant growth as biocontrol agents to be used against soil-borne plant pathogens has become very attractive in recent years for sustainable agriculture. These microorganisms reveal their induced systemic resistance (ISR), which strengthens the physical and mechanical of the cell wall and alters the synthesis of metabolites for defense against pathogens and the physiological and biochemical reaction of the host (Chaudhary et al. 2012).

6 Conclusions

Today, strategies that can help reduce chemicals used for agricultural products, a more economical product to be used instead of chemicals, and environmentally friendly agriculture are demanded. Various methods are tried to increase product

Table 18.4 Some cyanobacteria and their biocidal activities against plant pathogens (Kumar et al. 2019)

Cyanobacteria	Extract	Plant pathogens	References
Fischerella muscicola	Fischerellin	• *Uromyces appendiculatus* (brown rust) • *Erysiphe graminis* (powdery mildew) • *Phytophthora infestans* • *Pyricularia oryzae* (rice blast)	Hagmann and Juttner (1996)
Nostoc muscorum	Bis(2,3-dibromo-4,5-dihydroxybenzyl) (BDDE)	• *Sclerotinia sclerotiorum* (cottony rot of vegetables and flowers) • *Rhizoctonia solani* • *Candida albicans*	Borowitzka (1995)
Tolypothrix byssoidea	Antifungal peptides (dehydrohomoalanine, Dhha)	Antifungal activity against the yeast *Candida albicans*	Jaki et al. (2001)
Oscillatoria redekei syn. *Limnothrix redekei* HUB 051	Antibacterial fatty acids (α-dimorphecolic acid, a 9-hydroxy-10E,12Z-octadecadienoic acid (9-HODE), and coriolic acid)	Inhibited the growth of Gram-positive bacteria • *Bacillus subtilis* SBUG 14 • *Micrococcus flavus* SBUG 16 • *Staphylococcus aureus* SBUG11 and ATCC 25923	Mundt et al. (2003)
Nostoc sp.	Cryptophycin	Natural pesticides against the fungi, insects, and nematodes	Biondi et al. (2004)
Anabaena subcylindrica, *Nostoc muscorum*, *Oscillatoria angusta*	Efficient algal filtrate concentration (EAFC)	• *Alternaria alternata* • *M. phaseolina* • *F. saloni*	Abo-Shady et al. (2007)
Spirulina platensis, *Oscillatoria* sp., *Nostoc muscorum*		*Cercospora beticola* causing leaf spot of sugar beat	Mostafa et al. (2009)
Calothrix elenkenii	Ethyl acetate extract	*Pythium aphanidermatum*	Manjunath et al. (2010)
Lessonia trabeculata	Ethanolic extracts	Reduced number and size of the necrotic lesion in tomato leaves following infection with *Botrytis cinerea*	Jimenez et al. (2011)
Gracilaria chilensis (red algae)	Aqueous and ethanolic extracts	*Phytophthora cinnamomi*	Jimenez et al. (2011)
Durvillaea antarctica	Crude extracts	Tobacco mosaic virus (TMV) in tobacco leaves	Jimenez et al. (2011)

(continued)

Table 18.4 (continued)

Cyanobacteria	Extract	Plant pathogens	References
Anabaena variabilis RPAN59, *A. oscillarioides* RPAN69	Antifungal	• *Pythium debaryanum* • *Fusarium oxysporum lycopersici* • *F. moniliforme* • *Rhizoctonia solani*	Chaudhary et al. (2012)
Anabaena variabilis, *S. platensis*, *Synechococcus elongatus*	Butanol extract	• *Aspergillus niger* • *Alternaria solani*	Tiwari and Kaur (2014)
Nostoc muscorum, *Oscillatoria* sp.	Norharmane and α-isomethyl ionone	*Alternaria porri* (purple blotch of onion)	Abdel-Hafez et al. (2015)

yield. Cyanobacteria are abundant in agricultural areas and, especially in rice-cultivated soils, together with microalgae, are considered as microbial photosynthetic agents of the soil. Because of its important roles in nitrogen fixation, cyanobacteria are inevitable to be used in agriculture to increase vegetative production. Although there are several studies on nitrogen fixation abilities, their ecological roles are not fully understood. It has been determined that cyanobacterial inoculation in agricultural areas provides increased yield even in the presence of high doses of nitrogen fertilizers. In addition to increasing the nitrogen content of plants, cyanobacteria can be used to promote plant growth. For this reason, significant progress has been made in recent years in the development and application of cyanobacterial biofertilizers.

Biosynthesis of phytohormones, polysaccharides, vitamins, amino acids, and peptides is considered crucial for plant growth and development. Microorganisms release these active compounds in the rhizosphere where plant roots can absorb.

Cyanobacterial strains have been identified in studies that support the growth of the plant, usually by greenhouse and pot experiments performed under controlled conditions. New studies are needed to try cyanobacterial strains in field conditions. This chapter is expected to shed light on the work to be done in the application of cyanobacteria to agricultural fields.

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