Chapter 7
Endophytes and Their Applications as Biofertilizers

Gaurav Yadav, Rishita Srivastva, and Preeti Gupta

Abstract Endophytes are microorganisms residing inside plant tissues. The endophytes are not harmful for the plant health, and besides this, they provide nutrients to plants as well as protect plants from stress conditions and from plant pathogens. The endophytic microbial community includes different genus of bacteria, fungi, algae, actinomycetes, and transgenic microbes like *Bacillus* sp. and *Piriformospora indica*. These microbial strains can be used as consortium or single species as biofertilizers. These biofertilizers are free from chemicals and have a number of benefits for agricultural crops such as they help in plant growth, act as biocontrol agents, protect plants from stress, and also help in the recovery of diseased plant, N_2 fixation, and IAA production, etc. This compendium will accentuate on the different types of endophytic microorganisms and their extensive role as a biofertilizer in the field of agriculture.

Keywords Endophytes · Agriculture · Biocontrol · Biofertilizers

7.1 Introduction

There are some microorganisms, especially bacteria and fungi, which can thrive on their plant host externally, and are commonly known as epiphytes, i.e., present on leaf surfaces, and some live internally and are known as endophytes (Afzal et al. 2019). Endophytes are the microorganism which resides in the inner part of the plants' body such as xylem vessels without vitiating or infecting the plant, and there are approximately 300,000 plant species present on earth which carry one or two endophytes (Afzal et al. 2019; Fadiji and Babalola 2020; Maela and Serepa 2019). Endophytes are of two types: obligate endophytes and facultative endophytes.

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P. Bhatt et al. (eds.), *Microbial Technology for Sustainable Environment*,
https://doi.org/10.1007/978-981-16-3840-4_7

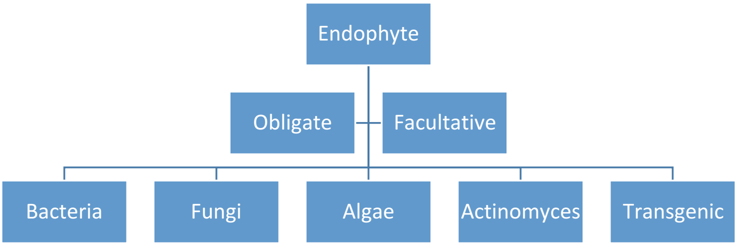


Fig. 7.1 Classification of an endophyte

Obligate endophytes are those which require more specific nutrients and strict conditions to grow in in vitro conditions; without them they cannot be cultivable, while facultative are those endophytes which do not need any specific nutrients or conditions to grow, i.e., non-fastidious in nature; they can harbour themselves in soil, artificial medium, and inside plants (Maela and Serepa 2019). These salutary microbes can be transmitted to various generation of plants through sexual units such as seeds and spores (Soldan et al. 2019). Wild species of dicotyledonous and monocotyledonous plants are also a hub of various endophytes. On the basis of various studies on endophytes, they are classified as bacteria, fungi, algae, actinomycetes, and transgenic endophytes as shown in Fig. 7.1. Archaebacterial and mycoplasma endophytes also exist in plants, but there are not enough studies on them (Maela and Serepa 2019; White et al. 2019).

These endophytes may perform various roles in plants such as adaptation and resistance against temperature stress and environmental stress and overcome the salinity, and they also help in stimulating plant growth, which may be direct and indirect. Direct roles are biological nitrogen fixation (BNF), phosphorus solubilization, potassium solubilization, siderophore production, IAA production, ACC utilization, ammonia excretion, lytic enzyme secretion, and phytohormone production, and indirect roles may be designated as production of metabolite, induction of plant resistance, and promotion of plant growth (Fadiji and Babalola 2020; Sansanwal et al. 2017). An endophyte can be a good candidate for biofertilizers. A biofertilizer is a consortium of viable microbes which when used on seeds, plants, and soil will colonize the rhizosphere and internal structures of plants, seed, etc. Furthermore, when these endophytes colonize the inner part of plants or its reproductive bodies, they exert direct beneficial effects. This exercise will obliterate the use of chemical fertilizers because of the adverse effect of chemical fertilizer on crops and on human health. They not only affect crops or humans but also deteriorate the quality of soil and damage the environment (Panpatte et al. 2017; Sansanwal et al. 2017). Endophytes also help in phytoremediation of heavy metals from soil, and they also produce gluconic acid (GA) (Oteino et al. 2015).

7.2 Mode of Transmission of Endophytes

Transmission is important for the survival of endophytes as well as for plant species because endophytes help plants in certain ways; thus, endophytes can be transmitted from parents to progeny and from one individual plant to another in the same community. Therefore, based on this view, the mode of transmission can be of two types (Kuzniar et al. 2019).

7.2.1 Vertical Mode of Transmission

It is a direct mode of transmission in which endophytes are transmitted from parents to offspring via seeds and through pollens.

7.2.1.1 Vertical Transmission Through Seeds

In the surface-sterilized seeds of various plant species such as alfalfa, maize, rice, coffee, tobacco, barley, pumpkin, and quinoa, various bacterial species are found to be more dominating than other microorganisms. These endophytic bacterial species have been also detected in a range of wild plant species, including *Pachycereus pringlei*, *Lolium rigidum*, *Eucalyptus* spp., and *Picea abies*. These endophytes are found to be present in different parts of seeds such as embryonic tissues, coat, and endosperm. *Bacillus*, *Pseudomonas*, *Staphylococcus*, *Acinetobacter*, and *Micrococcus* are examples of some common bacterial genera which are present as endophytes in seeds. Endophytes are comparable to biofertilizers as they are known to impart beneficial properties to plants. For example, in rye grass, they produce cytokines which help in releasing seed dormancy. Endophytes help in fixing nitrogen and help plants to survive in extreme environments. In vitro tests demonstrated that they also have antifungal properties against fungal plant pathogens. It was observed that in rice seed if endophytes are removed, seedling of the rice seed will become restricted (Frank et al. 2017). Those endophytes present inside the seeds protect plants against diseases and abiotic stress. They also help in better germination and preserve seeds for a longer period of time (Girsowicz et al. 2019).

7.2.1.2 Vertical Transfer Through Pollens

Male gametes are a possible way for transmission of endophytes, but pollens are also being a method of horizontal way of transmission because they can easily be colonized by the atmosphere, animals, and through pollinators. *Enterobacter* spp. were isolated from fertilized *P. brutia* ovules. 10^6–10^9 numbers of bacteria are found on per gram of pollen; they are present as clusters, biofilms, and single cells. There are different types of endophytes and it depends upon plant species, plant-specific endophytes, antimicrobial content of pollen or plants, and nutritional composition of plants.

7.2.2 Horizontal Mode of Transmission

It is an indirect mode of transmission which occurs between two individual plants in the same community. This mainly happens in fungal species in which fungal spores can be easily dispersed among plants through air, animals, and flying insects. Soil is the main source of microorganisms for both below and above the ground because soil contains most of the vital nutrients which are needed to survive in the environment. In the horizontal mode of transmission, endophytes can colonize seeds and roots via soil, and from soil, endophytes first colonize spermosphere, and in this endophytes have beneficial effects on the germination process. Secondly, they can also colonize through the root endosphere region via rhizosphere where vast numbers of microorganisms are present which promote plant growth and also protect against plant pathogens. Flowers and fruits and plant insects can also be a horizontal mode of transmission and colonization of leaves through stomata (Frank et al. 2017).

7.3 Bacteria

Previously isolated endophytic bacteria from Napier grass and characterized by molecular description include *Sphingomonas*, *Bacillus*, *Enterobacter* sp., and *Pantoea* sp. Endophytes were described after sequence analysis and after analysis of the phylogenetic relationship. In this study, representative isolates were selected for the purpose of observing their sequence-based plant developmental capacity and development relationship. Lately, four iso-member endophytic bacteria are capable of colonizing the plant root more rapidly. Plant growth-enhancing features such as production of IAA, production of siderophores, production of ammonia, solubility of phosphates, fixation of nitrogen, and ACC deaminase are the properties of endophytic bacteria and endophytic bacteria also produce some chemicals which have antagonist properties as shown in Table 7.1.

Endophytic bacteria have been able to cause an increase in shoot and length in hybrid pennisetum relative to inoculation controls in both saline and natural environments and to colonize host plant roots. Up to 200 mM NaCl were retained. These PGP attributes are therefore adorable to endophytic bacteria and favourable for growth of plants and higher yields in unfruitful soil, salt ground, and infertile areas. With this peculiarity of the endophytic population, the bioinoculants of agriculture will obviously be used as better biofertilizers. The growth of plants encourages endophytic bacteria and fuels plant growth by discrete mechanisms. They encourage phytohormone production, nutrient absorption (Bibi et al. 2012;

Table 7.1 Benefits and some chemicals produced by endophytes which help plants to grow and survive in stress condition, and these chemicals also have antagonist properties

Benefits of endophytes	Chemicals produced by endophytes	Bacterial spp.
Antibiotics	Antioxidants enzymes	*Acinetobacter*
Antiviral	Volatile compounds	*Cellulomonas*, *Azotobacter*
Immunosuppressive and anticancer compounds	Phytohormones	*Clavibacter*, *Azospirillum*
Antibacterial	IAA (indole acetic acid)	*Pseudomonas*, *Bacillus species*
Antifungal	Cytokinin	*Curtobacterium*, *Pseudomonas*
Antiprotozoal	GA (Gibberellic acid)	*Microbacterium*
Bio-insecticides		

Mei et al. 2014; Sturz et al. 2000), and biocontrol by reduction of phytopathogens. Throughout the plant life cycle, it is created at various times, through various mechanisms, to promote growth and produce endophytic bacteria (Glick 2003). The bioinoculant preparation can be used as a biofertilizer in the field in conformation of endophyte bacterial consortia by using these endophytic bacteria. The use of mixed useful endophytes in agriculture increases the consistency of the soil and eventually helps grow plants. Besides other PGP attributes, ACC deaminase is present in endophytic bacteria activity, and thus the plant root is capable of reducing ethylene levels compared to other endophytes which was recorded earlier with ACC deaminase activity. ACC (ethylene precursor) is converted to ammonia and alkaline butyrates using ACC deaminase enzymes in a stressed setting such as acidic soil conditions (Jha and Kumar 2009; Jha et al. 2012; Glick 1995; Alexander and Zuberer 1991; Burd et al. 2000; Nabti et al. 2010) and promotes the expansion of plants in adverse conditions. High deaminase activity (about 225.2–1106.6 nmol-KB/h/mg) in the endophytic bacterial population has been documented in contrast to non-endophytic deaminase activity (approximately 20 nmol-KB/h/mg) (Glick 2003). The use of plant-building endophytic bacteria as biofertilizer in a region, however, requires attention to maximize the gain within the host plant. In order to increase crop size, and growth use of different endophtes will be beneficial. Promoting low-dose chemical fertilizer and increased use of different biofertilizer has proven to be effective (Wolinska et al. 2017; Singh et al. 2021; Zhang et al. 2020a, b; Mishra et al. 2020; Feng et al. 2020; Lin et al. 2020; Zhan et al. 2020; Ye et al. 2019; Huang et al. 2019, 2020; Fan et al. 2020; Pang et al. 2020; Gangola et al. 2018; Gupta et al. 2018). By increasing the absorption of nutrients in plants and also by preserving soil microbial floral dynamics, biofertilizers are increasing soil fertility (Bhatt et al. 2020a, b, c, d, e, f, 2021a, b, c). Plants are immune to harmful conditions and pesticides by biofertilizers. By plant nutrient intake and also retaining the microbial dynamics of soil, biofertilizers improve soil fertility to enhance their health. Endophytic microbials are discussed in the current sense of how they can make better crop production. Studies show that PGPP (plant growth promotion) attributes are present in both Rhizobium and Pseudomonas and that they make plant nutrients accessible through metabolic modifications, phosphate solubilization, iron chelation, and many more attributes (Bhatt et al. 2015a, b, 2016a, b, 2019a, b, c; Huang et al. 2021).

7.4 Nitrogen-Fixing Endophytes

In the agricultural outlook, some important advantage of endophytes is nitrogen fixation, siderophore production and antagonism against phytopathogens (Franche et al. 2009). In soil, diverse kinds of microorganisms are found including bacteria, fungi, protozoa actinomycetes, and algae. Among all these spp., *Rhizobia* were studied extensively in various aspects like physiological, biochemical, and molecular level to facilitate plant growth and to increase plant productivity without fertilizers, and their applications are widely used in maize, wheat, etc. Diazotrophic endophytic bacteria not only promote plant growth; besides they produce a variety of compounds that have antagonistic properties and are used as a defense system as shown in Fig. 7.2. Endophytic microorganisms not only remove nitrogen from the environment but also provide nitrogen to plants for their stable growth.

The relation between nitrogen fixation and bacteria is very important but how endophytes fix nitogen is needed to understand and these are some organisms which help in fixing the nitrogen, *Azoarcus*, *Azospirillum brasilense*, *Burkholderia* spp., *Klebsiella*, *Gluconacetobacter*, *Herbaspirillum*, and *Serratia*, and many others

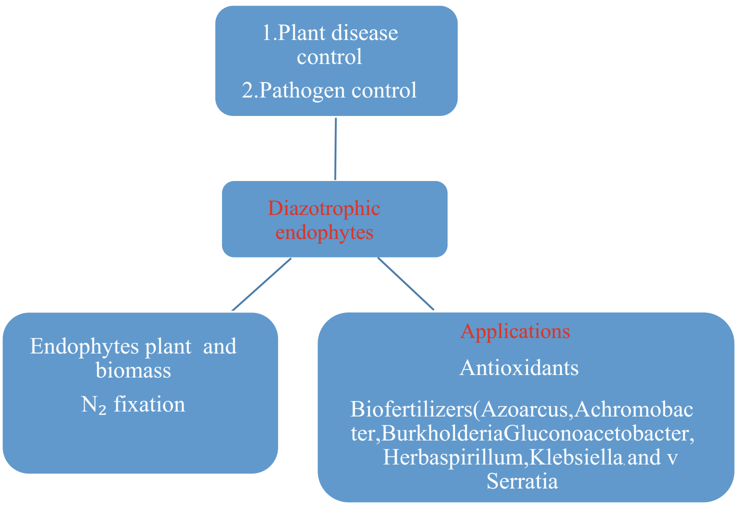


Fig. 7.2 Diazotrophic endophytes as biofertilizers

availability much easily (Rothballer et al. 2008; Ahmad et al. 2008). Various bacteria such as *Azoarcus* spp. produce siderophores to deplete the deficiency of iron (Newton 2000) by provided iron to plants by soil bacteria help in several situations like heavy metal pollution. However, the concentration of siderophores affects the growth of plants. Nitrogen attachment mechanism is performed in the *nif* genes, and a total of 16 ATP is consumed throughout the process. As compared to the free-living bacteria, symbiotic association fixes more nitrogen. Oxygen works as an inhibitor for enzyme nitrogenase and acts as a negative regulator of nif gene expression. The nitrogenase is responsible for catalysing reduction of (N_2) to ammonia (NO_3) (Gupta and Nath 2015). Nitrogenase enzyme is sensitive to oxygen that irreversibly inactivates diazotrophs (N_2) fixation which, on the other hand, permits supply of oxygen required for every regeneration and protects from deleterious effect of O_2. In this situation, bacterium *Rhizobium* spp., which populate internal plant tissue niche with or without minor complaint to host plants, switch on a process that is known as biological nitrogen fixation (Gupta et al. 2012). The ongoing research assuming that some endophytes such as diazotrophic *Gluconacetobacter*, *Serratia marcescens*, and *Azoarcus* sp. will be good as biofertilizers in agricultural areas (Annapurna et al. 2018). They are also suitable for use.

Information is also available on N fixation by non-legumes and bacteria other than rhizobia (Tanjung et al. 2017; Ohyama et al. 2014). *Sphingomonas azotifigens* were first identified in India as a novel bacterium when they were N fasteners (Naylor et al. 2017; Singh et al. 2017). The earlier documented or identified plant pathogens were *Stenotrophomonas maltophilia* and *Herbaspirillum rubrisubalbicans* that showed high N fixation and potentials for auxin production. Diazotrophic endophytes bacteria colonize the palm leaves and also found that *Bacillus cereus* do excessive nitrogen fixation (Aryantha and Hidiyah 2018; Sharma and Roy 2017). For *Exiguobacterium*, the ability to attach N has also confirmed N4 strong strain of *Amaranthus spinosus* colonization (Rodriguez et al. 2009).

7.5 Fungal Endophytes

Microorganisms have provided a large variety of biologically active compounds, which have broad applications in human health and diseases. Fungus is ubiquitous in nature, and it lives inside the host plant for being a part of their life cycle without causing visible proclamation. In 1928, antibiotic penicillin from *Penicillium notatum* was discovered by Alexander Fleming, which was used later during the Second World War. After that, various antibiotics were discovered, such as Chloramphenicol, Streptomycin, Tetracycline, Griseofulvin, Cyclosporine, and Taxol from different fungal species, and therefore, this period is known as the Antibiotics Era. After that in the twenty-first century, novel antibiotic compounds were isolated from different fungal species as it has the ability to produce potential pharmaceutical products which will be used for various purposes (Naylor et al. 2017; Singh et al. 2017; Aryantha and Hidiyah 2018; Sharma and Roy 2017; Rodriguez et al. 2009).

7.5.1 Classification of Endophytic Fungi

Fungi are classified into two major groups on the basis of their evolutionary relatedness, taxonomy, plant hosts, and ecological functions.

1. Clavicipitaceous endophytes
2. Non-clavicipitaceous endophytes

Apart from these two main groups, there are four classes of endophytic fungi:

- Class I endophytic fungi
- Class II endophytic fungi
- Class III endophytic fungi
- Class IV endophytic fungi

7.5.1.1 Class I Endophytic Fungi

Clavicipitaceous endophytes are the class I endophytes reported in the late nineteenth century by European investigators from seeds of *Lolium arvense*, *Lolium temulentum*, and *Lolium remotum* (Arnold et al. 2002).

7.5.1.2 Class II Endophytic Fungi

The class II endophytic fungi contain a great diversity of species belongs to Dikaryomycota, which consists of Ascomycota and Basidiomycota. In 1915, Rayner reported a phoma species called *Calluna vulgaris*. The crucial point is that they always colonized all parts of the plant including the seed coat. Now recently, they become a common root endophyte that confers benefit to plant.

7.5.1.3 Class III Endophytic Fungi

This class is differentiated on the basis of occurrence, that is, above-ground tissue; this class transmits horizontally and is extremely high in plant biodiversity. This class includes the hyper/high endophytic fungi that are associated with the leaves of tropical trees (Suryanarayanan et al. 2005). Class III endophytes span from above-ground tissues of non-vascular plants to the seedless vascular plants, conifers, and herbaceous angiosperms in biomes and differ from tropical forests to Boreal and Arctic/Antarctica communities (Arnold et al. 2002).

7.5.1.4 Class IV Endophytic Fungi

The discovery of class IV endophytes is concluded during the study of ectomycorrhizal fungi, where Naik Shankar et al. 2008 remarks a pigmented fungus, which is brown to blackish in appearance, and it is associated with terrestrial plant roots that are called as MRA. This species is found with mycorrhizal fungi and implied as pseudomycorrhizal fungi. Recently, these fungi are mentioned as DSE (dark septate endophytes) and come under class IV endophyte. A century has passed since it was discovered, but the role of these queer fungal symbionts is still unknown. Apart from diseases, fungi are beneficial to humans as they produce numerous alkaloids (ergot alkaloids from *Claviceps*), some enzymes (cellulose, lipase, ligninolytic enzymes), and also some pigments (anthraquinone, betalains, aroma, and flavours); besides these, they also play an important role in the control of nematodes. Some fungi are edible like mushrooms and they are useful to our health as they are abudant in minerals, vitamins and proteins like selenium, potassium, riboflavin, niacin, vitamin D, proteins. Endophytes are reported from plants that can be found in various environments including trophic, temperate, aquatic oceans, xerophytic deserts, Antarctic, geothermal soils, rainforests, mangrove swamps, and also coastal forests (Naik Shankar et al. 2008). Endophytic fungi from 15 shrubby medicinal plants grow in Malnad region and southern India (Raghukumar 2008). She also reported that the isolation of a greater number of endophytic fungi happens in the winter season rather than in monsoon and the summer season. In India less number of discoveries are available or we can say that few reports are available on endophytic fungi, blooming in mangrove plants. It is interesting that mangrove plants have shown to adapt to anaerobe soil, muddy saline waters, and brackish tidal activation. Narayanan et al. (2014) reported on cell wall enzymes such as pectinases, proteases, and pectate transeliminase from endophytic fungi and their leaf litter degradation activity when exposed to extreme conditions in terrestrial and marine environment such as high temperature at tropical areas, elevated hydrostatic pressure, low temperature in deep sea, and aloft hydrostatic pressure. Like all other endophytes, endophytic fungi with mangrove plants protect mangrove from adverse environment conditions (Jeffery 2008). Many species of fungi include *Aspergillus* (Narayanan et al. 2014; Jeffery 2008), *Beauveria bassiana*, *Trichoderma harzianum*, *Lecanicillium lecanii*, *Metarhizium anisopliae*, and *Fusarium* spp. According to reports, most common endophytes are *Aspergillus*, *Phomopsis*, *Wardomyces*, *Penicillium*, and many unidentified fungi. Species *Colletotrichum gloeosporioides*, *Fusarium solani*, *Pestalotia*, and *Phomopsis* were predominant endophytes though *Colletotrichum gloeosporioides* establish as endophyte and it is a pathogenic fungus for Cashew tree, which is reported by some authors during studying different hosts. A substantial research was go through using several other fungi isolated mainly a epiphytic in an attempt to Jurisdiction pathogen *C. gloeosporioides* being a thrichoderma strain, the most hopeful one. Fungal endophytes have the most unique adaptation in nature; with respect to future prospects that how endophytes communicate with each other in contrast to their pathogenicity for such innovative purposes, endophytic fungi should be an effective topic to study.

7.6 Actinomycetes Endophytes

Actinomycetes are one of the most abundant groups of microbes which is extensively distributed in nature. Predominantly, they are found in dry alkaline soils (Fouda et al. 2018). Endophytic population was greatly impacted by climatic conditions and locality where their host plant grows (Waheeda and Shyam 2017). Endophytes reside within plant tissue to finalize their life cycle, despite no deleterious effect, and play a noteworthy role in aggravate growth of host plant by producing phytohormone and build plant tolerant to various stresses, other growth-encouraging factors in order they are compensation with nutrients and shields within host plant as shown in Fig. 7.3.

Bacteria present in the rhizosphere is different from endophyte because endophytes are aunthetic and specific to its habitat as they resides within the plant tissue (Kumar and Jadeja 2016). Endophytic actinobacteria are examined to be a substitute to combat multidrug-resistant human pathogens as they serve as a latent source of novel antimicrobial compounds (Limaye et al. 2017). Plant diseases can be reduced by actinomycetes using distinct mechanisms. A method known as pyrosequencing is used to disclose a wide range of bacteria that live in and around roots of plants such as *Actinobacteria*, *Bacteroide*, *Verrucomicrobia*, and *Proteobacteria* (Limaye et al. 2017). Some actinomycetes secrete a range of enzymes that can entirely degrade all components of lignocelluloses such as lignin, hemicelluloses, and cellulose (Andreote et al. 2014). Because of their ability to secrete enzymes, they are virtual in attacking raw beer. Bioactive molecules from actinobacteria and their biosynthetic

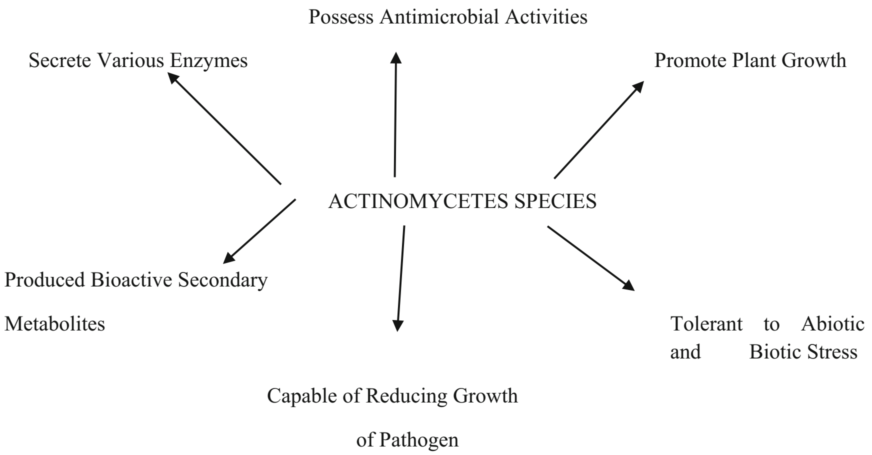


Fig. 7.3 Actinomycetes species and their various applications

genes have been less studied; bioprospecting of actinobacteria for bioactive molecules holds great promise.

There is an increasing necessity for discovery of new drugs, due to the increasing threats day by day which incorporate drug-resistant pathogens. In order to achieve this, novel strategies are needed to be applied to search for a new molecules to fight against resistan microorganism. One of which is "Renaissance" in antibacterial discovery from actinomycetes. Internally colonizing microbes play various roles in widening and plant fitness. A few of them also cause diseases (Yang et al. 2015) but the interaction is said to be beneficial. Antibacterial compound-producing strains belonging to genera *Streptomyces*, *Nocardiopsis*, *Pseudonocardia*, *Agrococcus*, and *Isoptericola* have been reported from mangrove plants in Beilun River, Beilum Estuary National Nature Reserve, China (Purushotham et al. 2018). Actinomycete strains have genetic ability to produce 10–20 secondary metabolites. *Pseudowintera colorata* (Horopito) is an indigenous medicinal plant of New Zealand. In the study of *Pseudowintera colorata endophytes* it was observed that microbial communities in roots and stems are not diverse but in leaves microbial communities were found to be spare diverse on the basis of DGGE pattern. Profusion of actinobacteria taxa was steeper in stems (39%) and roots (27%). However, three clones among them were identified as uncultured bacteria (Oskay et al. 2004). Compounds from the rare organisms include *Teicoplanin* and *Actinoplanes teichomyceticus* (Kaaria et al. 2012). In vitro actinomycetes isolated from Turkey's farming soil have shown the ability to inhibit *Erwinia amylovora* bacteria that cause fire blight to apple and *Agrobacterium tumefaciens*, a causal agent of crown gall diseases. In view of the increasing threats day by day which include drug-resistant pathogens, there is an increasing need for discovery of new drugs. In order to, this challenge, novel strategies are to be applied to searching new molecules.

7.7 Algae Endophytes

We all know that endophytes have a symbiotic association with plants, and sometimes they act as a biocontrol agent because they protect plants from animals to produce certain compounds which help plants to become safe. When we heard about the word endophyte, automatically in our mind bacterial endophytes strike. In various aspects of life, algal endophytes also play an important role (Bacon and White Jr. 2000). Marine algae is found in coastal regions including some cyanobacteria and other microbes. The marine microbes were isolated from red algae, green algae, and brown algae as shown in Fig. 7.4.

In red algae, brown algae and green algae, red algae has highest bioactivity among all. It is found that marine algae harbour some epiphytic and endophytic microbes that produce antimicrobial substances that can inhibit human pathogens. They also produce bioactive compounds that can be used by plants (Fremlin et al. 2009). Besides this, they produce some antiprotozoal, antiparasitic, antiviral, and

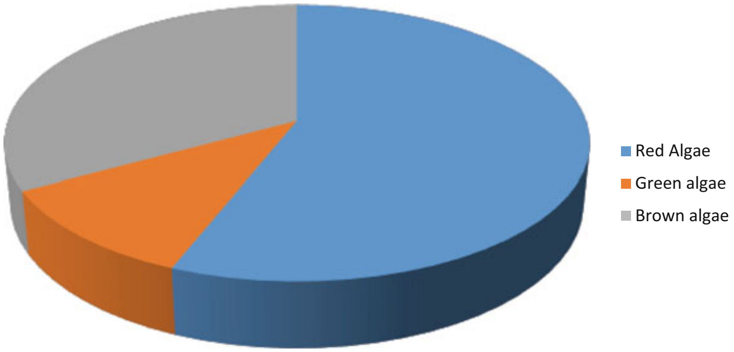
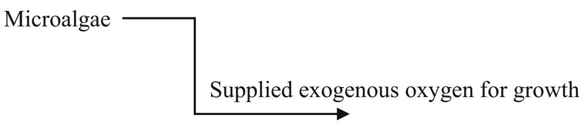


Fig. 7.4 Pie chart indicating the bioactivity (%) based on class of algae

antitumour activities (Vesterlund et al. 2011). It is shown that host plant tolerance to various stress, such as abiotic, is increased by endophytic infection (Gonzalez-Bashan et al. 2000) and biotic. There are some naturally grown microalgae which are found to be associated with bacteria (Suminto and Hirayama 1997). Currently it is seen that the plant growth-promoting bacterium (PGPB) *Flavobacterium* spp. was built to aid the growth of a marine alga (*diatom Chaetoceros gracilis*) which is used as a feed in oyster hatcheries (Correa et al. 1987). With the help of the above example, we understand how bacteria and microalgae are mutually beneficial for each other.



7.7.1 *Chlorella vulgaris*

There are several advantages of PGPB in which environmental application is most important, For example, *Azospirillum* species add in wastewater for its treatment with microalgae to enhancing the development microalgae metabolites. Microalgae have numerous uses such as water bioremediation. *Chlorella vulgaris* and *Scenedesmus dimorphus is* a unicellular microalgae, which is used for separating the phosphate and nearly all of the ammonium from dairy industry and pig farm wastewaters. Now in such studies, microalgae were in a shelving. Although these crisp populations of such algal endophytes are pigmented (Plumb 1999; Correa et al. 1988). Some endophytes have been capable of nutritional independence; this indicates that they have cultured separately from their host Acrochaete heteroclada (Nielsen 1979; Kumar et al. 2015) have previously been allocated to green algal *Chondrus* *crispus*-associated endophytes. A variety of endophytic strains are host to Stackhouse Red Algae *Chondrus Crispus*, including pigmented algae, Multicellular species (Chlorophyta) and pigmented brown (Heterokontophyta) respectively.

7.8 Methanogens as Endophytes

Methylotrophs are those, which can grow by using reduced carbon sources such as methanol or methane can grow by apply the diminish carbon substrates (Kumar et al. 2016; Meena et al. 2012) some are found advantageous and non-pathogenic for plants (Pirttila et al. 2005; Holland and Polacco 1992) during study of soybean seedling. Endophytic methylotrophic bacteria have been marked to increase seedling growth closely with root biomass growth (Dourado et al. 2012). Some methylotrophic endophytic reported are *Methylobacterium* sp., *Methylovorus mays*, mesophilic *methylobacterium extorquens* and *methanotropics*, directly or indirectly, plant growth plants directly or indirectly (Ferreira et al. 2008; Raghoebarsing et al. 2005). Some methanotrophs are described as biofertilizers to assembled the agricultural development up to the agricultural fields (Keerthi et al. 2015; Rekadwad 2014; Dourado et al. 2015). Ubiquity and worldwide appendage of genus *Methylobacterium* sp. is found as Epiphytic and Endophytic bacteria and PPFM of *Methylobacterium* sp. are found (pink pigmented facultative methylotroph) the biotechnology and agronomic future group is reported (Baldani et al. 2000). In the current conclusion, PPFM and the spinal pseudomonas Biofertilizers have differed and the intensification of plant growth has been shown in the field to be continuously forward with positive microbial soil production. Endophytic *Methylobacterium* species NPFM-SB3 was found to be remote from the Sesbania stem nodules, a symbiotic company with rice plant can be systemized (Gyaneshwar et al. 2005; James et al. 2000). Recently during Fe famine, *Methylobacterium phyllosphere* (insulated from the lowland rice phyllosphere) triggered the hydroxamate of the form siderophores, as well as tryptophan and tyrosine during Fe famine. The main forebear for methane producing by methanogenesis is frequently acetate, which is one of the largest products from anaerobic digestion of organic compound by bacterial metabolism (Karakashev et al. 2011; Smith and Mah 1978; Thauer 1998; Ardanov et al. 2011). Methylobacterium fertilizer and the priming ability of *Methylobacterium* sp. have been used in potato development. Also, IMBG290 was observed. The priming of plants with beneficial bacteria and advantage of using beneficial bacterial strain is that they induce host plant rescue energy and decrease growth and growth time. Plant priming the host saves energy and reduces the time taken by non-pathogenic bacteria during a pathogen attack for the development of the defense reaction (Doty 2008).

7.9 Transgenic Endophytes

Formerly research was conducted on plants to improvise its ability to reduce environmental pollution. Genes from many plants, microbes, and animals were inserted into plants to enhance their pollution degrading abilities, known as transgenic plants (Yang et al. 2017). For extensive use of endophytes in the field of agriculture and forestry, some useful genes can be inserted into endophytes to introduce new features into the microbes. In the study conducted by Glandorf et al. (2001) to control lepidoptera larvae, in which the insecticidal protein gene of *Bacillus thuringiensis* was inserted bacterial endophytes *Burkholderia pyrrocinia* JK-SH007 to control lepidopetra larvae. Cloning of cry218 gene was done using PCR, and PHKT2 expression vector was used for the introduction of gene into JK-SH007 (Glandorf et al. 2001). *Pseudomonas putida* WCS358r was genetically modified. Mini-Tn5 lacZ1 transposon was used as a delivery vector (size 6.8 kb), in this *Bgl*II-XbaI fragment was incorporated that carrying the *phzABCDEFG* genes from Pseudomonas fluorescens 2–79 and inserted into *Pseudomonas putida* to produce phenazine-I-carboxylic acid (PCA), which shown antifungal action, when released into wheat plant rhizosphere (Patra et al. 2017). Transgenic endophytes will have bright future in the field of agriculture because they can be used as biofertilizers, biocontrol agent and for plant growth promotion also by inserting the gene of interest into the endophytes.

7.10 Role of Endophytes as Biofertilizers

Biofertilizer is a consortium of living microorganisms together with minerals plus nutrients that help in plant growth promotion without changing soil properties; they also secrete secondary metabolites and bioactive compounds; biosynthesis of bactericides and fungicides protects plants from environmental stress (Kuzniar et al. 2019; Lobo et al. 2019). Biofertilizers provide plants a great amount of minerals such as potassium, phosphorous, nitrogen, and siderophores as well as exopolysaccharides (Lobo et al. 2019). Optimal condition must be followed to produce low cost-efficient inoculant consortium which can promote plant growth (Patle et al. 2018).

7.11 Plant Growth-Promoting Endophytes

Plant growth-promoting endophytes have vast functions like IAA production, phosphate solubilization, siderophores, N_2 fixation, and ACC utilization as shown in Fig. 7.5.

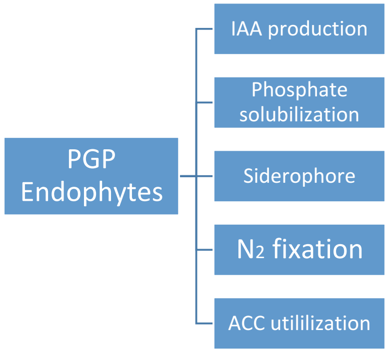


Fig. 7.5 Different roles of PGP endophytes

7.12 IAA Production

There are a lot of endophytic bacteria and fungi present, which can synthesize many phytohormones such as auxin, cytokines, and gibberellins, in which indole-3-acetic acid is very common and it contains the carboxyl group which is joined to the third carbon of indole group (Maela and Serepa 2019; Zahir et al. 2003; Valérie et al. 2007). IAA helps in cell division and enhances the root length and hair, thus increasing the number of sites for infection and nodulation. This change will help in better absorption of nutrients and in turn stimulate plant growth (Zahir et al. 2003; Susilowati et al. 2018). IAA helps in stimulation of tuber and germination of seed, it also increases the rate of root and xylem development, it stimulates pigment formation, and it also mediates the responses to gravity, florescence, and light and also affects photosynthesis (Sansanwal et al. 2017). It is the direct mechanism of PGPR that stimulated the growth and yield of plants but a high level of IAA can lead to abnormalities in plants during its development stage, and the low level of IAA stimulates root elongation (Maela and Serepa 2019). The production of IAA is stimulated by the amino acid known as L-tryptophan which acts as a physiological precursor for IAA production in plants and microorganisms. It was observed that the production of IAA can be increased up to 2.7 times in the presence of L-tryptophan amino acid (Audipudi et al. 2017). An increase in the amount of nitrogen in soil leads to the production of auxin that softens the cell wall, thus increasing the water retention capacity by increasing the cell size, and the addition of these cells can increase the weight of rice. Biofertilizers containing a mixture of *Azospirillum*, *Pseudomonas*, and *Bacillus* increase nutrient uptake and plant growth and also increase the size of the rice grain (Audipudi et al. 2017). Bacteria can convert tryptophan to IAA through four pathways, which include Indole-3-acetamide (IAM), Indole-3-pyruvate (IpyA), Tryptamine (TAM), and Indole-3-acetonitrile (IAN) pathways. The indole-3-acetamide pathway forms directly IAA without any intermediate compound. IAA-producing bacteria through the indole-3-pyruvate (IpyA) pathway are known, and the pathway is illustrated below in Fig. 7.6 (Audipudi et al. 2017).

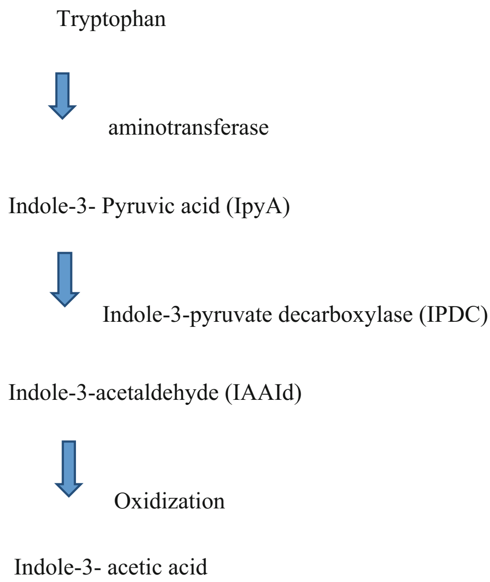


Fig. 7.6 IAA production through IpyA pathway

In one study the authors showed that 15 endophytes isolates were positive for IAA production out of 65 endophytes, and they produce 25 μg/mL of IAA. *Acetobacter diazotrophicus* and *Herbaspirillum seropedicae* produce IAA in chemically defined culture media. They tested ten isolates of *Typha australis*, of which seven isolates were positive for IAA production (Matos et al. 2017). In a study genera *Bacillus*, *Micrococcus*, *Escherichia*, *Staphylococcus*, and *Pseudomonas* were tested with wild herbaceous flora for the level of IAA production and growth of *Triticum aestivum*. Results were obtained using Gas Chromatography and Mass Spectrometry (GC-MS), which shows enhanced root length and seed weight by 16% and 70%, respectively, by bacterial endophytes (Maela and Serepa 2019).

7.13 Phosphate Solubilization

Phosphate is the second most essential macronutrient which plants need for their growth and development after nitrogen, and the average amount of phosphorous found in soil is 400–1200 mg/kg of soil. Soil types and its pH determine the precipitation and adsorption of phosphorous (Gull et al. 2004). It is hard to be utilized by plants itself because phosphate basically presents either as a mineral or in an insoluble form, which has poor mobility, and this is due to the reactivity of phosphate ion with other constituents present in the soil (Maela and Serepa 2019; Lin et al. 2013; Wei et al. 2018). Endophytic microorganisms secret some organic acids such as citric, acetic, succinic, and oxalic acid, and they also secret phosphate and also use mechanisms like acidification, chelation, and ion exchange, thus making phosphorous available to plants by converting it into soluble mono- and dibasic forms. Some environmental factors like pH, oxygen, humidity, and temperature can affect the whole process of phosphate solubilization (Afzal et al. 2019; Maela and Serepa 2019).

In one study, different bacterial endophytes were isolated from the two types of medicinal plants such as *Zingiber officinale* and *Azadirachta indica* on different culture media. After the isolation, isolates were screened for various activities like IAA, phosphate solubilization, siderophore production using biochemical characterization, morphological identification, and molecular ribotyping; fives isolates were characterized as *Bacillus tequilensis* (AAU K1), *Bacillus endophyticus* (AAU K2), *Beijerinckia fluminensis* (AAU K3), *Bacillus safensis* (AAU K4), and *Pseudomonas aeruginosa* (AAU K5). From the wheat root *Penicillium radicum* was isolated which is a phosphate solubilizing fungus; it shows plant promoting activity in vitro. Phosphate solubilizing endophytic bacteria can play a very important role in the field of agriculture as the demand for biofertilizers is increasing (Maela and Serepa 2019; Lacava et al. 2008).

Some of the compounds present in acidic soil such as weak aluminium, oxyhydroxides, and iron oxide can retain phosphorus and that results in a low amount of phosphorous. Phosphate fertilizers are of great importance, but in alkaline soil calcium leads to less efficient solubilization of phosphate fertilizers (Sansanwal et al. 2017; Panpatte et al. 2017). In one study, a total of 40 endophytic isolates were isolated from the root of banana tree and evaluated to check the phosphate solubilizing activity, in which 67.5% isolates solubilized phosphorus from tricalcium phosphate in solid medium and 7.5% isolates in soy lecithin solubilized phosphorus. In iron phosphate containing medium no isolates show P solubilization activity. Isolates *Aneurinibacillus* sp. and *Lysinibacillus* sp. showed best solubilization activity, and other genera and species that exhibited positive results were *Acetobacter* sp., *Agrobacterium tumefaciens*, *Bacillus amyloliquefaciens*, *Aneurinibacillus* sp., *Bacillus subtilis*, *Bacillus pumilus*, *Streptomyces* sp., *Micrococcus luteus*, and *Bacillus* sp. (Panpatte et al. 2017). Endophytes also prevent the absorption and fixation of phosphate when its amount is not sufficient (Afzal et al. 2019). Phosphate solubilizing bacteria (PSB) can solubilize inorganic phosphate, which is present in the form of $Ca_3(PO_4)^2$, $FePO_4$, and $AlPO_4$ by producing hydroxyl PGPB, organic acid, and siderophores in soil (Sansanwal et al. 2017).

7.14 Siderophore Production

Siderophores are the low molecular weight iron-containing complex present on the bacterial membrane in the form of Fe^{3+} and then get reduced to Fe^{2+} released into the cell from siderophore complex through the gating mechanism. When there is a high level of contamination of heavy metals and when plants starve from iron availability, bacterial endophytes make it available to plants (Fadiji and Babalola 2020; Sansanwal et al. 2017). Siderophores sometimes also serve as a great biocontrol agent such as phenolate, hydroxymate, and catecholate type which are produced by endophytes species, and they also help in fixing atmospheric nitrogen in diazotrophic organisms because for the functioning and biosynthesis of enzyme nitrogenase (key enzyme in N_2 fixation) diazotrophic organisms require Fe^{2+} and Mo factor (Fadiji and Babalola 2020). In the absence of heavy metal contamination, absorption of iron can be performed by other mechanisms like iron chelates directly lead to siderophores absorption or through ligand exchange. *Pseudomonas* strain GRP3 which is a siderophore-producing strain was tested for iron nutrition on *Vigna radiata*. Forty-five days of evaluation with endophytic organism, showed betterment in iron availability and in chlorotic symptoms and there is also an increment in the amount of chlorophyll a and b as compared to the control results in plants (Fadiji and Babalola 2020; Sansanwal et al. 2017). Actinomycetes endophytic species like *S. acidiscabies E*13, *Streptomyces* sp. Mhcr0816, *Nocardia* sp., *Streptomyces* sp. UKCW/8, and *Streptomyces* sp. GMKU 3100 are great producers of siderophores (1). In one study conducted on *Methylobacterium* sp. which belongs to the same niche as *X. fastidiosa* subsp. *pauca* (Xfp) isolated from citrus variegated chlorosis (CVC) showed that catechol-type siderophore is not produced by *Methylobacterium* sp. and it is the producer of hydroxamate-type siderophores (Tang et al. 2019).

7.15 N_2 Fixation

Endophytes perform various vital functions for plants, in which nitrogen fixation is one that abolishes the use of chemical fertilizer to prevent crops as well as the environment from harmful effects. Basically, nitrogen fixation is done by legume plant rhizobium. For the first time in India *Sphingomonas azotifigens* is a novel bacterium reported to be N_2 fixing bacteria. *Bacillus cereus* showed highest N_2 fixing ability in oil palm leaves. *Herbispirillum rubrisubalbicans* and *Stenotrophomonas maltophilia* were considered as plant pathogens but were efficient to do biological nitrogen fixation. *Exiguobacterium profundum* strain N4 which colonizes *Amaranthus spinosus*, *Azospirillum*, *Rhizobium*, *Agrobacterium*, and *Sphingomonas* in wild rye tissue also performs nitrogen fixation (Kuzniar et al. 2019). One non-rhizobial endophytic consortium which shows very promising results in BNF includes *Achromobacter*, *Burkholderia*, *Herbaspirillum*, *Azoarcus*, *Gluconacetobacter*, *Serratia*, and *Klebsiella*. In sugarcane *Gluconacetobacter diazotrophicus* is an endophytic organism which has the ability to fix nitrogen up to 150 kg N ha^{-1} $year^{-1}$. In kallar grass, obligate endophytic diazotrophs known as *Azoarcus* fix nitrogen (Sansanwal et al. 2017). A fungus known as *Phomopsis liquidambari* in rice promoted better functioning of nitrogen and phosphorus by inhibiting or promoting various indigenous soil microbes (Card et al. 2016).

7.16 1-Aminocyclopropane-1-Carboxylate (ACC) Utilization

Ethylene is the most essential plant hormone or metabolite which every plant has and that helps in the growth and development of the plant. It is affected by different abiotic and biotic stresses, and it also controls many activities in plants like cell elongation, leaf senescence, root nodulation, abscission, auxin transport, and fruit ripening (Afzal et al. 2019; Fadiji and Babalola 2020). Many stress conditions like drought, high salinity, pathogenicity, and the presence of extreme concentration of heavy metals cause the elevation of ethylene levels which lead to inhibition of root elongation, formation of root hairs, and alteration in cellular processes. In these stress conditions, endophytic organisms which reside inside the plant produce an enzyme known as 1-aminocyclopropane-1-carboxylate (ACC) deaminase; it is a pyridoxal phosphate-independent enzyme which breaks down the ACC (precursor of ethylene). ACC-degrading genera include *Agrobacterium*, *Enterobacter*, *Bacillus*, *Achromobacter*, *Acinetobacter*, *Pseudomonas*, *Alcaligenes*, *Ralstonia*, *Serratia*, *Rhizobium*, and *Burkholderia*. These organisms can bind to roots of plants and break down the ACC into α-ketobutyrate and ammonia and use ammonia as a nitrogen source, thus promoting plant growth under extreme conditions (Afzal et al. 2019; Fadiji and Babalola 2020). *Pseudomonas putida* HS-2, which has purified ACC enzyme, was used to enhance the growth of tobacco plants (Maela and Serepa 2019).

7.17 Biocontrol Activity by Endophytes

Protection of plants from plant pathogens or phytopathogens which can retard plant growth and can make plants diseased and sabotage the agricultural crop is known as biocontrol activity. Chemical fertilizers can prevent plants from phytopathogens but these chemicals have harmful effects on soil, environment, and microflora of plants and soil, so endophytic organisms are a great way to control phytopathogens. Some endophytes release bioactive compounds in their specific host plant species as mentioned in Table 7.2.

Endophytes that act as BCA have shown four mechanisms to control pathogens: (1) antibiosis, (2) competition, (3) host-induced resistance, and (4) direct parasitism. Some bacterial endophytes have shown plant protection from various diseases such as Fusarium, Verticillium, Eggplant, and Verticillium wilt, and these endophytes are *Erwinia persicina*, *Pantoea agglomerans*, *Achromobacter piechaudii*, *Enterobacter cloacae*, *P. fluorescens*, *Serratia plymuthica*, *S. marcescens*, *B. amyloliquefaciens*, *Paenibacillus*, sp., *Enterobacter* sp., *Bacillus subtilis*, etc. (Lobo et al. 2019; Agrillo et al. 2019). Siderophores play an important role to fight against phytopathogens by endophytes because endophytes release siderophores such as salicylic acid, chelate iron, and pyochelin which bind all available iron, so that other organisms starve for it and eventually die. 2,4-diacetylphloroglucinol (DAPG) is an antimicrobial

Table 7.2 Examples of endophytic strains and their bioactive compounds which help plants in different biotic and abiotic stress conditions (modified from Bhatt et al. 2019a)

S. No	Endophytes	Bioactive compounds	References
1	*Trichoderma harzianum*	Phytohormones and degradation of cell wall	Glick (2003)
2	*Bacillus amyloliquefaciens*	Antifungal compounds	Yang et al. (2015)
3	*Epichloe festucae* var. *lolii*	Alkaloids	Glick (2003)
4	*Arthrobacter endophyticus SYSU 33332*, *Nocardiopsis alba SYSU 333140*	Genes for water and potassium ion uptake, survival in stress condition	Yang et al. (2015)
5	*Aeromicrobium ponti*	1-Acetyl-β-carboline, indole-3-carbaldehyde,3-(Hydroxyacetyl)-Indole, Brevianamide F, and Cyclo-(L-Pro-L-Phe)	Burd et al. (2000)
6	*Serendipita vermifera*	Hydrolytic enzyme genes, protection from plant pathogen infection	Yang et al. (2015)
7	*Pseudomonas putida*	Trichloroethylene	Burd et al. (2000)
8	*Gibberella moniliformis*	Lawsone	Yang et al. (2015)

compound which is released by endophytes, which inhibit disease causing microorganisms. *Beauveria bassiana* is an entomopathogenic fungi for borer insects in coffee seedlings. Various fungi that have shown great biocontrol activity in the field of agriculture are *Trichoderma koningiopsis*, *Gibberella fujikuroi*, *Aspergillus tubingensis*, *A. flavus*, *Galactomyces geotrichum*, *P. simplicissimum*, *Eupenicillium javanicum*, and *P. ochrochloron* (Lobo et al. 2019). The most studied endophytic BCA are *Bacillus subtilis*, *Beauveria bassiana*, *Asexual Epichloe* spp., *Lecanicillium lecanii*, *Piriformospora indica*, *Rhizobia*, and *Trichoderma* spp. *Beauveria bassiana* works against a wide range of pests such as aphids, beetles, caterpillars, termites, thrips and whitefly; to use *Beauveria bassiana* fungi, regular spray of fungi should be done on infected plants. Asexual Epichloe belong to the family *clavicipitaceae* which are not found in the roots of plants. They have strong mutualism with grass species. Epichloe include *E. festucae* var. *lolii* and *E. coenophiala* which produce alkaloids—secondary metabolites during symbiosis and that work against invertebrate pests. *Lecanicillium lecanii* is a ubiquitous entomopathogenic fungi, which horizontally transmit from one plant to another plant such as from cotton plants to an insect known as *Aphis gossypii* and from insects to leaves. *L. lecanii* strain 41185 is pathogenic to aphides spp., such as *Myzus persicae*, *A. gossypii*, and *Aphis craccivora*. *L. lecanii* also has anti-fungal activity against *Sphaerotheca macularis* and *Hemileia vastatrix* and it also possesses anti-algae activity against soil-borne pathogens like *Pythium ultimum* by producing host-induced resistance and some structural barriers in the plant roots. *Piriformospora indica* is a root-colonizing fungus which is found in the root of xerophytic plants present in Indian Thar dessert. It also colonizes both mono- and dicotyledonous plants such as barley, tobacco, and *Arabidopsis thaliana*. *P. indica* has plant growth-promoting activity and function in both abiotic stress such as salinity, drought, water, cold, high temperature, and heavy metals and biotic stress like antagonism against root pathogens. *Trichoderma* is a fungal species which has a variety of advantages like anti-fungal properties, can survive in various conditions, simple nutritional requirement for growth in vivo and in vitro, fast growth, etc. *Trichoderma* genus involves many species like *T. atroviride*, *T. asperellum*, *T. harzianum*, *T. polysporum*, *T. viride*, and *T. hamatum*. These *Trichoderma* species can be used to target different soil fungal pathogens such as *Phytophthora*, *Rhizoctonia*, *Sclerotinia*, *Pythium*, and *Verticillium* and also work against foliar fungal pathogens like *Botrytis* and *Alternaria* (Valérie et al. 2007). *Erwinia carotovora* is a bacterial pathogen which causes food spoilage and is inhibited by the bacterial endophytes such as *Pseudomonas* sp., *Pantoea agglomerans* and *Curtobacterium luteum*. A fungal species *Cryphonectria parasitica* causing chestnut blight is inhibited by bacterial endophytes, i.e., *Bacillus subtilis*. *Clavibacter michiganensis* subsp. *Sepedonicus* was inhibited by bacterial endophytes isolated from potato stem tissues (Audipudi et al. 2017; Matos et al. 2017). Some bacterial endophytes have anti-nematode properties like *Bacillus megaterium* BP17 and *Curtobacterium luteum* TC10, which work against *Radopholus similis* Thorne. Bacterial species like *Bacillus thuringiensis* and *Serratia marcescens* produce toxin and enzyme chitinases which target the *Eldana saccharina* larvae (sugarcane borer). Some bacterial genus like *Pseudomonas*, *Bacillus*, and *Serratia* can protect plants by a mechanism known as induced systemic resistance (ISR). ISR can be initiated by three of the pathways: (1) salicylic acid [SA], (2) ethylene [ET], and (3) jasmonic acid [JA]. *Actinobacteria* was inoculated in a plant, i.e., *A. thaliana* showed that bacterial endophytes protected the plant from *Erwinia carotovora* and *Fusarium oxysporum* (Afzal et al. 2019). *Pseudomonas protegens* N has antifungal properties against the genus *Alternaria* and stops spore germination (Gull et al. 2004; Lin et al. 2013; Wei et al. 2018; Lacava et al. 2008; Tang et al. 2019; Card et al. 2016; Agrillo et al. 2019; Walitang et al. 2017).

7.18 Role of Endophytes in Overcoming Oxidative Stress, Salinity, Drought, and Temperature Stress

Endophytes play an important role in the prevention of crop loss by preventing different types of abiotic stress such as extreme heat, salinity, oxidative stress, drought, and temperature. Extreme conditions cause change in phenotype and genetic changes (Sansanwal et al. 2017). Endophytes produce osmoprotectant compounds such as proline, trehalose, exopolysaccharides, and volatile organic molecules (Kuzniar et al. 2019). *Pseudomonas* spp. help *Asparagus* spp. do better seedling and seed germination in extreme water stress. In coastal areas where high saline condition is present, *Pseudomonas fluorescens* MSP-393 has proven to act as PGPR for many crops in that area. *Pseudomonas putida* RS-198 has proven to promote cotton seedling in extreme salt presence by inhibiting the absorption of Na^{+} and increasing the uptake of Mg^{2+}, K^{+}, and Ca^{2+}. Some species of bacterial endophytes such as *Bacillus polymyxa*, *Mycobacterium phlei*, *Alcaligenes* sp., and *Paenibacillus* sp., produce some compounds such as calcisol which has proven to promote the growth of maize plant under extreme temperature and saline conditions (Sansanwal et al. 2017). *Pseudomonas migulae* 8R6 and *Pseudomonas fluorescens* YsS6 can reduce salt stress in tomato plants by secreting ACC deaminase, and it was observed that ACC deaminase activity helps in the production of a greater amount of chlorophyll and increase in dry and fresh biomass. Plants infected with fungal endophytes, i.e., *Neotyphodium lolii* increase the survival chance of plants in drought conditions. Endophytic fungi belong to the group *Ascomycota* and *Basidiomycota*, which increase the tolerance of plants in drought and heat conditions. Endophytic fungi belongs to the genus *Penicillium*, *Trichoderma*, *Aspergillus sydowii*, *Myxotrichum stipitatum*, and *Acremonium variecolor*, which exhibit saline resistance (Kumar et al. 2016). During an environmental stress in plants that can trigger the production of reactive oxygen species such as superoxide, hydroperoxyl radicals, hydrogen peroxide, and hydroxyl radicals, these can cause damage to plant proteins, nucleic acids, and membranes. White et al. (2019) showed that colonization of bacteria at an early stage causes upregulated transcript level of ROS degrading genes which include the genes of SOD and glutathione reductase. *Festuca arundinacea* infected by the endophytic fungi, i.e., *Epichloe coenophiala* has greater concentration of mannitol. Osmoprotectants and other fungal carbohydrate which helps plant to survive in oxidative stress. Metagenomics analysis of rice crop endophytes has proven to have the presence of numerous genes which encode enzymes for protection from ROS (White et al. 2019). *Xanthomonas* sp., *Microbacterium* sp., and *Flavobacterium* sp. help plants to survive in osmotic and salinity stress conditions (Walitang et al. 2017).

7.19 Conclusion

A vast majority of endophytic microorganisms have been isolated from a variety of plants; they help plants in various aspects like plant growth, prevention to pathogen, phytoremediation, and nutrient availability; besides this, they also help plants to adapt to different biotic and abiotic stresses. The understanding of plant-endophyte mutual association has to be better, to give consistent results under field conditions. However, PGPR has an advantageous impact on the quality of plants by means of various action mechanisms. Endophytes synthesize a collection of bioactive metabolic compounds which are used to prevent viral infections as effective medicine. Secondary metabolites are also synthesized by some endophytes including flavonoids, alkaloids, steroids, tannin, quinones, benzopyrones, etc. divided according to their functional groups. Sometimes, it is difficult to identify some rare endophytes microorganisms that have beneficial characteristics, and these have a huge role to bring about less and minimal consumption of diverse types of agrochemical substances which could include pesticides, chemical fertilizers, and so on. If it is studied in more details, then it is very surprising, and interesting facts will come out, which will increase the interest of other people. The current compilation shows the numerous forms of advantageous endophytic microbes that are used to increase soil fertility as biofertilizers in the field and better crop yield and crop production.

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