

# Chapter 1

## Cyanobacteria and Algae as Biocontrol Agents Against Fungal and Bacterial Plant Pathogens



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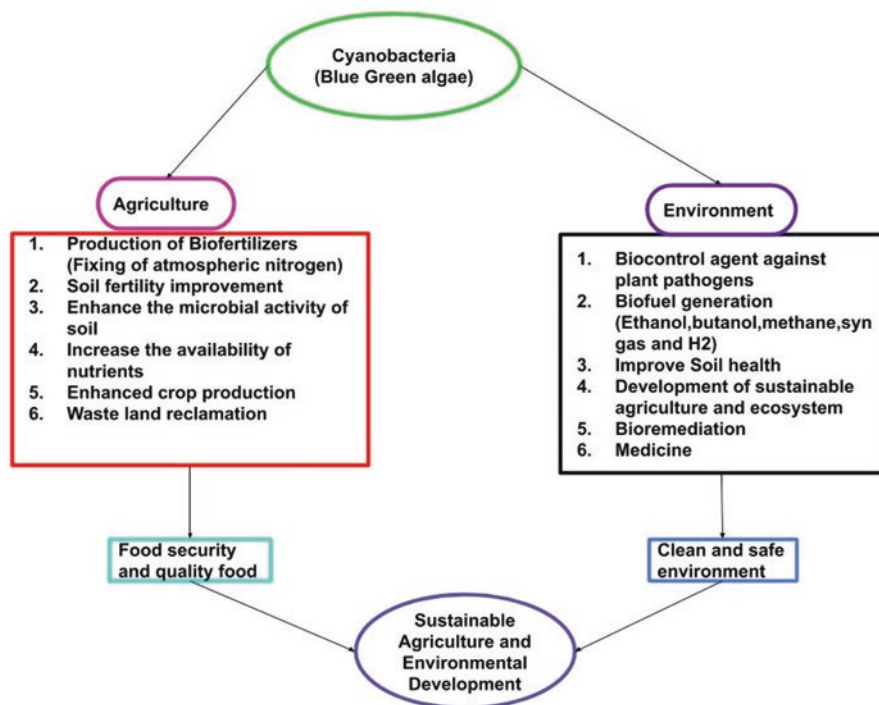
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## 1 Introduction

Present sustainable agricultural farming is severely reliant on an intensive use of tillages, excessive fertilizer use and irrigation, and chemical pesticides; with no doubt, the food requirement of the majority of countries has been fulfilled, even though this raised many health and environmental problems. Now the question of enhancing the crop production in agriculture sector without deteriorating the environment and harming water resources and land/soil fertility has arisen (Singh and Strong 2016). The need of quality environment and food crops production can be fulfilled with sustainable practices of agriculture (Singh and Strong 2016); this philosophy of sustainable agricultural production includes environmentally friendly farming with low cost through natural techniques of resources conservation, i.e. water and soil, maintaining the crop profitability and productivity and also making the agricultural ecosystem self-regulating and resilient (Koller et al. 2012). For the last few decades, green energy production of various processes of microbes has attained great attention as a sustainable technique for biofuel generation, namely, ethanol, butanol, methane (CH<sub>4</sub>), syngas and H<sub>2</sub>. Recent studies reported remarkable growth in cyanobacterial biomass production for biofertilizers; a different supplement of foods, i.e. superfoods; and biofuels for farming of safe agricultural production (Benson et al. 2014).

A highly diversified group of various microorganisms have been found in association to different plant species in the endosphere, rhizosphere and phyllosphere. These microorganisms associated to plants and known for metabolite production may have a neutral, beneficial or harmful impact on crop productivity (Mendes et al. 2013). Ever since, the approach of sustainable crop protection can be characterized by synthetic pesticide alternatives, i.e. derived compounds and microorganisms of plants (Gwinn 2018). Amongst all the alternatives, cyanobacteria and algae are distinguished bioactive agents which have gained a remarkable consideration by scientists globally.

Phytopathogenic biocontrol agents (Fig. 1.1) in the very wide-ranging sense encompass the methods for utilization of organisms except for human. Remarkable research literature can be found as a result of this long-lasting present strategy, with an impetus principle of the enhanced activity and limitations to the application of chemical pesticides. This also included high costs of purchase, concerns to the environment and the highly increased regulations and restrictions of governments. Cyanobacteria, autotrophic blue-green algae which are known to be the most diverse, largest and abundantly distributed group of small, prokaryotic, unicellular and photosynthetic organism, found specifically in fresh and marine water, all together with eukaryotic algae 'could have been the world's largest biomass'. As a promising biocontrol agent growing in huge colonies and causing plant diseases, no great attention has been attained by cyanobacteria (Pisciotta et al. 2010). Cyanobacteria with diversified sizes and shapes have covered 150 identified genera with the features of oldest-ever fossils of 3.5 billion years, approximately, and are responsible for the oxygenic environment of the current days (Hoekman et al. 2012).



**Fig. 1.1** The theoretical framework shows potential cyanobacterial functions in the environment or sustainable agriculture

A proposed classification of cyanobacteria since 1985, with four bacterial orders, has been recognized, namely, *Oscillatoriales*, *Chroococcales*, *Stigonematales* and *Nostocales*, with their phyla *Gloeobacterales*, *Pleurocapsales* and *Chroococcales*. Cyanobacteria are associated with the periods of origin of plants. The cyanobacteria are immensely important in determining the path of evolution and ecological changes all over the earth's history. In the late Proterozoic or the early Cambrian period, cyanobacteria began to take up residence within certain eukaryote cells, this event is called endosymbiosis, for the origin of the eukaryotes. They have the potential to fix atmospheric nitrogen, so that could be used as a biofertilizer for the cultivation of economically important crops such as rice and beans (El-sohaimy 2012; Meena et al. 2019; Koller 2015) (Fig. 1.1). Mostly, the eukaryotic algae have been categorized in 18 different taxonomic classes (Wainwright et al. 1993), where a majority of the algae can be found either in marine or in freshwater habitats and almost 147 genera have a large number of species found in soil. They are mostly photosynthetic; however, a great number are heterotrophic facultative species while few are non-photosynthetic (heterotrophic obligates). These are largely untapped and rich sources of a varied wide collection of naturally active products. This chapter is aimed to understand cyanobacteria as an alternative for sustainable development without the harmful effect of chemicals, synthetic fertilizers and other

pesticides/insecticides, to elaborate the antifungal and antibacterial activities of cyanobacterial extract against pathogenic colonial growth and to study the role of Cyanobacteria as a source of exopolysaccharides to improve soil structure and microbial growth.

## 2 Cyanobacteria and Algae Against Phytopathogens

Since a long time, cyanobacteria and algae have been used scarcely as beneficial extracts against pathogenic fungus because of their stimulation effect for plant productivity and vigour. They have also been used as media substrates for microbial cultures and biofuel production (Fig. 1.1). A fungal pathogen may be responsible for causing infection in cultivated cropping systems, severe postharvest losses and fruit decay. *Schlerotinia sclerotiorum* and various other species of *Fusarium*, *Rhizoctonia*, *Verticillium*, *Pythium* and *Phytophthora* are known to be the most significant polyphagous fungi found in soil (Pastrana et al. 2016). While hindering water absorption and nutrients in the soil, they directly attack root structures and cause wilting, damping off, yellowing, root rot and color rot. Amongst leaf-related pathogens, fungus of Erysiphales order are strong mediators of the disease powdery mildew causing huge economic losses, thus the need for various applications of chemicals (Romero et al. 2007; Jarvis et al. 2002). *Colletotrichum* spp. and *Botrytis cinerea* are the vectors for anthracnose and grey mould, respectively, and many other *Rhizopus*, *Mucor* and *Penicillium* species are the fungal pathogens which are responsible for postharvest losses and fruit decay (Husaini and Neri 2016). Such fungal pathogens could be controlled normally by the fungicidal applications during the time of growing crop cycle from the time of flowering to harvest time.

### 2.1 Cyanobacteria: A Prevalent Evolutionary Phylum

The most successfully emerged phyla of prokaryotes which were sustained during the evolutionary course were cyanobacteria. They are known to be the most primitive forms of life on the Earth planet, and their evidence reported chloroplasts with eukaryotic photosynthesis have their origin from cyanobacteria, bringing about the evolutionary aerobic respiration as long time ago (2.22–2.45 billion years) (Dixit and Suseela 2013; Gothwal and Bajpai 2012). Even though the autotrophic nutritional mode is more dominant while some of the species of cyanobacteria can grow well in dark and anaerobic environments including *Oscillatoria* and *Nostoc*, few cyanobacterial species, i.e. *Nostoc*, can also function in atmospheric nitrogen fixation (Yadav et al. 2011; Uzair et al. 2012). However, cyanobacteria can be included in those phyla where simple and unicellular structures have developed complex and multicellular structures during the evolutionary era (Schirrmeister et al. 2011). Extending from a range of unicellular gram-negative to colonial and multicellular filamentous forms (Singh et al. 2011), being the principal phytoplankton constituent, this provides sufficient opportunity to exploit them as a secondary metabolite

producer. Along with so many applications in nutraceuticals, pharmaceuticals, food and feed industries, the ecological, morphological and genetic cyanobacterial diversity has led to the wide array of compound production (Tan 2007).

### 2.1.1 Antifungal Activity

Cyanobacteria have been found to be the most significant source of naturally occurring bioactive compound with antiprotozoal, antimicrobial, antibacterial, antiviral, anti-proliferative and anticancer activities (Dixit and Suseela 2013; Russo and Cesario 2012; Simmons et al. 2008). Many authors revealed efficiency against the growth of the fungal colony of various phytopathogens is among the different activities of cyanobacteria (Table 1.1). Many studies have observed numerous species of *Nostoc*, *Microcystis* and *Anabaena*. Crude source of ethanol extracted from *Anabaena laxa* reported an inhibitory effect and a counter to various fungi, namely,

**Table 1.1** Antifungal activity of cyanobacterial extracts on plant pathogenic colonial growth

Cyanobacteria	Pathogen	References
<i>Anabaena</i> sp.	<i>Alternaria alternata</i> , <i>Botrytis cinerea</i> , <i>Colletotrichum gloeosporioides</i> , <i>Fusarium oxysporum</i>	Kim (2006)
<i>Anabaena</i> sp.	<i>Macrophomina phaseolina</i> , <i>Fusarium moniliforme</i> , <i>Alternaria solani</i> , <i>Pythium aphanidermatum</i> , <i>Fusarium solani</i>	Prasanna et al. (2008)
<i>A. laxa</i>	<i>F. moniliforme</i> , <i>F. oxysporum</i> f. sp. <i>lycopersici</i>	Prasanna et al. (2015)
<i>Anabaena variabilis</i>	<i>F. moniliforme</i> , <i>F. oxysporum</i> f. sp. <i>lycopersici</i>	Prasanna et al. (2015)
<i>A. variabilis</i>	<i>Aspergillus Niger</i> , <i>A. solani</i>	Tiwari and Kaur (2014)
<i>Calothrix</i> sp.	<i>A. alternata</i> , <i>B. cinerea</i> , <i>C. gloeosporioides</i> , <i>F. oxysporum</i> , <i>Phytophthora capsici</i> , <i>Pythium ultimum</i>	Kim (2006)
<i>Microcystis aeruginosa</i>	<i>F. Oxysporum</i> , <i>M. phaseolina</i> , <i>P. aphanidermatum</i> , <i>Pythium oedochilum</i> , <i>Rhizoctonia solani</i>	Khalid et al. (2010)
<i>Microcystis aeruginosa</i>	<i>Aspergillus flavus</i> , <i>Fusarium verticillioides</i> , <i>Fusarium proliferatum</i>	Marrez and Sultan (2016)
<i>Nostoc</i> sp.	<i>A. alternata</i> , <i>B. cinerea</i> , <i>C. gloeosporioides</i> , <i>F. oxysporum</i> , <i>P. capsici</i> , <i>P. ultimum</i> , <i>Rhizopus stolonifer</i>	Kim (2006)
<i>Nostoc commune</i>	<i>F. oxysporum</i> f. sp. <i>lycopersici</i>	Kim and Kim (2008)
<i>Nostoc entophytum</i>	<i>R. solani</i>	Osman et al. (2011)
<i>N. muscorum</i>	<i>R. solani</i>	Osman et al. (2011)
<i>Chlorella</i> sp. <i>Halopithys</i> sp.	<i>R. solani</i>	Righini et al. (2020)
<i>Anabaena</i> sp. <i>Ecklonia</i> sp. <i>Jania</i> sp.	<i>Botrytis cinerea</i>	Righini et al. (2019)

*Candida albicans*, *Aspergillus oryzae*, *Saccharomyces cerevisiae*, *Trichophyton mentagrophytes* and *Penicillium notatum*. The colony growth of *Fusarium moniliforme* was reduced by 23 different *Anabaena* strains observed in a screening (Prasanna et al. 2008), whereas *Alternaria solani* and *Nostoc muscorum* were observed as an effective counter to *R. solani*, inhibited by 17 several strains. Different *Anabaena* and *Calothrix* strains carried action countering to various species of *Rhizoctonia* and *Pythium* (Manjunath et al. 2010). *Nostoc muscorum* is known to be effective against *R. solani*, and was effective and inhibited the colony growth more than *N. entophytum* (Osman et al. 2011). Among all the compounds synthesized by cyanobacteria, chitosanase homologues, endoglucanase and benzoic acid were detected, and their presence was correlated to the activity against fungi (Gupta et al. 2011). The terpenoid noscomin, as an extract of *N. commune*, was tested to function against *Escherichia coli*, *Bacillus cereus* and *Staphylococcus epidermidis* (Jaki et al. 2000). Methanolic extract taken from *M. aeruginosa* exhibited an activity of fungus contrary to seven different pathogens of human and eight saprophytic and five phytopathogens (Khalid et al. 2010). *M. aeruginosa* strain revealed the growth inhibition of *Aspergillus flavus* and *A. niger* and *Fusarium verticillioides* (Marrez and Sultan 2016).

### 2.1.2 Antibacterial Activity

Recently, nosocomial infections (Enterococci and *Staphylococcus aureus* resistant to vancomycin and methycillin, respectively, Amp C  $\beta$ -lactamase produced by Enterobacteriaceae) showing a big threat worldwide and a challenge to therapeutic studies are caused by bacteria resistant to multidrug (Reinert et al. 2007). Cyanobacteria having antibacterial activity and possibly energetic against bacteria are of great importance to scientists to produce new antibiotics (Biondi et al. 2008). Noscomin shows antibacterial activity against *Escherichia coli*, *Staphylococcus epidermidis* and *Bacillus cereus* taken from *Nostoc commune* (Jaki et al. 2000). Furthermore, stronger inhibition of green algae as compared to cyanobacteria was observed from isolated Nostocine A from *Nostoc spongiaeforme* (Hirata et al. 2003), while the growth of other cyanobacteria and green algae was introverted by *Nostoc*-isolated nostocarboline (Blom et al. 2006). Growth of *Salmonella typhi* MTCC3216, *E. coli* ATCC25992, *Mycobacterium tuberculosis* H37Rv, *Enterobacter aerogenes* MTCC2822, *Staphylococcus aureus* ATCC25923 and *Pseudomonas aeruginosa* ATCC27853 was inhibited by hapalindole isolated from *Fischerella* sp. and *Nostoc* CCC537, thus showing antimicrobial activity (Asthana et al. 2009).

### 2.1.3 Control of Diseases

Some studies are carried out on cyanobacterial activity on the suppression of plant pathogen both in plant (especially leaf portion) and soil. The activity of *R. solina* was significantly reduced by *N. entophytum* and *Nostoc muscorum*, which also

increased the survival rate, plant height, dry weight of root and shoot of soybean (Osman et al. 2011). Wilt disease of tomato caused by *F. oxysporum* was significantly controlled by *Nostoc linckia* when applied in soil (Alwathnani and Perveen (2012). Powdery mildew caused by *P. xanthii* in zucchini was significantly reduced by application of *Anabaena* sp. which also enhanced the defense enzyme activities (Roberti et al. 2015) which were also confirmed by Prasanna et al. (2015) in maize.

## 2.2 Algae

A varied assemblage of photosynthetic species mostly aquatic is known as algae. Algae mostly include green algae which are unicellular organisms (*Chlorella*) and seaweeds which are marine multicellular algae (*Sargassum*). Table 1.2 shows the

**Table 1.2** Classification of algae

Phylum/class	Alga species
Chlorophyta	<i>Caulerpa sertularioides</i>
	<i>Chlorella</i>
	<i>Ulva lactuca</i>
	<i>Zygnema czurdae</i>
	<i>Zygnema stellinum</i>
	<i>Zygnema tenue</i>
Phaeophyceae	<i>Ascophyllum nodosum</i>
	<i>Cystoseira myriophylloides</i>
	<i>Ecklonia</i> sp.
	<i>Ecklonia kurome</i>
	<i>Durvillaea potatorum</i>
	<i>Fucus spiralis</i>
	<i>Laminaria digitata</i>
	<i>Leathesia nana</i>
	<i>Padina gymnospora</i>
	<i>Pelvetia canaliculata</i>
	<i>Sargassum</i>
	<i>Sargassum filipendula</i>
	<i>Sargassum liebmannii</i>
	<i>Styopodium zonale</i>
<i>Undaria pinnatifida</i>	
Rhodophyta	<i>Corallina</i> sp.
	<i>Eucheuma denticulatum</i>
	<i>Gelidium pusillum</i>
	<i>Gracilaria edulis</i>
	<i>Halopithys</i> sp.
	<i>Kappaphycus alvarezii</i>
	<i>Porphyra umbilicalis</i>
<i>Rhodomela confervoides</i>	



different phyla that include red algae (Rhodophyta), chlorophyta (green algae) and Ochrophyta (brown algae) (Guiry 2012). Algal composition is effected by harvest season, compounds such as polysaccharides and geographic location (Schiener et al. 2015), essential nutrients (Cu, Zn, Mn, Co, Mo etc.) and plant hormones (auxins, abscisic acid and cytokinins (Craigie 2011). Furthermore, algae also show antiviral, antioxidant, antimicrobial and antifungal activities which have many applications in cosmetics, bioactive substances, pharmaceuticals and pigments production (Sharma and Sharma 2017). Due to all these properties, algal application plays an important role in soil fertility and crop productivity (Arioli et al. 2015) in different agronomic and horticultural crops (Alam et al. 2013). The increment in postharvest life, disease control and resistance to biotic and abiotic stresses was reported in fruits due to the application of various algal extracts (Esserti et al. 2017).

### 2.2.1 Antifungal Activity

Several studies have shown the direct importance of pathogen resistance by algal extract (brown algae) having antifungal activity. Mycelial growth of *Aspergillus* spp. and *Penicillium* spp. and *Fusarium oxysporum* was significantly reduced by cyclohexanic and aqueous extracts from *Sargassum* sp. (Khallil et al. 2015). Colonies of *Rhizoctonia* and *Fusarium solani* were inhibited by *Padina gymnospora* and *Sargassum laetifolium* which contain methanolic extract (Ibraheem et al. 2017). *Ascophyllum nodosum*, *stypopodium zonale*, *Fucus spiralis*, *Pelvetia canaliculata* and *Sargassum muticum* extracts contain terpenes and phenols which can suppress the growth of *Colletotrichum lagenarium* (Fernandes Peres et al. 2012). De Corato et al. (2017) reported that the mycelial growth and germination of spores of *Botrytis cinerea* were completely inhibited by *Undaria Pinnatifida* and *Laminaria digitata*. Furthermore, *Gracilaria edulis* that contains methanolic extract significantly inhibits the mycelial growth of *Macrophomina phaseolina* (Ambika and Sujatha 2015) while water extract obtained from *Gracilaria edulis* minimized infections of *Corallina* sp. and *Halopithys* in zucchini (Roberti et al. 2016). Brown algae (*Leathesia nana*) and red algae (*Rhodomela confervoides*) contain bromophenol bis(2,3 dibrom-4,5- dihydroxybenzyl) ether which is an antifungal substance which reduced *B. cinerea* growth and *Colletotrichum gloeosporioides* (Liu et al. 2014). An extract acquired from *Chlorella vulgaris* (green microalgae) by process of enzymatic digestion can reduce the growth of *B. cinerea* (El-ghanam et al. 2015) and showed antifungal activity associated with flavonoids and phenols. These antioxidant compounds are found abundant in alga (Ahmed 2016).

### 2.2.2 Antibacterial Activities

Active metabolites such as alkaloids, sterols, peptides and phlorotannins produced by marine macroalgae have a wide range of biocontrol activities against different pathogens in the ecosystem (Abdel-Raouf et al. 2015) which have attained much



consideration due to their antibacterial, antioxidant and cytotoxic properties (Moubayed et al. 2017). For example, leaf spot disease of *Gymnema sylvestris* (a precious medicinal plant) caused by *Pseudomonas syringae* can be minimized by methanolic extract obtained by *Sargassum wightii* (Kumar et al. 2008) but the little effect has been shown by ethyl acetate extract. Several other studies have shown that other taxa (*Turbinaria conoides*, *Ulva lactuca*, *G. verrucosa*, *Chaetomorpha antennina* and *Halimeda tuna*) have less effective antibacterial activities against *P. syringae* though an evident effect was recorded by acetonic extract from *Sargassum polyceratium* (brown macroalgae) against *Erwinia carotovora*, *Escherichia coli*, etc. (Kumar et al. 2008). Now ethanolic extract acquired from *Caulerpa racemosa* and *S. polyceratium* can work actively against *Staphylococcus aureus* (Arunkumar et al. 2005). Esserti et al. (2017) reported a reduction of crown gall disease of tomato caused by *Agrobacterium tumefaciens* by foliar application of aqueous macroalgal solution obtained from *Fucus spiralis* and *Cystoseira myriophylloides*.

### 2.2.3 Control of Diseases

The effectiveness of algal extract through soil or foliar application against different diseases has been reported in different crops in which disease control ability of brown algal extract is extensively reported (Righini et al. 2018). *E. maxima* algal extract applied through soil minimized the incidence of *Verticillium* wilt of pepper (Rekanović et al. 2010), while *Ecklonia* sp. algal extract applied as foliar spray was effective against powdery mildew in zucchini caused by *P. xanthii* (Roberti et al. 2016). This fungal activity is due to the antioxidant activities of secondary metabolites especially phenols that work both against plant and human pathogens. Moreover, Nagayama et al. (2002) reported the effectiveness of phlorotannins (algal phenols) acquired from *Ecklonia kurome* against methicillin-resistant *Staphylococcus aureus*. Athukorala et al. (2006) described the anticancer and antioxidant activity of *Ecklonia cava* phenols which was effective against murine colon cancer cell line CT-26.

In a 2-year experiment, Pugliese et al. (2018) reported minimizing powdery mildew (causal agent: *Erysiphe necator*) in grapevine by applying laminarin which also controlled powdery mildew and leaf spot in several strawberry cultivars which were caused by *B. cinerea* and *M. fragariae*, respectively (Meszka and Bielenin 2011). Furthermore, the application of laminarin can be used as an alternative against grey mould in raspberry (Krawiec et al. 2016) and disease severity in strawberry caused by (Feliziani et al. 2015). *B. cinerea* hence can reduce *B. cinerea* resistance to fungicide (Krawiec et al. 2016). Bromophenol (BDDE), a compound extracted from brown algae and red algae, can be used to treat strawberry for disease control caused by *B. cinerea* (Liu et al. 2014).

As previously mentioned, algal extracts can work directly (antifungal activity) or indirectly (induce plant resistance) against a fungal pathogen. In particular, it has been shown that cell wall and storage polysaccharides from green, brown and red seaweeds (marine macroalgae) corresponding to ulvans, alginates, fucans,

laminarin and carrageenans can trigger defense responses in plants enhancing protection against pathogens (Vera et al. 2011). Extracts obtained from brown algae (*A. nodosum*) is successfully investigated on many plant species especially in carrot against *Alternaria radicina* (Jayaraj et al. 2008) and cucumber against *F. oxysporum*, *Alternaria cucumerinum* and *B. cinerea* (Jayaraman et al. 2011). This might be due to their role to enhance enzymatic activities and synthesis of pathogenesis-related proteins (PRs) by brown algal extract (Abkhoo and Sabbagh 2016). *Sargassum filipendula* extract (Ramkissoon et al. 2017) and polysaccharide-enriched extract from green algae *Ulva lactuca* (Hernández-Herrera et al. 2014) are effectively used to control disease symptoms in tomato caused by *Xanthomonas campestris* and *A. solani*, respectively.

### 3 Role of Algae in the Agriculture Sector

A diversified class of microbes that can perform photosynthesis is known as algae, which play a vital role in agriculture, used as a soil stabilizer and biofertilizer. Seaweeds from algal source can be grown on arid, desert and waste lands with very low demand of water and are used as a fertilizer and more effective to reduce runoff of phosphorus and nitrogen as compared to seaweed obtained from manures of livestock producing a carbon-less and healthy food. These are produced around the world which can be consumed as food supplements. These are an essential source of iodine, and levels of iodine in milk depend upon the feeding mechanism of a cow which is increased by application of seaweeds. Feed seasonings with algae enhanced the rate of egg-laying in hen (Abdel-Raouf et al. 2012).

### 4 Biocontrol Strategy of Phytopathogen

The protection of plants by using precise and directed components of an ecosystem is termed as biocontrol. Similarly, biological control is the regulation of pests' population by use of biotic organisms, i.e. parasites, predators, and pathogens. It is also the use of organisms that live inside the host cells or utilization of introduced organisms other than host plants resistant to the diseases for combating multiplication in their populations. They are classified based on their contribution to controlling phytopathogen attacks like facultative symbionts of plants and hyperparasites, and saprophytes. The use of environmentally friendly methods like biological control is of great importance in maintaining the natural balance of pest population and is a slow process, acquiring few quick profits, but their effect is long-lasting and environmentally friendly.

#### 4.1 *Biological Control of Phytopathogen by Cyanobacteria*

Different alternative methods of synthetic pesticides by natural microbial sources and light components have been used for controlling the attack of the pathogen in different ways as agents of insecticides, fungicides, and acaricide (Hassan 2007; Safonova and Reisser 2005; Amer et al. 2000; Ibraheem and Abdel-Raouf 2007; Duke 2002). These environmentally friendly methods despite their lethal effect on pests are widely used for maintaining the health of the environment and fauna distribution without effecting beneficial organisms. Biological agents like fungi and bacteria have been used for control of soil-borne pathogens. Various concentrations of nitrogen-fixing cyanobacterium (*N. muscorum* Ag) were used against damping-off disease. It was observed that the growth of damping causal agents like *Sclerotinia sclerotiorum* and *Rhizoctonia solani* growth was inhibited by the use of extracts from cells of *N. muscorum* or by extracellular products of this cyanobacterium (Caire et al. 1997). The usage of biological control agents like different algal taxa of different habitats was found effective against different plants or animal diseases and also against some plant pests. Some other studies were reported about the residual effect of algal sources against insect pests (Nassar et al. 1999). They also reported the larval development inhibition and the development and survival delay of adult female mosquitoes by cyanobacteria- and green algae-producing substances. The production of some potential substances by blue-green algae is of great importance quantitatively which acts as an approach to integrated pest management, and also a suitable environmental system of disease control revealing the significance of biological control agent as a basic component of techniques for the management of pests (Hassan 2007).

#### 4.2 *Exopolysaccharide*

Cyanobacteria can be counted as the most significant source of exopolysaccharides, the extracellular polymers with changed chemical composition improving microbial growth and soil structure, as well as exoenzymes activity (Hamed 2007; Ibraheem 2007). Sustainable agricultural farming to yield high crop production could be achieved by maintaining an adequate quantity of organic matters available in the soil. Cultivation of crops on soil with adequate nutrient changes the structural characteristics of soil and causes reduction of nitrogen amount and organic matter. Reduction in organic matter availability in the soil disturbs the soil aggregate stability. Some cyanobacteria increase the availability of nutrients and improve soil structure by excreting mucilage or slime which spread all around the organism to an extent of dissolution in the soil solution or culture medium partially. The reclamation of uncultivated soil such as saline and calcareous soil could be made suitable for agricultural operations by application of algal biofertilizers (Hedge et al. 1999). *N. muscorum* is one of the cyanobacteria that excrete exopolysaccharides and enhance the overall saline soil stability (Caire et al. 1997).

## 5 Role of Cyanobacterial Products on Antagonistic Activity of Fungal and Bacterial Agents

Wide-ranging mechanisms have been used as defensive agents against pathogen development and disease incidence by showing different responses, i.e. to prevent, combat or control plant disease. For achieving maximum productivity and quality products, most of the growers depend on inorganic fertilizer and pesticides. However, the excessive use of agrochemicals for controlling disease and pest attack causes environmental pollution, adversely affecting the health of the environment, and also fear-mongering by some challengers of pesticides which significantly changed the attitude of people towards chemical pesticide use in the agriculture sector. Many plant diseases could be successfully controlled with the application of biocontrol agents, i.e. antagonistic microorganisms. However, their effect is very slow and costly, but its effect is time lasting and acts as the best control method of disease in greenhouse farming. The concern of people towards pesticide use as a preventive measure against pest and disease problems has brought the increasing interest in using alternatives to inorganic pesticides. Currently, few eco-friendly biological control vectors were used to control plant pathogenic fungi causing soil-borne disease. The biologically active compound produced by cyanobacteria (blue-green algae) and eukaryotic algae exhibiting antifungal, antibiotic and toxic activity counters to phytopathogens (Schlegel et al. 1998). *Anabaena* spp., *Scytonema* spp. and *Nostoc* spp. were found active against the growth of *Cunninghamella blakesleeana* (soil-borne fungus) and damping-off (Bloor and England 1989). Seeds were treated with culture filtrates, or extracts produced by cyanobacteria and algae performed better against damping-off fungi, i.e. *Pythium* spp., *Rhizoctonia solani* and *Furarium* spp. (Kulik 1995).

## 6 Mechanism of Interaction Between Pathogenic and Plant Diseases Biocontrol Agent

A combination of different types of interaction between organisms results in biological control under different experimental conditions; many mechanisms are operated during the characterization of mechanism followed in the biocontrol process. Almost in all conditions, the presence and activities of other organisms encounter the antagonistic effect of pathogens. Therefore, the adaptation of different antagonistic mechanisms produced by the directional spectrum associated with the specificity of interactions and the interspecies contact quantity has been focused in this study (Fig. 1.2).

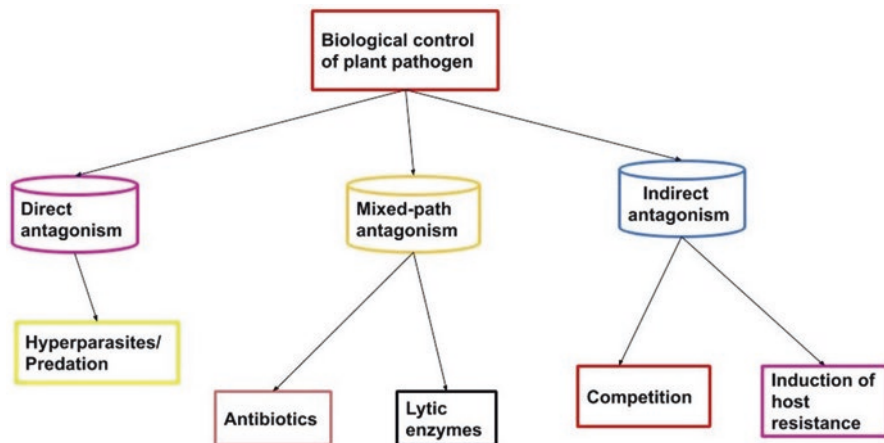


Fig. 1.2 Mechanism of interaction between pathogenic and plant diseases biocontrol agent

### 6.1 Hyperparasites and Predation

In hyperparasitism, biological control agents (BCA) are used to kill directly the pathogen or its propagules. Generally, hyperparasites are classified into major four classes, i.e. hypoviruses, obligate bacterial pathogens, facultative predators and parasites. An obligate bacterial pathogen of root-knot nematode, i.e. *Pasteuria penetrans*, was used as an agent of biological control. Hyperparasites such as hypoviruses (a fungus, i.e. *Cryphonectria parasitica*) that cause chest nut diseases were infected by virus that shows the effective result in reducing the disease-producing ability of the pathogen (hypovirulence) (Milgroom and Cortesi 2004). However, the success or failure of hypovirulence is dependent on the interaction of viruses, fungus, trees and the environment. A number of plant pathogenic fungal parasites have been specified where some of them like *Coniothyrium minitans* attack on sclerotia and others like *Pythium oligandrum* attack on living hyphae, whereas hyperparasites attack on the individual fungal pathogen, e.g. pathogens of powdery mildew were parasitized by a small fungal group, i.e. *Acrodontium crateriforme*, *Acremonium alternatum*, *Ampelomyces quisqualis*, *Cladosporium oxysporum* and *Gliocladium virens* (Kiss 2003). Some other attack on different developmental stages of phytopathogenic nematodes (e.g. *Dactylella oviparasitica*, and *Paecilomyces lilacinus*). Microbial predation compared to hyperparasitism gives less predictable results of disease control and is more general and pathogen nonspecific. However, some under limited availability of nutrients show predatory behaviour compared to typical growing conditions. Some species of *Trichoderma* show differential response by activating the chitinase genes that are helpful against the cell wall of fungi to parasitize *R. saloni*.

## 6.2 Antibiotic-Mediated Suppression

Antibiotics are known as microbial toxins which damage or kill different other organisms a minute quantity. Some of the microbes are considered as an important source of producing and secreting either single or many compounds with an antibiotic action which play an effective role in suppressing disease-causing plant pathogens. The growth of the target pathogens has been significantly suppressed by using antibiotics in vitro/in situ. Different biocontrol agents are important means of in situ antibiotics production (Pal and McSpadden 2006); moreover, estimated effective quantities are hard to measure because of their small quantity products as compared to other less toxic organic compounds available in the phytosphere. The suppression of diverse microbial competitors could be resolved by the production of antibiotics. Biological control could be enhanced by the production of antibiotics that inhibit the activity of different pathogens differentially. Phenazine and DAPG were produced by genetically engineered strains of *Pseudomonas putida* WCS358r and have been found effective by suppressing phyto-disease in wheat grown in the field (Glandorf et al. 2001).

## 6.3 Lytic Enzymes and Other By-Products of Microbial Life

The activity and growth of pathogen were significantly effective in the production of metabolites of a diverse group of microorganisms. Many microbes are used in suppressing plant pathogen activity directly by secreting lytic enzymes which hydrolyze several polymeric compounds, i.e. chitin, proteins, cellulose, hemicellulose and DNA. Biocontrol activities of *Lysobacter enzymogenes* strain C3 significantly show a positive response by a  $\beta$ -1,3-glucanase (Palumbo et al. 2005). The fungal plant pathogen is suppressed by *Lysobacter* and *Myxobacteria* that produce a significantly large number of lytic enzymes (Bull et al. 2002). In addition to these, indirect suppression of disease could be achieved by the activity of some products of the lytic enzyme. Oligosaccharides obtained from the cell wall of fungus are identified as an important source of plant host defense induction. Plant host resistance against diseases was achieved by a strain of *Lysobacter enzymogenes* (C3) (Kilic-Ekici and Yuen 2003), though induction of these activities is not clearly understood. The ratio and composition of C:N of organic matter in the soil is mostly dependent on the activity of any and above compounds in disease suppression of phytopathogens that play a major role in providing a nutrient-rich environment in the soil and rhizosphere. Sometimes maximum disease suppression could be achieved by the improvement of these activities. The use of chitosan as a postharvest biocontrol agent can stimulate the damage of microbial activity similar to that of using hyperparasites (Benhamou 2004) and also found effective against root rot caused by *Fusarium oxysporum* f. sp. *radices lycopersici* in tomato plant.

## 7 Role of Cyanobacteria in Crop Protection

### 7.1 *Cyanobacteria and Allelopathy*

Biologically active metabolites used by single species are effectively used in inhibiting sympatric species growth which may act as a potential competitor for controlling annual variability and resources in the communities of phytoplankton (Vardi et al. 2002). Several heterocystous cyanophycean genera such as *Anabaena sp.*, *Nostoc sp.*, *Cylindrospermum*, *Scytonema*, *Calothrix*, *Rivularia*, *Chlorogloea*, *Gloeotrichia*, and *Nostochopsis* have been shown to fix atmospheric nitrogen efficiently, which improve the nutritional status of soil. *Fischerella* produce fischerellins (A and B), and play role as alternative approach of allelopathy (Ganter et al. 2008) but also play a role as alternative approach of allelopathy. The pentacyclic calothrixins produced by *Calothrix* strains act in allelopathic interactions in inhibiting RNA polymerase and DNA synthesis (Doan et al. 2000). *Nostoc 78-12A* produced nostocarboline (a carboline alkaloid) that helps in inhibition of the toxin produced by cyanobacterium. *Microcystis aeruginosa* acts as an allelopathic agent and has significant effects on photosynthesis (Shao et al. 2009).

### 7.2 *Application of Cyanobacterial Secondary Metabolites*

Cyanobacteria are a major source of bioactive metabolites or compounds that contain a varied range of nitrogen-rich alkaloids and peptides (Gervick et al. 2001). The significance of such microbes, which are known as the source of cyano-toxins and different other newly found biologically active compounds, is accepted and recognized worldwide (Mundt et al. 2001; Kumar et al. 2005); however, their role as a chemical potential agent like biocontrol agents or in crop protection is less explored in agriculture. The attack of a disease-causing organism like bacteria, fungi, zooplankton and eukaryotic microalgae could be reduced possibly by using cyanobacteria as a potential defense option of synthesis of highly active toxins.

### 7.3 *Biological Control Perspective of Cyanobacteria Against Diseases*

Cyanobacteria produce various secondary metabolites having hormonal, toxic, antimicrobial and antineoplastic effects (Jaki et al. 2000) and are targeting prokaryotic as well as eukaryotic microorganism. Selected microorganisms show bioassays of aqueous and organic solvent extracts of antimicrobial compounds. Bioactive compounds showed fungal activity against important fungi that act as a synthesis of antibiotics by lead production and open a gateway in the agriculture sector (Nagle



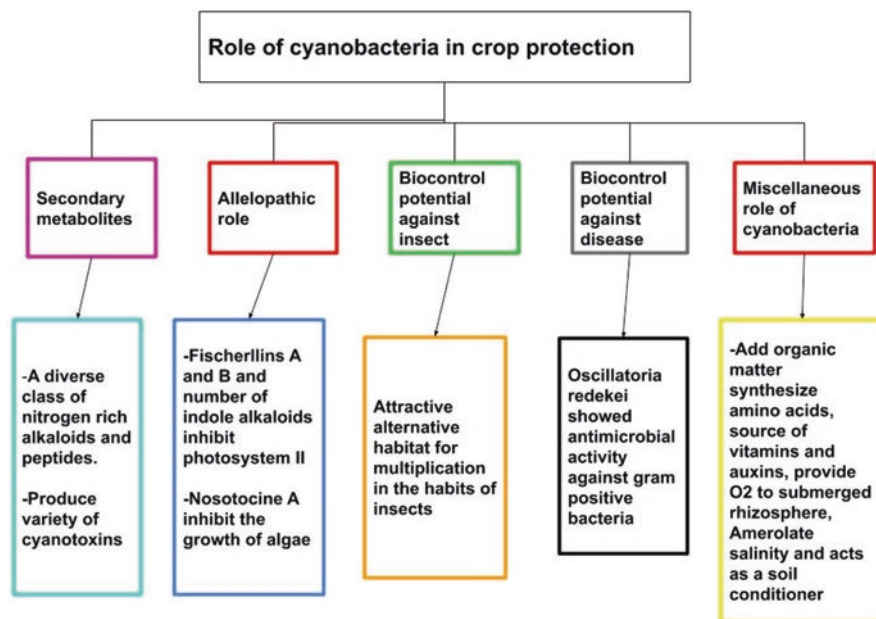


Fig. 1.3 Biological control perspective of cyanobacteria against diseases

and Wedge 2002; Volk and Furkert 2006). *Tolypothrix tjipanensis*, cyanobacterium that produced tjipanazoles, revealed an effective response of showing fungicidal activity against *Aspergillus flavus* (Ozdemir et al. 2004). Several pathogenic fungi activities were reduced by fischerellin-A from *Fischerella*. Gram-positive bacteria showed antimicrobial activity by an unsaturated mixture of fatty acids from *Oscillatoria redekei* (Sabin et al. 2003). Gram-positive bacteria showed positive activity in a sample of 22 different strains of cyanobacteria obtained either from terrestrial or freshwater environments while reported minute activity counters to gram-negative bacteria (Fig. 1.3).

#### 7.4 Multiple Significant Roles of Cyanobacteria

Cyanobacteria can be considered as an excellent source of organic matter to the soil, synthesis of amino acid, auxins and vitamins, and oxygen supply in submerged conditions, increase phosphate solubility and enhance fertilizer efficiency in plants, while decreasing the contents of oxidizable matter and salinity (Kaushik 2004). They are also considered as an important agent of soil conditioner and nitrogen that represent renewable biomass resource which is increasing as a source of the novelty of bioactive molecules. They promote the production of plant hormones, and their antibiotics or toxic compounds have been observed in enzymes inhibiting the

activities of phytopathogen (Sergeeva et al. 2002). Besides toxins, cyanobacterial biomass is also a source of a large number of active substances having fungicide, cytotoxic, algicidal, antibacterial and antiviral activities (Jaki et al. 1999). Green algae in paddy fields were controlled by the use of algicides obtained from cyanobacteria, and their better growth was also observed. The major component of Nostoc 31 was nostocyclamide that has antibiotic and algicide activities. Mundt et al. (2002) observed the response of lipophilic and hydrophilic extracts for antibiotic, immunomodulating, antiviral and inhibiting activity of various enzymes in in vitro systems reporting various interesting effects.

## 8 Conclusion

For sustainable environmentally friendly farming, the reduction of synthetic fertilizers application and pesticides use is an interesting topic of the recent time. There has been improved progress in cyanobacterial and algal biofertilizer products. On the other hand, application of cyanobacteria and algae use in controlling fungal and bacterial diseases is an innovative concept in sustainable agriculture. Recent studies reported remarkable growth in cyanobacterial biomass production for biofertilizers; a different supplement of foods, i.e. superfoods; and biofuels for farming of safe agricultural production. The most successfully emerged phyla of prokaryotes which were sustained during the evolutionary course were cyanobacteria. Along with so many applications in nutraceuticals, pharmaceuticals, food and feed industries, the ecological, morphological and genetic cyanobacterial diversity has led to the wide array of compounds production. The autotrophic nutritional mode is more dominant while some of the species of cyanobacteria can grow well in dark and anaerobic environments including *Oscillatoria* and *Nostoc*, while few cyanobacterial species, i.e. *Nostoc*, can also function in atmospheric nitrogen fixation. The cyanobacterial activity against phytopathogens has been studied both through their applications on leaves and soil surfaces. Green algae being unicellular and photosynthetic organisms, i.e. seaweeds (multicellular marine algae), and *Chlorella*, such as a brown alga named *Sargassum* can reach up to a length of 1–3 m. Cyclohexane and aqueous extracts from *Sargassum* sp. inhibit mycelial growth of *Aspergillus* spp. by 37–54.5%. Marine microalgae with an enormous spectrum production of synthetically vigorous metabolites, i.e. polysaccharides, cyclic peptides, sterols, polyketides, diterpenoids, alkaloids, quinones, glycerols and lipids, have a wide-ranging capability of bacterial/biological activity function against many other organisms. Both cyanobacteria and algae play a key role in sustainable agricultural farming as biological control agents. They also play a vital role as allelopathic sources and are eco-friendly for safe sustainable crop production.

## References

- Abdel-Raouf N, Al-Homaidan AA, Ibraheem IBM (2012) Agricultural importance of algae. *Afr J Biotechnol* 11(54):11648–11658
- Abdel-Raouf N, Al-Enazi NM, Al-Homaidan AA, Ibraheem IBM, Al-Othman MR, Hatamleh AA (2015) Antibacterial b-amyirin isolated from *Laurencia microcladia*. *Arab J Chem* 8:32–37
- Abkhoo J, Sabbagh SK (2016) Control of *Phytophthora melonis* damping-off, induction of defense responses, and gene expression of cucumber treated with commercial extract from *Ascophyllum nodosum*. *J Appl Phycol* 28:1333–1342
- Ahmed EA (2016) Antimicrobial activity of microalgal extracts isolated from Baharia Oasis, Egypt. *Glob Adv Res J Microbiol* 5:033–041
- Alam MZ, Braun G, Norrie J, Hodges DM (2013) Effect of *Ascophyllum* extract application on plant growth, fruit yield and soil microbial communities of strawberry. *Can J Plant Sci* 93:23–36
- Alwathnani HA, Perveen K (2012) Biological control of Fusarium wilt of tomato by antagonist fungi and cyanobacteria. *Afr J Biotechnol* 11:1100–1105
- Ambika S, Sujatha K (2015) Antifungal activity of brown, red and green alga seaweed extracts against *Macrophomina phaseolina* (Tassi) Goid., in pidgeonpea var. CO (Rg) 7. *Int J Agric Sci* 11:210–216
- Amer SAA, Mohamed SM, El-Gengaihi S, Dimetry NZ (2000) Acaricidal activity of lipoidal matter of different plant extracts against the two-spotted mite *Tetranychus urticae koch*. *Insect Sci Appl* 20(3):191–194
- Arioli T, Mattner SW, Winberg PC (2015) Applications of seaweed extracts in Australian agriculture: past, present and future. *J Appl Phycol* 27:2007–2015
- Arunkumar K, Selvapalam N, Rengasamy R (2005) The antibacterial compound sulphoglycerolipid 1–0 palmitoyl-3–0(6-sulpho-aquinoxypyranosyl)-glycerol from *Sargassum wightii* Greville (Phaeophyceae). *Botanica Mar* 40:441–445
- Asthana RK, Tripathi MK, Deepali A et al (2009) Isolation and identification of a new antibacterial entity from the Antarctic cyanobacterium *Nostoc* CCC 537. *J Appl Phycol* 21:81–88
- Athukorala Y, Kim KN, Jeon YJ (2006) Antiproliferative and antioxidant properties of an enzymatic hydrolysate from brown alga, *Ecklonia cava*. *Food Chem Toxicol* 44:1065–1074
- Benhamou N (2004) Potential of the mycoparasite, *Verticillium lecanii*, to protect citrus fruit against *Penicillium digitatum*, the causal agent of green mold: a comparison with the effect of chitosan. *Phytopathology* 94:693–705
- Benson D, Kerry K, Malin G (2014) Algal biofuels: impact significance and implications for EU multi-level governance. *J Clean Prod* 72:4–13. <https://doi.org/10.1016/j.jclepro.2014.02.060>
- Biondi N, Tredici MR, Taton A et al (2008) Cyanobacteria from benthic mats of Antarctic lakes as a new source of bioactivities. *J Appl Microbiol* 105:105–115
- Blom JF, Brutsch T, Barbaras D et al (2006) Potent algicides based on the cyanobacterial alkaloid nostocarboline. *Org Lett* 8:737–740
- Bloor S, England RR (1989) Antibiotic production by the cyanobacterium *Nostoc muscorum*. *J Appl Phycol* 1(4):367–372
- Bull CT, Shetty KG, Subbarao KV (2002) Interactions between Myxobacteria, plantpathogenic fungi, and biocontrol agents. *Plant Dis* 86:889–896
- Caire G, de Cano SM, de Mulé ZMC, Palma RM, Colombo K (1997) Exopolysaccharides of *Nostoc muscorum* ag. (cyanobacteria) in the aggregation of soil particles. *J Appl Phycol* 9:249–253
- Craigie JS (2011) Seaweed extract stimuli in plant science and agriculture. *J Appl Phycol* 23:371–393
- De Corato U, Salimbeni R, De Pretis A, Avella N, Patruno G (2017) Antifungal activity of crude extracts from brown and red seaweeds by a supercritical carbon dioxide technique against fruit postharvest fungal diseases. *Postharvest Biol Technol* 131:16–30
- Dixit RB, Suseela MR (2013) Cyanobacteria: potential candidates for drug discovery. *Antonie Van Leeuwenhoek* 103:947–961

- Doan NT, Rickards RW, Rothschild JM, Smith GD (2000) Allelopathic actions of the alkaloid 12-epi-Hapalindole E Isonitrile and Calothrixin A from cyanobacteria of the genera Fischerella and Calothrix. *J Appl Phycol* 12:409–416
- Duke SO (2002) Chemicals from nature for weed management. *Weed Sci* 50:138–151
- El-ghanam AA, Farfour SA, Ragab SS (2015) Bio-suppression of strawberry fruit rot disease caused by *Botrytis cinerea*. *J Plant Pathol Microbiol* S3:005
- El-Sohaimy SA (2012) Functional foods and nutraceuticals—modern approach to food science. *World Appl Sci J* 20(5):691–708
- Esserti S, Smaili A, Rifai LA, Koussa T, Makroum K, Belfaiza M, Kabil EM, Faize L, Burgos L, Albuquerque N, Faize M (2017) Protective effect of three brown seaweed extracts against fungal and bacterial diseases of tomato. *J Appl Phycol* 29:1081–1093
- Feliziani E, Landi L, Romanazzi G (2015) Preharvest treatments with chitosan and other alternatives to conventional fungicides to control postharvest decay of strawberry. *Carbohydr Polym* 132:111–117
- Fernandes Peres JC, de Carvalho LR, Gonçalves E, Saggion Berian LO, D'arc Felício J (2012) Evaluation of antifungal activity of seaweed extracts. *Ciênc Agrotec Lavras* 36:294–299
- Ganter M, Berry JP, Thomas S, Wang M, Perez R, Rein K (2008) Allelopathic activity among cyanobacteria and microalgae isolated from Florida freshwater habitats. *FEMS Microbiol Lett* 64:55–64
- Gervick WM, Tan LT, Siachitta N (2001) Nitrogen-containing metabolites from marine cyanobacteria. In: Cordell G (ed) *The alkaloids*. Academic Press, San Diego, pp 75–184
- Glandorf DC, Verheggen P, Jansen T, Jorritsma JW, Smit E, Leefang P, Wernars K, Thomashow LS, Laureijs E, Thomas-Oates JE, Bakker PA, Van Loon LC (2001) Effect of genetically modified *Pseudomonas putida* WCS358r on the fungal rhizosphere microflora of field-grown wheat. *Appl Environ Microbiol* 67:3371–3378
- Gothalwal R, Bajpai P (2012) Cyanobacteria a comprehensive review. *Int Res J Pharm* 3(2):53–57
- Guiry MD (2012) How many species of algae are there? *J Phycol* 48:1057–1063
- Gupta V, Natarajan C, Kumar K, Prasanna R (2011) Identification and characterization of endoglucanases for fungicidal activity in *Anabaena laxa*. *J Appl Phycol* 23:73–81
- Gwinn KD (2018) Bioactive natural products in plant disease control. In: Atta-ur-Rahman (ed) *Studies in natural products chemistry*, vol 56. Elsevier, Amsterdam, pp 229–246
- Hamed SMM (2007) Studies on nitrogen fixing cyanobacteria. M.Sc. Thesis, Botany Department, Faculty of Science, Beni-Suef University, Beni-Suef, Egypt
- Hassan NAM (2007) Studies on the algal flora distributed at Wadi-Sannur of the eastern- desert of Egypt. M.Sc. Thesis, Faculty of Science, Beni-Suef University, Egypt
- Hedge DM, Dwivedi BS, Sudhakara-Babu SN (1999) Biofertilizers for cereal production in India—a review. *Indian J Agric Sci* 69(2):73–83
- Hernández-Herrera RM, Virgen-Calleros G, Ruiz-López M, Zañudo-Hernández J, Délano-Frier JP, Sánchez-Hernández C (2014) Extracts from green and brown seaweeds protect tomato (*Solanum lycopersicum*) against the necrotrophic fungus *Alternaria solani*. *J Appl Phycol* 26:1607–1614
- Hirata K, Yoshitomi S, Dwi S, Iwabe O, Mahakhant A, Polchai J, Miyamoto K (2003) Bioactivities of nostocine A produced by a freshwater cyanobacterium *Nostoc spongiaforme* TISTR 8169. *J Biosci Bioeng* 95:512–517
- Hoekman SK, Broch A, Robbins C, Ceniceros E, Natarajan M (2012) Review of biodiesel composition, properties, and specifications. *Renew Sustain Energy Rev* 16(1): 143–169
- Husaini AM, Neri D (2016) Strawberry growth, development and diseases. CABI, Wallingford
- Ibraheem IBM (2007) Cyanobacteria as alternative biological conditioners for bioremediation of barren soil. *Egypt J Phycol* 8:99–116
- Ibraheem IBM, Abdel-Raouf N (2007) Allelopathic activity of some local cyanobacterial extra metabolites against some pathogenic bacteria. *Egypt J Phycol* 8:120–129

- Ibraheem IBM, Hamed SM, Abd Elrhman AA, Farag FM, Abdel-Raouf N (2017) Antimicrobial activities of some brown macroalgae against some soil borne plant pathogens and in vivo management of *Solanum melongena* root diseases. *Aust J Basic Appl Sci* 11:157–168
- Jaki B, Orjala J, Sticher O (1999) A novel extracellular diterpenoides with antibacterial activity from the cyanobacterium, *Nostoc commune*. *J Nat Prod* 62:502–503
- Jaki B, Orjala J, Heilmann J, Linden A, Vogler B, Sticher O (2000) Novel extracellular diterpenoids with biological activity from the cyanobacterium *Nostoc commune*. *J Nat Prod* 63:339–343
- Jarvis WR, Gubler WD, Grove GG (2002) Epidemiology of powdery mildews in agricultural pathosystems. In: Bélanger RR, Bushnell WR, Dik AJ, Carver TLW (eds) *The powdery mildews: a comprehensive treatise*. APS, St. Paul, pp 169–199
- Jayaraj J, Wan A, Rahman M, Punja ZK (2008) Seaweed extract reduces foliar fungal diseases on carrot. *Crop Prot* 27:1360–1366
- Jayaraman J, Norrie J, Punja ZK (2011) Commercial extract from the brown seaweed *Ascophyllum nodosum* reduces fungal diseases in greenhouse cucumber. *J Appl Phycol* 23:353–361
- Kaushik BD (2004) Use of blue-green algae and Azolla biofertilizers in rice cultivation and their influence on soil properties. In: Jain PC (ed) *Microbiology and biotechnology for sustainable development*. CBS Publishers & Distributors, New Delhi, pp 166–184
- Khalid M, Shameel M, Ahmed V, Shahzad S, Lghani S (2010) Studies on the bioactivity and phycochemistry of *Microcystis aeruginosa* (Cyanophyta) from Sindh. *Pak J Bot* 42(4):2635–2646
- Khallil AM, Daghman IM, Fady AA (2015) Antifungal potential in crude extracts of five selected brown seaweeds collected from the western Libya coast. *J Micro Creat* 1:103–107
- Kilic-Ekici O, Yuen GY (2003) Induced resistance as mechanisms of biological control by *Lysobacter enzymogenes* strain C3. *Phytopathology* 93:1103–1110
- Kim JD (2006) Screening of Cyanobacteria (Blue-Green algae) from Rice Paddy Soil for Antifungal Activity against Plant Pathogenic Fungi. *Mycobiology* 34(3): 138–142
- Kim J, Kim JD (2008) Inhibitory effect of algal extracts on mycelia growth of the tomato-wilt pathogen, *Fusarium oxysporum* f. sp. lycopersici. *Mycobiol* 36: 242–248
- Kiss L (2003) A review of fungal antagonists of powdery mildews and their potential as biocontrol agents. *Pest Manag Sci* 59:475–483
- Koller M (2015) Cyanobacterial polyhydroxyalkanoate production: status quo and quo vadis? *Curr Biotechnol* 4(4):464–480
- Koller M, Salerno A, Tuffner P, Koinigg M, Bochezeltb H, Schoberd S et al (2012) Characteristics and potential of microalgal cultivation strategies: a review. *J Clean Prod* 37:377–388. <https://doi.org/10.1016/j.jclepro.2012.07.044>
- Krawiec M, Szot I, Krawiec P (2016) The use of laminarin as an effective tool for anti-resistance management in chemical control of grey mould in raspberry. *Acta Hort* 1133:469–472
- Kulik MM (1995) The potential for using cyanobacteria (blue-green algae) and algae in the biological control of plant pathogenic bacteria and fungi. *Eur J Plant Pathol* 101(6):585–599
- Kumar K, Lakshmanan A, Kannaiyan S (2005) Bioregulatory and therapeutic effects of blue green algae. *Indian J Microbiol* 43:9–16
- Kumar CS, Raju D, Sarada VL, Rengasamy R (2008) Seaweed extracts control the leaf spot disease of the medicinal plant *Gymnema sylvestre*. *Indian J Sci Technol* 1:93–94
- Liu M, Wang G, Xiao L, Xu X, Liu X, Xu P, Lin X (2014) Bis (2,3-dibromo-4,5-dihydroxybenzyl) ether, a marine algae derived bromophenol, inhibits the growth of *Botrytis cinerea* and interacts with DNA molecules. *Mar Drugs* 12:3838–3851
- Manjunath M, Prasanna R, Nain L, Dureja P, Singh R, Kumar A, Jaggi S, Kaushik BD (2010) Biocontrol potential of cyanobacterial metabolites against damping off disease caused by *Pythium aphanidermatum* in solanaceous vegetables. *Arch Phytopathol PFL* 43:666–677
- Marrez DA, Sultan YY (2016) Antifungal activity of the cyanobacterium *Microcystis aeruginosa* against mycotoxigenic fungi. *J Appl Pharm Sci* 6:191–198
- Meena M, Divyanshu K, Kumar S, Swapnil P, Zehra A, Shukla V, Yadav M, Upadhyay RS (2019) Regulation of L-proline biosynthesis, signal transduction, transport, accumulation and its vital

- role in plants during variable environmental conditions. *Heliyon* 5(12):e02951. <https://doi.org/10.1016/j.heliyon.2019.e02952>
- Mendes R, Garbeva P, Raaijmakers JM (2013) The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS Microbiol Rev* 37:634–663
- Meszka B, Bielenin A (2011) Activity of laminarin in control of strawberry diseases. *Phytopathologia* 62:15–23
- Milgroom MG, Cortesi P (2004) Biological control of chestnut blight with hypovirulence: a critical analysis. *Annu Rev Phytopathol* 42:311–338
- Moubayed NMS, Al Hourri HJ, AlKhulaifi MM, Al Farraj DA (2017) Antimicrobial, antioxidant properties and chemical composition of seaweeds collected from Saudi Arabia (Red Sea and Arabian gulf). *Saudi J Biol Sci* 24:162–169
- Mundt S, Kreitlow S, Nowotny A, Effmert U (2001) Biochemical and pharmacological investigations of selected cyanobacteria. *Int J Hygiene Env Health* 203:327–334
- Nagayama K, Iwamura Y, Shibata T, Hirayama I, Nakamura T (2002) Bactericidal activity of phlorotannins from the brown alga *Ecklonia kurome*. *J Antimicrob Chemother* 50:889–893
- Nagle DG, Wedge DE (2002) Chemical ecology of plants. In: Malik B (ed) *Allelopathy in aquatic and terrestrial ecosystems*. Birkhauser Verlag, Basel, pp 7–32
- Nassar MMI, Hafez ST, Nagaty I, Khalaf M, Samy AA (1999) Insecticidal activity of cyanobacteria against four insects, two of medical importance and two agricultural pests with reference to the action on albino mice. *Egypt Soc Parasitol* 29(3):939–949
- Osman MEH, El-Sheekh MM, Metwally AM, AEA I, Ismail M (2011) Antagonistic activity of some fungi and cyanobacteria species against *Rhizoctonia solani*. *Int J Plant Pathol* 2(3):101–114
- Ozdemir G, Karabay NU, Dalay MC, Pazarbasi B (2004) Antibacterial activity of volatile component and various extracts of *Spirulina platensis*. *Phytother Res* 18:754–757
- Pal KK, McSpadden BG (2006) Biological control of plant pathogens. *Plant Health Instruct*. <https://doi.org/10.1094/PHI-A-2006-1117-02>
- Palumbo JD, Yuen GY, Jochum CC, Tatum K, Kobayashi DY (2005) Mutagenesis of beta-1,3-glucanase genes in *Lysobacter enzymogenes* strain C3 results in reduced biological control activity toward *Bipolaris* leaf spot of tall fescue and *Pythium* damping off of sugar beet. *Phytopathology* 95:701–707
- Pastrana AM, Basallote-Ureba MJ, Aguado A, Akdi K, Capote N (2016) Biological control of strawberry soil-borne pathogens *Macrophomina phaseolina* and *Fusarium solani*, using *Trichoderma asperellum* and *Bacillus spp.* *Phytopathol Mediterr* 55:109–120
- Pisciotta JM, Zou Y, Baskakov IV (2010) Light-dependent electrogenic activity of cyanobacteria. *PLoS One* 5(5):e10821. <https://doi.org/10.1371/journal.pone.0010821>
- Prasanna R, Nain L, Tripathi R, Gupta V, Chaudhary V, Middha S et al (2008) Evaluation of fungicidal activity of extracellular filtrates of cyanobacteria—possible role of hydrolytic enzymes. *J Basic Microbiol* 48:186–194
- Prasanna R, Bidyarani N, Babu S, Hossain F, Shivay YS, Nain L (2015) Cyanobacterial inoculation elicits plant defense response and enhanced Zn mobilization in maize hybrids. *Cogent Food Agric* 1:998507. <https://doi.org/10.1080/23311932.2014.998507>
- Pugliese M, Monchiero M, Gullino ML et al (2018) Application of laminarin and calcium oxide for the control of grape powdery mildew on *Vitis vinifera* cv. Moscato *J Plant Dis Prot* 125:477. <https://doi.org/10.1007/s41348-018-0162-8>
- Ramkissoon A, Ramsubhag A, Jayaraman J (2017) Phytoelicitor activity of three Caribbean seaweed species on suppression of pathogenic infections in tomato plants. *J Appl Phycol* 29:3235–3244
- Reinert R, Donald EL, Rosi FX, Watal C, Dowzicky M (2007) Antimicrobial susceptibility among organisms from the Asia/Pacific rim, Europe and Latin and North America collected as part of TEST and the in vitro activity of tigecycline. *J Antimicrob Chemother* 60:1018–1029



- Rekanović E, Potočnik I, Milijašević-Marčić S, Stepanović M, Todorović B, Mihajlović M (2010) Efficacy of seaweed concentrate from *Ecklonia maxima* (Osbeck) and conventional fungicides in the control of *Verticillium* wilt of pepper. *Pestic Phytomed* 25:319–324
- Righini H, Roberti R, Baraldi E (2018) Use of algae in strawberry management. *J Appl Phycol* 30:3551–3564
- Righini H, Baraldi E, GarcíaFernández Y, Martel Quintana A, Roberti R (2019) Different antifungal activity of *Anabaena* sp., *Ecklonia* sp., and *Jania* sp. against *Botrytis cinerea*. *Mar Drugs* 17:299
- Righini H, Roberti R, Quintana AM (2020) Biocontrol of *Rhizoctoniasolani* by water extracts from *Chlorella* sp. and *Halophytys* sp. *Open Acc J Agric Res. OAJAR-100029*
- Roberti R, Galletti S, Burzi PL, Righini H, Cetrullo S, Perez C (2015) Induction of defense responses in zucchini (*Cucurbita pepo*) by *Anabaena* sp. water extract. *Biol Control* 82:61–68
- Roberti R, Righini H, Pérez Reyes C (2016) Activity of seaweed and cyanobacteria water extracts against *Podosphaera xanthii* on zucchini. *Ital J Mycol* 45:66–77
- Romero D, de Vicente A, Zerriouh H, Cazorla FM, Fernández-Ortuño D, Torés JA, Pérez-García A (2007) Evaluation of biological control agents for managing cucurbit powdery mildew on greenhouse-grown melon. *Plant Pathol* 56:976–986
- Russo P, Cesario A (2012) New anticancer drugs from marine cyanobacteria. *Curr Drug Targets* 13(8):1048–1053
- Sabin M, Susann K, Jansen R (2003) Fatty acids with antibacterial activity from the cyanobacterium *Oscillatoria redekei* HUB 051. *J Appl Phycol* 15:263–267
- Safonova E, Reisser W (2005) Growth promoting and inhibiting effects of extracellular substances of soil microalgae and cyanobacteria on *Escherichia coli* and *Micrococcus luteus*. *Phycol Res* 53:189–193
- Schiener P, Black KD, Stanley MS, Green DH (2015) The seasonal variation in the chemical composition of the kelp species *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*. *J Appl Phycol* 27:363–373
- Schirmeister BE, Antonelli A, Bagheri HC (2011) The origin of multicellularity in cyanobacteria. *BMC Evolution*. *Biol* 11(45):1–21
- Schlegel I, Doan NT, De Chazal N, Smith GD (1998) Antibiotic activity of new cyanobacterial isolates from Australia and Asia against green algae and cyanobacteria. *J Appl Phycol* 10(5):471–479
- Sergeeva E, Liaimer A, Bergman B (2002) Evidence for production of the phytohormone indole 3-acetic acid by cyanobacteria. *Planta* 215:229–238
- Shao J, Wu Z, Yu G, Peng X, Li R (2009) Allelopathic mechanism of pyrogallol to *Microcystis aeruginosa* PCC7806 (Cyanobacteria): from views of gene expression and antioxidant system. *Chemosphere* 75: 924–928
- Sharma P, Sharma N (2017) Industrial and biotechnological applications of algae: a review. *J Adv Plant Biol* 1:1–25
- Simmons TL, Engene N, Ureña LD, Romero LI, Ortega-Barría E, Gerwick L, Gerwick WH (2008) Viridamides a and B, lipodepsipeptides with antiprotozoal activity from the marine cyanobacterium *Oscillatoria nigro-viridis*. *J Nat Prod* 71:1544–1550
- Singh JS, Strong PJ (2016) Biologically derived fertilizer: a multifaceted bio-tool in methane mitigation. *Ecotoxicol Environ Saf* 124:267–276. <https://doi.org/10.1016/j.ecoenv.2015.10.018>
- Singh RK, Tiwari SP, Rai AK, Mohapatra TM (2011) Cyanobacteria: an emerging source for drug discovery. *J Antibiot* 64:401–412
- Tan LT (2007) Bioactive natural products from marine cyanobacteria for drug discovery. *Phytochemistry* 68:954–979
- Tiwari A, Kaur A (2014) Allelopathic impact of Cyanobacteria on pathogenic fungi. *Int J Pure App Biosci* 2 (3): 63–70
- Uzair B, Tabassum S, Rasheed M, Rehman SF (2012) Exploring marine cyanobacteria for lead compounds of pharmaceutical importance. *Sci World J* 179(82):1–10



- Vardi A, Schatz D, Beeri K, Motro U, Sukenik A, Levine A, Kaplan A (2002) Dinoflagellate cyanobacterium communication may determine the composition of phytoplankton assemblage in a mesotrophic lake. *Curr Biol* 12:1767–1772
- Vera J, Castro J, Gonzalez A, Moenne A (2011) Review-seaweed polysaccharides and derived oligosaccharides stimulate defense responses and protection against pathogens in plants. *Mar Drugs* 9:2514–2525
- Volk BR, Furkert HF (2006) Antialgal, antibacterial and antifungal activity of two metabolites produced and excreted by cyanobacteria during growth. *Microbiol Res* 161:180–186
- Wainwright PO, Hinkle G, Sogin ML, Stickel SK (1993) Monophyletic origins of the metazoa: an evolutionary link with the fungi. *Science* 260:340–342
- Yadav S, Sinha RP, Tyagi MB, Kumar A (2011) Cyanobacterial secondary metabolites. *Int J Pharma Bio Sci* 2(2):144–167