Endophytic Microbiomes and Their Plant Growth-Promoting Attributes for Plant Health

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Abstract

Endophytes reside within internal tissues of living plants without causing any harm to the host. The influence of these microbial communities on plant growth, yield, stress, and disease resistance, has been identified as potential research priorities in agriculture. In this chapter, we aim to explore the diverse host–endophyte interactions for plant growth promotion and health. Initially, the colonization of endophytes in specific plant tissues is discussed along with their mechanism of entry, habitat selection, response to stimuli, and evasion of the plant immunity. Endophytic microbes promote plant growth through different types of direct and indirect mechanisms. Plant growth-promoting endophytes (PGPE) play a vital role in phytohormone production, nutrient acquisition, nitrogen fixation, and solubilization of minerals. Further, indirect mechanisms (like suppression of plant pathogens by producing volatile organic compounds, antagonizing agents, and quorum quenchers) are also discussed in detail. Siderophores production and the secretion of different hydrolytic enzymes like chitinases, glucanases, and proteases also help in the induction of systemic resistance and protection of the host plants. Bioactive metabolites derived from endophytes serve as excellent therapeutic agents and have potential applications in agriculture, cosmetics, pharmaceutical, and food industries. Hereby, this chapter highlights the scientific rationale behind using endophytic microbiomes as potential biofertilizers, biopesticides, and biocontrol agents.
11.1 Introduction

Increasing crop yield has attracted wide attention in order to meet global demand considering the increase in the world’s population. However, conventional farming practices have certain limitations under increasing challenges like shortage of fertile lands, climate change, pests, and other associated abiotic and biotic stress. Thus, various plant growth-promoting microbes are being explored as biofertilizers in agriculture which seems to be a promising innovation to provide viable and environmentally friendly solutions with the potential to ensure food security (Glick 2014). However, this can only be achieved through in-depth knowledge about the underlying plant–microbe interactions. Microbes that reside within the plants without causing any negative impacts are called endophytes. Stimulation of plant defense responses is some inherent properties of endophytes (de Matos et al. 2001).

Plants are significant atmospheric CO$_2$ fixers on Earth. The solar energy enables plants to utilize CO$_2$ and reduce it to glucose and further various carbonaceous compounds. Hence, plant-associated heterotrophic microbes derive carbon, nitrogen, and energy from the host plants (Vandenhoornhuyse et al. 2007). On the other hand, plants require the microflora for their growth and stress tolerance. Thus, mutualistic relationships and interdependence exist between microbes and their host plants (Thrall et al. 2007; Sharaff et al. 2020; Suman et al. 2016). Potential uses of plant-associated bacteria as plant growth stimulating agents and management of soil as well as plant health have been portrayed in numerous literatures. Plant growth-promoting bacteria (PGPB) are associated with many, if not all, plant species and are commonly present in many environments (Bashan and Holguin 1998). PGPB are generally plant growth-promoting rhizobacteria (PGPR) that colonize the root surfaces and the rhizosphere (the closely adhering soil interface). Some of these PGPR can also enter the root interior and establish endophytic populations. Prime sites for bacterial colonization are lateral root emergence sites, outer cell layers, root cortex, phloem, and xylem, which may occur both intracellularly and inside the apoplast (Fig. 11.1).

Microbes can evade the endodermis barrier, moving from the root cortex to the vascular system, and eventually colonize as endophytes in roots, shoot, leaves, tubers, flowers, and other organs. Internal tissues of root, internodes, and leaves of grapevine are colonized by the PGBP _Burkholderia_ sp. strain PsJN. Similarly, the surface and interior of roots, stems, and needles of lodgepole pine (_Pinus contorta_ Dougl. var. _latifolia_ Engelm.) harbor the diazotrophic bacterial strain _Paenibacillus polymyxa_ P2b-2R (Liu et al. 2017). A facultative intracellular symbiont of _Methylobacterium extorquens_ strain DSM13060 was isolated from the Scots pine
(Pinus sylvestris L.) shoot tips where the bacteria aggregated within the living cells surrounding the nucleus (Koskimäki et al. 2015). Microbes adapt to particular internal tissue environment by varying its extent of colonization within host plant organs and tissues (Gray and Smith 2005; Rana et al. 2019b). Consequently, close
associations between endophytes and host plants are formed without causing any adverse effects to the plant. These endophytes do not cause harm to the plant and establish a mutualistic association with the host plant (Rana et al. 2019c). This chapter covers diverse aspects of plant growth-promoting endophytic bacteria and fungus. Endophyte-associated distribution patterns; nutrient uptake, phytohormone production, and stress tolerance are elaborated with minute details. Further, their role in augmenting the phytoremediation potential of host plants is also discussed.

11.2 Endophytes

The term “endophyte” is a microbe that asymptotically colonizes internal living tissues of plants (host) during a particular period of their life span (Stone et al. 2000). Endophytes do not harm the host plant and can be isolated from surface-sterilized plant tissue or the inner tissues of the host plant (Hallman et al. 1997). A few of these microbes are believed to actively infiltrate plant tissues through invading wounds or openings or using hydrolytic enzymes like pectinase and cellulase. Some endophytes emerge from the rhizosphere or phylloplane microflora, by infiltrating and colonizing root tissue as a passage to the xylem. However, on infection with endophytes, plants become healthy and exhibit enhanced tolerance to abiotic and biotic stress compared to their endophyte-free counterparts (Bonnet et al. 2000). Endophytic microbes can be bacteria, actinomycetes, or fungi (Rana et al. 2019a; 2020a, c).

It seems bacteria are most suitable for living inside plants by natural selection. The source of bacterial endophytes is microbial diversity of soil or rhizosphere and their clones. Endophytes are known for >120 years (Haridoim et al. 2009). In 1926, endophytic growth was recognized as a particular stage in the life of bacteria, described as an advanced stage of infection, and as having a close relationship with mutualistic symbiosis (Perotti 1926). Since then, various endophytes are isolated from surface-disinfected plant organs (Henning and Villforth 1940). Potato-associated bacterial communities indicated, in a large study conducted, that species richness and diversity were lower for endophytes than the rhizosphere of potato (Berg et al. 2005). However, the microbiome in the root endosphere is significantly less diverse compared to the microbiomes in the rhizosphere and bulk soil. Hence, roots can work as the most effective habitat filters, restricting community membership resulting in more narrowly defined lineages as the niche from soil to roots. Root endophytic bacterial communities are typically dominated by Proteobacteria (~ 50% in relative abundance), Actinobacteria (~ 10%), Firmicutes (~ 10%), and Bacteroidetes (~ 10%) apart from other bacterial phyla that include Chloroflexi, Cyanobacteria, Armatimonadetes, Verrucomicrobia, Planctomycetes, and Nitrospirae.
11.3 Ubiquity of Endophytes

The presence of endophytes is thought to be ubiquitous in plants as they can be detected in almost all parts including root, shoot, leaves, internodes, and reproductive tissues as well. The differences between the endosphere microbiomes of the root and shoot determine the source of dominant endophytes in them. Root-associated endophytes are primarily derived from soil, which then colonizes internal tissues of stems and leaves through the apoplast in xylem vessels. Therefore, it is common to have microbes of the plant leaf/shoot endosphere significantly overlapping with those in roots at both the taxonomic and functional levels. Recent molecular identification provides a strong evidence of diverse genera and species in endophytes. Kobayashi and Palumbo (2000) reported both Gram-positive and Gram-negative bacterial endophytes from different internal tissues of diverse plant species. Significant variations in populations of both indigenous and infiltrated endophytes were reported which might be attributed to the tissue type, source, plant age, time of sampling, and the environment. Interactions of the internal microflora of plants are needed to be investigated that might lead to beneficial effects due to their combined activities.

There is a deep underlying genetic basis for the differential colonization of various plant tissues by endophytes. Degradation of the cell wall facilitates entry of the bacteria within the interior for translocation to the apoplast. The genome of endophytic bacteria harbors numerous genes encoding cell wall–degrading enzymes (Straub et al. 2013). Genes encoding plant polymer degrading enzymes like cellulases, endoglucanase, xylanases, celllobiohydrolases, and cellulose-binding proteins have been reported in high copy numbers in the metagenome of rice root endophytic bacterial communities (Sessitsch et al. 2012). Bacteria in the phyllosphere may be

![Fig. 11.2](image-url) A schematic representation of bacterial colonization patterns in a leaf. The picture shown on the left demonstrates that the presence of bacteria has been detected in the leaf petiole, midrib, and veins. The picture shown on the right is a magnified leaf cross section, which demonstrates that endophytic bacteria may not only colonize the apoplast but are also present intracellularly. Endophytic bacteria are believed to be able to ascend from roots to the leaf via the vascular tissues of the xylem and phloem. Adapted with permission from Liu et al. (2017)
derived from soil or may have entered through natural openings (e.g., stomata and hydathodes), wounds, and cracks generated by wind, insects, and pathogen attacks (Vorholt 2012). Figure 11.2 shows that specific sites of bacterial colonization in a leaf are mostly upper epidermis cells, palisade mesophyll cells, xylem vessels as well as spaces between spongy mesophyll layer cells (Olivares et al. 1997). Bacterial endophytes are detected in plant reproductive organs, such as flowers, fruits, and seeds, although in small numbers. Table 11.1 represents various bacterial endophytes from crop plants.

Table 11.1 Complete genomes from bacterial endophytes and their plant-growth promoting traits

| Endophytic microbes                  | Genome size Mb (Replicons) | Host plant                  | PGP traits                                      |
|--------------------------------------|-----------------------------|-----------------------------|-------------------------------------------------|
| *Azoarcus* sp. BH72                  | 4.37 (1 chr, 0 pl)          | Rice                        | Nitrogen fixation                               |
| *Azospirillum lipoferum* 4B           | 6.85 (1 chr, 6 pl)          | Rice, maize, wheat          | Nitrogen fixation, phytohormone secretion       |
| *Azospirillum* sp. B510              | 7.6 (1 chr, 6 pl)           | Rice                        | Nitrogen fixation, phytohormone secretion       |
| *Burkholderia phytofirmans* PsJN     | 8.2 (2 chr, 1 pl)           | Potato, tomato, maize, barley, onion, canola, grapevine | IAA synthesis, ACC deaminase                    |
| *Burkholderia* spp. KJ006            | 6.6 (3 chr, 1 pl)           | Rice                        | ACC deaminase, *nif* gene cluster, antifungal action (indirect PGP) |
| *Enterobacter cloacae* ENHKU01       | 4.7 (1 chr, 0 pl)           | Pepper                      | Unknown role in PGP                             |
| *Enterobacter* sp. 638               | 4.67 (1 chr, 1 pl)          | Poplar                      | Siderophore, IAA, acetoin and 2,3-butanediol synthesis, antifungal action (indirect PGP) |
| *Gluconacetobacter diazotrophicus* PaI5 | 3.9 (1 chr, 2 pl)        | Sugarcane, rice, coffee, tea | Nitrogen fixation, auxin synthesis              |
| *Klebsiella pneumoniae* 342          | 5.9 (1 chr, 2 pl)           | Maize, wheat                | Nitrogen fixation                               |
| *Pseudomonas putida* W619            | 5.77 (1 chr, 0 pl)          | Poplar                      | AA synthesis, ACC deaminase                     |
| *Pseudomonas stutzeri* A1501         | 4.5 (1 chr, 0 pl)           | Rice                        | Nitrogen fixation                               |
| *Serratia proteamaculans* 568         | 5.5 (1 chr, 1 pl)           | Soybean                     | IAA synthesis, ACC deaminase, acetoin, and 2,3-butanediol synthesis |
| *Stenotrophomonas maltophilia* R551–3 | 4.57 (1 chr, 0 pl)         | Poplar                      | IAA synthesis, ACC deaminase                    |

Source: Adapted with permission from Santoyo et al. (2016)
11.4 Role of Endophytes in Plant Growth Promotion

Benefits conferred by endophytes are well recognized but it may not always be clear which population of microorganisms (endophytes or rhizospheric bacteria) promotes plant growth. Differential gene expression might facilitate entry, colonization, and also plant growth promotion. Nitrogen fixation (Iniguez et al. 2004) or the production of phytohormones, by enhancing the availability of minerals (Sessitsch et al. 2004; Sturz et al. 2000), may help to promote plant growth. Further endophytes may lay a critical role in biocontrol of phytopathogens as they colonize the same ecological niche. Various mechanism of biocontrol includes production of antifungal or antibacterial agents, siderophore production, nutrient competition, and induction of systematic-acquired host resistance or immunity (Thakur et al. 2020). Endophytic microorganisms have the capacity to control pathogens, insects, and nematodes (Rana et al. 2020b). In some cases, they also have the capacity to accelerate seedling emergence and promote plant establishment under adverse conditions. Endophytes can confer metal resistance to plants and reduce metal toxicity due to their own metal resistance capability (Ma et al. 2016).

11.5 Mechanisms of Plant Growth Promotion

A deficiency in macro and micronutrients in the soil is detrimental to crop yield and the affected plants become more prone to soil-borne pathogens such as Fusarium, Pythium, and Phytophthora. Hence chemical fertilizers, herbicides, fungicides, and pesticides are largely used in order to overcome the problems. However, these harmful and toxic chemicals pose a potential threat to human health and the environment as well (Aktar et al. 2009; Kour et al. 2020b). Endophytes enable the plants to overcome habitat-imposed abiotic and biotic stresses which otherwise result in major losses in plant yield. Endophytic bacteria are capable of promoting plant growth and development through a wide variety of not only direct mechanisms which include nutrient (e.g., phosphorous, nitrogen, and iron) acquisition and production of various phytohormones (Santoyo et al. 2016; Yadav et al. 2020) but also indirect mechanisms for plant growth promotion such as antagonistic effects toward phytopathogens (Compant et al. 2010; Rastegari et al. 2020a, b). It also includes the production of defense-related enzymes like chitinase and β-1,3-glucanase, secreting antimicrobial compounds, lowering endogenous stress-related ethylene (ET), induction of systemic resistance (ISR), quenching the quorum sensing (QS) of phytopathogens, and competition for niche and/or resources (Compant et al. 2010; Glick 2014; Santoyo et al. 2016; Singh et al. 2020a). In the following section, various direct and indirect mechanisms of plant growth promotion by endophytic bacteria are elaborated (Ma et al. 2016).
11.5.1 Direct Mechanisms

Endophytes directly promote plant growth using various mechanisms that include phytohormone production, nutrient acquisition, nitrogen fixation, and solubilization of minerals.

11.5.1.1 Phytohormone Production

Five types of phytohormones, e.g., ethylene, indole-3-acetic acid (IAA), cytokinins, gibberellins, and abscisic acid may play an important role in several stages such as cell elongation, cell division, tissue differentiation, and apical dominance. Both host plants and their endophytes can synthesize these hormones. Hormonal balance of the plant can be altered by plant-associated bacteria as well.

Ethylene is an important example to show that the balance is most important for the effect of hormones. An ubiquitous plant hormone, it plays a vital role in plant growth and survival, to abiotic and biotic stresses including root initiation and nodulation, cell elongation, leaf senescence, abscission, and fruit ripening as well as auxin transport (Ma et al. 2016). While normally considered as an inhibitor of plant growth and known as a senescence hormone, at reduced levels it can stimulate plant growth in *Arabidopsis thaliana* (Pierik et al. 2006). Stress-mediated ethylene production inhibits root elongation, lateral root growth, and root hair formation. It is interesting to note that the endophytes can reduce the ethylene level. The compound 1-aminocyclopropane-1-carboxylate (ACC) is a precursor of ethylene in plants. ACC-deaminase-producing bacteria can degrade ACC into α-ketobutyrate and ammonia, which can be metabolized by the microbes as nitrogen source. Thus, bacteria-mediated reduction of endogenous ACC levels results in root growth (Glick 2005). ACC deaminase-producing bacteria have an additional potential to protect plants against biotic and abiotic stress owing to the fact that ethylene is also a stress hormone (Ma et al. 2016; Saleem et al. 2007).

Indole acetic acid (IAA), one of the most physiologically active auxins, is produced by various plant organs like young leaves and germinating seeds by utilizing the amino acid tryptophan. IAA plays a significant role in plant growth by bringing about apical dominance, promoting root development and proliferation, tropisms (phototropism in the case of shoots and gravitropism in the case of roots), and inducing cell division and differentiation (Tiwari et al. 2020). IAA is a common product of L-tryptophan metabolism by several endophytes leading to plant morphogenic effects. Evidence suggests that endophytes produce IAA while colonizing the internal plant tissues and thereby promoting plant growth. The *Pseudomonas stutzeri* P3 strain was found to produce IAA in *Echinacea* plants and help in the proliferation of these plants even after micropropagation, likewise, a number of bacteria such as *Agrobacterium tumefaciens*, *A. rhizogenes*, *Pseudomonas savastanoi*, *Pseudomonas* spp., *Rhizobium* spp., *Bradyrhizobium* spp., *Azospirillum* spp., and *Acinetobacter* spp. associated with the plants are known to produce IAA (Huddenar et al. 2002; Rao 1986; Baldi et al. 1991; Leinhos 1994).
11.5.1.2 Nutrient Acquisition

Nitrogen

Improved nutrient acquisition helps to promote plant growth directly. Plant-associated microorganisms can supply macronutrients and micronutrients, most significant example being bacterial nitrogen fixation. Nitrogen-fixing bacteria can use root exudates (carbohydrates) and in return provide nitrogen to the plant that can be used for amino acid synthesis. *Azospirillum*, *Burkholderia*, and *Stenotrophomonas* are free-living nitrogen-fixing bacteria (Dobbelare et al. 2003). Brazilian sugarcane requires minimum amounts of fertilizer and shows no N₂ deficiencies due to N₂ fixing endophytes within them. However, level of N₂ fixed by endophytes and amount available to the host plant is still needed to be investigated (Giller and Merckx 2003). Different reports suggest that 30–80 kg N/ha/year are available (Boddey et al. 1995). Under optimal conditions, some plant genotypes seem to obtain part of their N requirements from nitrogen fixation. Kallar grass grows in nitrogen-deficient soils in Pakistan and a diversity of *Azoarcus* spp. was recovered (Reinhold-Hurek et al. 1993). Inside wheat, *Klebsiella* sp. strain Kp342 fixes N₂ that also increases maize yield in the field (Iniguez et al. 2004; Riggs et al. 2001).

Similarly, nitrogen-fixing endophytes seem to relieve N₂ deficiencies of sweet potato (*Ipomoea batatas*) in N₂-poor soils (Reiter et al. 2003). Grasses growing in nutrient-poor sand dunes contain members of genera *Pseudomonas*, *Stenotrophomonas* as well as *Burkholderia*. *Burkholderia* endophytes could contribute nitrogen to the grasses because nitrogenase was detected in roots and cell walls of stems and rhizomes (Dalton et al. 2004). Similarly, the endophytic genera *Burkholderia*, *Rahnella*, *Sphingomonas*, and *Acinetobacter* isolated from the stem of *Populus trichocarpa* and *Salix sitchensis* enhanced the growth of plants by providing abundant nitrogen owing to their nitrogen-fixing ability (Doty et al. 2009). Some endophytic bacteria possess both nitrogen fixation (e.g., *nifH*) and denitrification genes. The nitrogen-fixing isolates *P. polymyxa* P2b-2R isolated from lodgepole pine tissue could effectively colonize both rhizosphere and endosphere of maize plants resulting in plant growth promotion (Puri et al. 2016).

Phosphorous

Phosphorous (P) is an essential micronutrient that helps in the proper functioning of metabolic activities, glucose transport, development of roots, and many other physiological processes (Ahemad 2015). Since more than 75% of applied phosphorus forms complexes and are unavailable for plant uptake, endophytes may either solubilize precipitated phosphates by acidification, chelation (i.e., PO₄³⁻), ion exchange, and release of organic acid or secrete extracellular acid phosphatase to mineralize organic phosphorus resulting in phosphorous availability to plants (van der Hiejden et al. 2008; Kour et al. 2020a; Singh et al. 2020b).

Endophytic bacteria possess the capacity to solubilize phosphates. It was suggested that the endophytic bacteria from soybeans may also participate in phosphate assimilation (Kuklinsky-Sobral et al. 2004). Recently, de Werra et al. (2009) reported that *Pseudomonas fluorescens* CHA0 could reduce the pH of its
surrounding environment that helps in solubilization of mineral phosphate. This acidification was strongly dependent on gluconic acid-producing ability of the endophyte that can be strongly correlated with antagonistic activity against plant pathogens. Further, Idriss et al. (2002) demonstrated that plants inoculated with a phytase-secreting *Bacillus amyloliquefaciens* FZB45 under P-limitation may result in significant growth enhancement in maize seedlings compared to non-inoculated controls. However, there are no reports of naturally occurring endophytic bacteria with phytase-secreting ability (Ma et al. 2016).

### Iron
Iron (Fe) is vital as iron-containing proteins involved in enzymatic reactions are essential for various physiological activities like transpiration (Bothwell 1995). Iron exists in soil in highly insoluble ferric (Fe$^{3+}$) forms such as oxides, hydroxides, phosphates, and carbonates not available for plant uptake. Microbially secreted chelating agents (e.g., siderophores) help to solubilize Fe under conditions of iron deficiency. Siderophores, low-molecular weight organic compounds (500–1500 Da) having an affinity for Fe$^{3+}$ ions, also bind other bivalent metal ions or Fe$^{2+}$ that can be assimilated by the plant (Rajkumar et al. 2009). The siderophore is discussed in more detail in the indirect mechanisms section.

#### 11.5.2 Indirect Mechanisms of Plant Growth Promotion

Indirect mechanisms mainly include the suppression of the growth or survival of plant pathogens (phytopathogens) and, thus, bring about the promotion of plant growth by microbial antagonism. Endophytes may produce substances like volatile organic compounds, antagonizing agents, and quorum quenchers that may effectively resist phytopathogen-associated disease. Further, siderophore production and secretion of diverse hydrolytic enzymes (such as chitinases, proteases, and gluca- nases) and induction of systemic resistance also protect the host plants (Sheoran et al. 2015; Mondal et al. 2020).

##### 11.5.2.1 Competition for Colonization Sites
The root surface and internal tissues of plants are significant carbon sinks (Rovira et al. 1965) and nutrient-rich niches that attract diverse groups of microbes including phytopathogens. PGPB protects plants by competing with the phytopathogens over these nutrients and niches (Duffy 2001). Brock et al. (2013) reported that a potent endophyte, *Enterobacter radicincitans* DSM 16656, induced priming in *Arabidopsis* via SA- and JA/ET-dependent pathways. Likewise, endofungal bacterium *R. radiobacter* F4 exhibited nonspecific plant root colonization and enhanced plant resistance against the bacterial leaf pathogens *Xanthomonas translucens* pv. *translucens* and *Pseudomonas syringae* pv. tomato DC3000 (Liu et al. 2017). However, it is yet to be investigated whether endophytes contribute to priming and ISR.
11.5.2.2 Volatile Organic Compounds and Antagonizing Agents
Endophytic bacteria produce volatile organic compounds (VOCs) that can render resistance to the host plants against the phytopathogens (Chung et al. 2016). On inoculation with endophytic Enterobacter aerogenes that produce VOC 2,3-butanediol (2,3-BD), maize plants exhibited increased resistance against Setosphaeria turcica associated northern corn leaf blight disease (D’Alessandro et al. 2014). The endophytic Pseudomonas poae strain RE*1–1-14 isolated from sugar beet roots suppressed the fungal pathogen Rhizoctonia solani (Zachow et al. 2015). Further, P. poae produced a novel lipopeptide poaeamide that suppressed R. solani-associated pathogenesis in sugar beetroots. Similarly, endophytic B. amylofaciens was reported to produce a series of isoforms of iturins that can confer protection to its host against pathogens (Han et al. 2015). VOCs produced by P. fluorescens and Serratia plymuthica inhibited tumorigenic strains of A. tumefaciens and A. vitis induced crown gall disease in tomatoes. Solid-phase microextraction–gas chromatography–mass spectrometry analysis revealed dimethyl disulfide (DMDS) and 1-Undecene as the major VOCs produced by S. plymuthica IC1270 and P. fluorescens strains, respectively (Dandurishvili et al. 2011).

11.5.2.3 Quorum Quenching
Quorum sensing is an important phenomenon exhibited by numerous pathogenic microbes in order to survive in a specific ecological niche, communicate between cells, undergo multiplication, control biofilm formation, and induce competence and also adaptation (Miller and Bassler 2001). Certain endophytic bacteria employ QS quenching as an antivirulence strategy to control phytopathogen. Endophytic bacterial strains, Bacillus sp. strain B3, Bacillus megaterium strain B4, Brevibacillus borstelensis strain B8, and Bacillus sp. strain B11 from Cannabis sativa efficiently disrupt cell-to-cell communication in Chromobacterium violaceum via quenching its QS signals (Kusari et al. 2014). It is important to note that a diffusible signal factor (DSF) is essential in several Xanthomonas species and Xylella fastidiosa-associated phytopathogenesis (Newman et al. 2008). Bacillus and Pseudomonas were reported to complement carAB, a gene responsible for fast DSF degradation in the Pseudomonas spp. strain G. This mechanism can be exploited as a powerful strategy in the biocontrol of DSF producing pathogens and, thus, can be deployed in agriculture (Liu et al. 2017).

11.5.2.4 Siderophores Production
Iron is a vital metal for growth in all living organisms. There is a great competition for bioavailable iron in soil habitats as well as on plant surfaces. Under iron-limiting conditions, endophytes produce low-molecular-weight compounds called siderophores to competitively acquire ferric ion (Whipps 2001). Although various bacterial siderophores differ in their abilities to sequester iron, in general, they deprive pathogenic fungi of this essential element since the fungal siderophores have lower affinity (Loper and Henkels 1999; O’Sullivan and O’Gara 1992). Some plant growth-promoting endophytes go one step further and draw iron from heterologous siderophores produced by cohabiting microorganisms (Wang et al. 2003; Whipps...
2001). Primarily, siderophores help to acquire iron either from iron adsorbed to solid surfaces or from insoluble hydroxides. Siderophores can also extract iron from soluble and insoluble iron compounds, such as ferric-citrate, Fe-transferrin, ferric phosphate, ferritin, or iron bound to sugars, plant flavone pigments, and glycosides or even from artificial chelators like EDTA and nitritriacetate by Fe(III)/ligand-exchange reactions. Hence, although siderophores don’t play a direct role in iron solubilization, they can act as carrier for exchange between extracellular iron stores and membrane-located siderophore-transport systems (Winkelmann 2002). Siderophores play a significant role in microbial metabolism because of the following facts:

1. Siderophores mainly consist of hydroxamate, catecholate, or α-hydroxycarboxylate ligands that form hexadentate Fe(III) complexes, satisfying the six coordination sites on ferric ions which make them most significant iron-binding ligands.

2. Siderophore biosynthesis is a highly regulated process which is triggered by iron limitation resulting in building up of high local concentrations of siderophores in the vicinity of microbial cells.

3. Siderophores exhibit structural and conformational specificities to fit into membrane receptors and/or transporters besides their ability to solubilize iron and to function as external iron carriers (Stintzi et al. 2000; Huschka et al. 1986; Ecker et al. 1988).

Endophytic isolates of *Phialocephala fortinii* from *P. sylvestris* root, *Carex curvula*, *Abies alba*, *Picea abies*, and *P. sylvestris* showed that siderophore production is a function of pH values and iron(III) concentrations; 4.0–4.5 was the range of pH at which maximum siderophore production was found with the optimal ferric iron concentration of 20–40 μg iron (III) L\(^{-1}\) (0.36–0.72 μM, respectively). The most predominant siderophores produced by *P. fortinii* is ferricrocin (a hydroxamate siderophore) followed by ferrirubin and ferrichrome C (Bartholdy et al. 2001). An endophytic *Streptomyces* sp. GMKU 3100 isolated from the roots of a Thai jasmine rice plant (*Oryza sativa* L. cv. KDML105) exhibited remarkably high level of siderophore production. Inactivation of desD-like gene that codes a key enzyme responsible for the final step in siderophore biosynthesis resulted in impairment of siderophore production. Rice and mungbean plants inoculated with the wild-type strain-enhanced plant growth and significantly increased root and shoot biomass and lengths unlike siderophore-deficient mutant treatments (Figs. 11.3 and 11.4). Endophytic actinomycetes, therefore, can be applied as a potentially safe and environmentally friendly biofertilizer in agriculture (Rungin et al. 2012).

### 11.5.2.5 Lytic Enzyme Production

Various extracellular enzymes from microbes perform their function outside the cell which is significant to host–endophyte interdependence. Bacteria and fungi produce various extracellular enzymes that include hydrolases, lyases, oxidoreductases, and transferases (Traving et al. 2015; Kour et al. 2019b). The substrates are mostly
macromolecules such as carbohydrates, proteins, lignin, sugar-based polymers, and organic phosphate which are broken down into simpler forms that can be easily transported, absorbed, and assimilated. Enzymes secreted by endophytes help to initiate the association with the host and symbiosis process. Extracellular hydrolyases counteract plant pathogenic infection (Leo et al. 2016). In fact, certain categories of enzymes namely, cellulases, xylanases, phytases, hemicellulases, asparaginase, proteases, gelatinase, pectinases, tyrosinase, chitinase, amylases, etc., are some of the key enzymes produced by endophytic bacteria and fungi.

Endophytic bacterial strains have been isolated from various plants such as pea (P. sativum), tomato (Lycopersicum esculentum), corn (Zea mays), wheat (Triticum aestivum), oat (Avena sativa), canola (Brassica napus), barley (Hordeum vulgare), radish (Raphanus sativus) soybean (Glycine max), potato (Solanum tuberosum), lettuce (Lactuca serriola), and cucumber (Cucumis sativa) were identified and characterized that belong to the genus Arthrobacter, Actinobacter, Aeromonas, Agrobacterium, Alcaligenes, Bacillus, Azospirillum, Enterobacter, Flavobacterium Pseudomonas, Acinetobacter, Azotobacter, Beijerinckia, Burkholderia, Enterobacter, Erwinia, Flavobacterium, Rhizobium, and Serratia (Khan et al. 2017; Gray and Smith 2005). Vijayalakshmi et al. (2016) isolated endophytic bacteria from medicinally important plants, producing α-amylase, protease, and cellulase. Similarly, Leo et al. (2016) reported endophytic bacteria, Alcaligenes faecalis, Burkholderia
cepacia, and Enterobacter hormaechei from perennial grasses that showed the hyper-enzymatic activity of α-amylase, protease, and cellulose (Table 11.2).

A variety of microorganisms also exhibited hyperparasitic activity, attacking pathogens by excreting cell wall hydrolases. Chitinase produced by S. plymuthica C48 inhibited spore germination and germ-tube elongation in Botrytis cinerea (Frankowski et al. 2001). The ability to produce extracellular chitinases is considered crucial for Serratia marcescens to antagonize Sclerotium rolfsii (Ordentlich et al. 1988). Using similar mechanisms, Paenibacillus sp. and Streptomyces sp. suppress Fusarium oxysporum while Pseudomonas sp. suppresses Fusarium solani, the commonly known plant pathogen (Lim et al. 1991). Many endophytic fungi like Alternaria alternate, Hymenoscyphus ericae, and Aspergillus terreus also produce extracellular enzyme xylanase producers including those found in Table 11.3. Similarly, the endophyte Periconia sp. produced β-glucosidase, while Acremonium species produced cellulases and hemicellulases.

11.5.2.6 Induced Systemic Resistance

Induced systemic resistance (ISR) is the immunity response mechanism inherent in crop plants that can be triggered by beneficial microbial endophytes during biotic and abiotic stress conditions which may include temperature, salinity, drought,
### Table 11.2  Endophytic bacterial strains producing extracellular enzymes

| Endophytic Microbes | Enzyme                        | Detection method          |
|---------------------|-------------------------------|---------------------------|
| *Actinomyces pyogenes*, *Bacillus circulans*, *Bacillus coagulans*, *Bacillus licheniformis*, *Bacillus megaterium*, *Corynebacterium renale*, *Pseudomonas stutzeri*, *Staphylococcus sp.*, *Bacillus sp.* | Amylase, esterase, Lipase, protease | Agar medium |
| *Pseudomonas oryzihabitans* | Asparaginase | Spectrophotometer |
| *Bacillus sp.*, *Bacillus claussii*, *Bacillus pumilus*, *Bacillus licheniformis* | Amylase, protease, cellullose, lipase | Agar medium |
| *Pseudomonas sp.* | Exo-β-agarase | Spectrophotometer, NMR |
| *Bacillus sp.* | l-asparaginase | Spectrophotometer |
| *Bacillus amyloliquefaciens* | Phytase | Spectrophotometer |
| *Paenibacillus polymyxa* | Fibrinolytic enzymes | Agar medium, SDS Page |
| *Rhizobium*, *Massilia*, *Kosakonia*, *Pseudorhodoferax*, *Caulobacter*, *Pantoea*, *Sphingomonas*, *Burkholderia*, *Methylobacterium*, *Bacillus*, *Curtobacterium*, *Microbacterium*, *Mucilaginibacter*, *Chitinophaga* | ACC deaminase, endoglucanase, protease | Agar medium |
| *Acinetobacter sp.*, *Bacillus sp.* | ACC deaminase, cellulase, protease, amylase, pectinase | Agar medium |
| *Bacillus licheniformis*, *Bacillus pseudomycoideas*, *Paenibacillus senitriformus* | l-asparaginase | M9 medium |
| *Pseudomonas hibiscicola*, *Macrococcus caseolyticus*, *Enterobacter ludwigi*, *Bacillus anthracis*, *Bacillus tequilensis*, *Pseudomonas entomophila*, *Chryseobacterium indologenes*, *Bacillus aerophilus* | Cellulase, xylanase, amalyase, pectinase | Agar diffusion method |
| *Bacillus thuringiensis* | Anthracene | Spectrophotometer |
| *Bacillus amyloliquefaciens* | Exopolysaccharides | Colorimetric method |
| *Bacillus subtilis* | YbdN protein | SDS-PAGE, MALD-TOF-MS |
| *Serratia marcescens*, *Bacillus subtilis*, *Bacillus methylotrophicus*, *Bacillus siamensis* | l-asparaginase | Spectrophotometer |
| *Paenibacillus polymyxa*, *Bacillus sp.* | Cellulase, xylanase, pectinase | Agar diffusion method |
| *Paenibacillus amyloyticus* | Pectin lyase | Spectrophotometer |
| *Alcaligenes faecalis*, *Burkholderia cepacia*, *Enterobacter hormaechei* | Cellulosic, hemicellulosic, lignin | National renewable energy laboratory methods |

Sources: Adapted with permission from Khan et al. (2017)
| Microbes                                                                 | Enzyme produced                  | Detection method               |
|--------------------------------------------------------------------------|----------------------------------|--------------------------------|
| *Penicillium funiculos*, *Trichoderma viride*                           | Amylase, cellulose, protease, lipase | Agar plate base test           |
| *Colletotrichum, Fusarium, Phoma, Penicillium*                          | 1-Asparaginase                   | Pink zones on agar, nesslerization |
| *Aspergillus* sp.                                                      | Amylase                          | Agar medium                    |
| *Pochonia chlamydosporia*                                               | Protease                         | Spectrophotometer               |
| *Colletotrichum gloeosporioides*                                        | Protease, chitinase, amylase     |                                |
| *Fusarium sp., Chaetomium sp., Colletotrichum sp., Aspergillus flavus, Cynredocephalum sp., Coniothyrium sp., Phoma sp., Aspergillus niger, Colletotrichum sp., Mycelia sterilia sp., Aspergillus fumigates, Alternaria sp., Colletotrichum gloeosporoides, Colletotrichum sp., Myrothecium sp., Fusarium chlamydosporum, Xylaria sp., Fusicoccum sp., Mycelia sterilia sp., Aspergillus sp., Pestalotiopsis sp., Colletotrichum sp., Talaromyces emersonii, Pylostita sp., Pestalotiopsis sp., Discosia sp., Aspergillus sp., Mycelia streilis sp., Isaria sp., Xylaria sp., Phoma sp., Pestalotiopsis disseminata, Fusarium oxysporum, Paeclomyces variotii, Fusarium chlamydosporum, Acremonium implicatum, Nigrospora sphaerica, Fusarium solani, Penicillium sp., Mycelia sterilia sp., Phoma sp., Basidiomyces sp., Colletotrichum falcatum, Phomopsis longicolla Fusarium oxysporum, Colletotrichum gloeosporoides, Colletotrichum truncatum, Drechslera sp., Cladosporium sp., Myrothecium sp. | Amylase, cellulase, laccase, lipase, pectinase, protease | Agar medium |
| *Cladosporium sp., Rhizoctonia sp., Aspergillus sp., Chaetomium sp., Biosporus sp., Fusarium sp., Curvularia sp., Cladosporium sp., Colletotrichum sp.* | Amylase, protease, cellulose, lipase | Agar medium, spectrophotometer |
| *Cladosporium cladosporioides, Curvularia brachyspira, C. verruciformis, Drechslera awaientesis, Colletotrichum carssipes, Colletotrichum falcatum, Colletotrichum gloeosporoides, Lasiodiplodia theobromae, Nigrospora sphaerica, Phyllosticta sp.* | Amylase, cellulase, laccase, lipase, protease | Agar medium |
| *Cladosporium cladosporioides, C. sphaerospermum, Acremonium terricola, Monodictys castaneae, Penicillium glandicola, Phoma tropica, Tetraploa aristata* | Pectinases, cellulases, xylanases, proteases | Agar medium |

(continued)


| Microbes                                                                 | Enzyme produced                      | Detection method          |
|-------------------------------------------------------------------------|---------------------------------------|---------------------------|
| *Amanita muscaria, A. muscaria, A. spissa, Boletus luridus, Cenococcum geophilum, Cortinarius glaucopus, C. purpurascens, Hydnum rufescens, Hymenoscyphus ericace, Laccaria cf., Lactarius acerrimus, L. auriflora, L.chrysorrheus, L. controversus, L. delicius, L. deterrimus, L. evosmus, L. pubescens, L. quieticolor, L. quietus, L. rufus, L. semisanguifluus, L. subdulcis, L. subumbonatus, L. zonarius, Piceirhiza bicolorata, Piloderma fallax, Piloderma byssinum, Russula chloroides, R. sanguinea, Suillus luteus, S. luteus, Tricholoma cf. equestre, S. variegatus, T. fulvum, T. scalpturatum* | Protease                               | Agar medium                |
| *Eurotiales, Chaelomiaceae, Incertae sadis, Aureobasidiuaceae, Nectriaceae, Sporomiaceae* | Celluloses, phosphatases, glucosidases | Spectrophotometer          |
| *Colletotrichum sp., Macrophomina phaseolina, Nigrospora sphaerica, Fusarium solani* | Cellulase, protease, amylase           | Agar medium                |
| *Cochliobolus lunatus, C. australiensis, Gibberella baccata, Myxomycetum schulzeri, Penicillium commune, Phoma putaminum, Acremonium curvulum, Aspergillus Niger, A. ochraceus, P. glabrum, C. Lunatus, G. fujikuroi, Myrothecium verrucaria, Nodulisporium, Trichoderma piluliferum, A. chartarum, A. ochraceus, P. glabrum, Pithomyces atro-olivaceus* | Cellulase, protease, xylanase, lipase  | Agar medium                |
| *Penicillium chrysogenum, Alternaria alternate, Sterile hyphae*         | Amylase, pectinase, cellulase, gelatinase, xylanase, tyrosinase | Agar medium                |
| *Aspergillus terreus*                                                   | L-asparaginase                        | Agar medium, spectrophotometer |
| *Phialocephala fortinii s.l., Meliniomyces variabilis, Umbelopsis isabellina, Hebeloma incarnatum, Laccaria bicolor* | Protease                               |                           |
| *Hormonema sp., Pringsheimia smilacis, Ulocladium sp., Neofusisoccum luteum, Neofusisoccum austral* | Laccase                               | Agar medium, spectrophotometer |
| *Acremonium sp., Alternaria sp., Aspergillus sp., Fusarium sp., Pestalotiopsis sp.* | Amylase, cellulase, lipase, protease  | Agar medium                |

(continued)
heavy metal, and phytopathogenic infections. A diverse group of metabolites produced by the endophytes can impart the host plant to overcome the stress (Khan et al. 2017). Immunized through ISR plays a vital role in the protection from pathogenic invasions, exhibition of varied resistance methods, efficient utilization of energy, and exploitation of genetic ability to induce resistance in the plants which are vulnerable for diseases (Latha et al. 2019). Plants are also protected from the parasitic nematodes due to ISR. Bacterial endophytes like *B. amyloliquefaciens*, *Bacillus pumilus*, *Bacillus subtilis*, *P. fluorescens*, *P. syringae*, and *S. marcescens* can induce ISR (Latha et al. 2019). The following section gives an elaborate account of the endophyte-associated ISR in plants.

**Detoxification and Degradation of Virulence Factors**

Detoxification of pathogen virulence factors is another mechanism of biological control. For example, certain biocontrol agents are able to detoxify albicidin toxin produced by *Xanthomonas albilineans* (Basnayake and Birch 1995; Zhang and Birch 1997). Endophytic bacterial strains of *B. cepacia* and *Ralstonia solanacearum* were reported to suppress the activity of fusaric acid, a toxin secreted by *Fusarium* species, a major wilt-causing pathogen (Toyoda and Utsumi 1991). The autoinducer-mediated quorum-sensing of endophytes can impair the virulence of pathogens to inflict diseases, which is of paramount importance (Latha et al. 2019).

**Insect and Pest Tolerance**

Endophytes also play a critical role in insect and pest-induced biotic stress in plants. Entomopathogenic microorganisms inhibit/antagonize other pathogenic microbes that not only help to protect plants but also reduce use of chemical pesticides. Since being established due to their capacity to protect their hosts against insects–pests, pathogens and even herbivores endophytic microorganisms have received considerable attention in the last 20 years. Webber (1981) first reported that endophytic fungus *Phomopsis oblonga* protected elm trees from the beetle *Physocnemun brevilineum*. *P. oblonga* controlled the beetle *P. brevilineum* which is the vector for *Ceratocystis ulmi*, responsible for the elm Dutch disease. Another endophytic fungi belonging to the *Xylariacea* family synthesized secondary metabolites in hosts of the genus *Fagus* that affected the beetle larvae. Owing to toxin production,
endophytic fungus repels insects, induces weight loss, inhibits growth and development, and even increases pest mortality. Another mode of action might be rendering the plant unpalatable to several types of pests like aphids, grasshoppers, beetles, etc. due to metabolites secreted by the endophytes. Endophytic isolates of *Neotyphodium* sp. produced N-formilonine and a paxiline in the host *Echinopogum ovatus* that exhibited insecticidal activity against *L. bonariensis* and other insects (Azevedo et al. 2000).

White spruce *Picea glauca*, death rate in the Homoptera *Adelges abietis* increased when galls were infected with the endophytic fungus *Cladosporium sphaerosperum* while weight gain and survival of the insect–pest, *Spodoptera frugiperda*, were severely compromised when their hosts were colonized by endophytic fungi like *Balansa cypri*. It is important to note that larvae from the bluegrass webworm *Parapediasia teterrella* preferred endophyte-free plants of *L. perenne* and *F. arundinacea*, to a point that the larvae would starve to death if only plants infected with *Acremonium* were available. Field studies revealed that endophyte-free species were severely attacked by insects, whereas those infected with *Acremonium* stayed almost free of insect larvae (Azevedo et al. 2000).

**Cold and Drought Stress Tolerance**

Endophytic microbes render the plant its ability to tolerate abiotic stress during severe temperatures and water scarcity. Tomato plants inoculated with psychrotolerant endophytic bacteria *Pseudomonas vancouverensis* OB155 and *P. frederiksb ergensis* OS261 were able to overcome cold stress (10–12 °C). Lesser membrane damage with increased antioxidant activity was observed in endophyte-colonized plants compared to endophyte-free control plants. Further, cold acclimation genes (*LeCBF1* and *LeCBF3*) were induced in bacteria-inoculated plants (Subramanian et al. 2015). Similarly, the bacterial endophyte *Burkholderia phytofirmans* strain PsJN resulted in enhancement of *Arabidopsis* growth and strengthened its cell wall, and thereby increased cold stress resistance (Šu et al. 2015). Increased plant tolerance to drought was also seen due to endophytic bacteria. *B. phytofirmans* PsJN modulated transcriptional regulation, cellular homeostasis, and ROS detoxification in a drought stress-affected potato (Sheibani-Tezerji et al. 2015). These facts strongly rationalize that endophytes can be potential protective agents in crops under extreme climatic environments as they can influence plant physiological responses to stresses (Liu et al. 2017).

**Metal Stress Tolerance**

Endophytes can mitigate metal toxicity in plants through their own metal resistance system and encourage plant growth under metal stress. Endophytes improve plant growth in metal-polluted soils either directly or indirectly by metal detoxification, accumulation, or translocation in plants. They can even alter metal accumulation capacity in plants by excreting metal immobilizing extracellular polymeric substances as well as metal mobilizing organic acids and biosurfactants. The metal stress can be circumvented by various mechanisms, which include efflux of metal ions exterior to the cell, transformation of metal ions to less toxic forms,
sequestration of metals on the cell surface or in intracellular polymers, and precipitation, adsorption/desorption, or biomethylation (Rajkumar et al. 2013). Inoculation of seeds or seedlings of hyperaccumulator plants with metal resistant endophytes results in accelerated phytoremediation in naturally and/or artificially metal-contaminated soil and improved plant growth.

The endophytic bacterial strain Bacillus sp. MN3-4 exhibited metal-resistance owing to active export via a P-type ATPase efflux pump that can transport metal ions across biological membranes against the concentration gradient using energy released by ATP hydrolysis (Shin et al. 2012). Further, endophytic bacteria can modulate the activity of plant antioxidant enzymes (such as POS, CAT, SOD, glutathione peroxidase, and ascorbate peroxidase) as well as lipid peroxidation (malondialdehyde formation) that collectively enable the host plant to overcome heavy metal-induced oxidative stress. Methylation is another significant way to gain metal resistance or detoxification. Endophytic bacteria with mercury-resistant (Mer) operons express MerB gene-encoding organomercurial lyase, which cleaves organomercurials into mercuric ion (Hg\textsuperscript{2+}) (Brown et al. 2003). MerA gene encodes mercuric reductase that converts highly toxic ionic Hg\textsuperscript{2+} into less toxic volatile Hg\textsuperscript{0} (Cursino et al. 2000), thus alleviating metal toxicity and improving the efficiency of phytovolatilization. Lead-resistant endophytic bacteria Bacillus sp. MN3-4 isolated from the roots of the metal hyperaccumulator plant Alnus firma enhanced reduced metal phytoavailability by extracellular sequestration and intracellular accumulation (Shin et al. 2012).

Similarly, cadmium-resistant endophytic bacterium Serratia sp. LRE07 reduced metal stress by absorbing over 65% of Cd and 35% of Zn in bacterial cells from a single metal solution. Endophytes can also alter phytoavailability of heavy metals through the release of metal chelating agents (e.g., siderophores, biosurfactants, and organic acid), acidification of soils, redox activity, and phosphate solubilization. Extracellular polymeric substances (EPS) secreted by endophytes are composed of polysaccharides, proteins, nucleic acids, and lipids that are significantly responsible in metal complexation thereby reducing their bioaccessibility and bioavailability (Ma et al. 2016).

Nickel (Ni)-resistant endophytic bacterium Pseudomonas sp. A3R3 increased plant biomass (nonhost Brassica juncea) and Ni accumulation in plants (host A. serpyllifolium) grown in artificially Ni-contaminated soil (Ma et al. 2011). These effects can be attributed to the ability of endophytes to produce plant growth-promoting substances (ACC deaminase, siderophores, IAA, and P solubilization) and plant polymer-hydrolyzing enzymes like cellulase and pectinase (Table 11.4).

11.6 Bioactive Compounds from Endophytes

Gouda et al. (2016) have summarized the discovery of a number of bioactive metabolites from endophytes that serve as an excellent source of drugs for the treatment against various diseases and with potential applications in agriculture, medicine, food, and the cosmetic industries (Table 11.5). Ezra et al. (2004) reported that
Table 11.4  Endophytic bacterial enhanced phytoremediation of metal contaminated soil

| Endophytic bacteria | Host plant | Metal stress | Plant growth-promoting traits | Mechanisms |
|---------------------|------------|--------------|-------------------------------|------------|
| *Bacillus thuringiensis* GDB-1 | *Alnus firma* | As, Cu, Cd, Ni, Pb, and Zn | Production of IAA, siderophores, ACCD, and solubilization of P | Bioremoval of Pb, Zn, As, Cd, Cu, and Ni in metal-amended and mine tailing extract medium; increased biomass, chlorophyll content, nodule number and metal (As, Cu, Pb, Ni, and Zn) accumulation in *A. firma* |
| *Pseudomonas koreensis* AGB-1 | *Miscanthus sinensis* | As, Cd, Cu, Pb, and Zn | nd | Increased plant biomass, chlorophyll, protein content, superoxide dismutase and catalase activities, and metal uptake; however, decreased malondialdehyde content in plants |
| *Staphylococcus, Curtobacterium, Bacillus, Pseudomonas, Microbacterium, Arthrobacter, Leifsonia, Paenibacillus* | *Alyssum bertolonii* | Ni, Co, Cr, Cu, and Zn | Production of siderophores | Had an ability to colonize plant tissues |
| *Serratia nematodiphila* LRE07, *Enterobacter aerogenes* LRE17, *Enterobacter* sp. LSE04 *Acinetobacter* sp. LSE06 | *Solanum nigrum* L. | Cd | Production of IAA, siderophores, ACCD, and solubilization of P | Increased Cd mobilization in soils; stimulated plant growth and influenced Cd accumulation in plant tissues; colonized the rhizosphere soil and some colonized plant interior tissues |
| *Pseudomonas* sp. Lk9 | *Solanum nigrum* | Cd, Zn, and Cu | nd | Improved soil Fe, P, and heavy metal availability, shoot dry biomass, and uptake of Cd, Zn, and Cu |
| *P. monteilii* PsF84, *P. plecoglossicida* PsF610 | *Pelargonium graveolens* | Cr | Production of IAA and siderophores, solubilization of P | Increased plant dry biomass, essential oil yield, and chlorophyll helped Cr(VI) sequester in roots |

(continued)
### Table 11.4 (continued)

| Endophytic bacteria                  | Host plant                  | Metal stress | Plant growth-promoting traits | Mechanisms                                                                 |
|--------------------------------------|-----------------------------|--------------|-------------------------------|-----------------------------------------------------------------------------|
| *Rahnella* sp. JN6                   | *Polygonum pubescens*       | Cd, Pb, and Zn | Production of IAA, siderophores, ACCD, and solubilization of P | Showed high Cd, Pb, Zn tolerance and mobilization; promoted plant growth and Cd, Pb, Zn uptake by rapes; high level of colonization in tissue interior of rapes |
| Actinobacterium                      | *Salix caprea*              | Cd and Zn    | Production of siderophores and ACCD | Enhanced plant growth and metal accumulation in leaves                       |
| *Burkholderia cepacia* L.S.2.4, *Herbaspirillum seropedicae* LMG2284 | *Lupinus luteus* L.          | Cu, Cd, Co, Ni, Pb, and Zn | nd                            | Bioremoval of Ni, thus reduced metal toxicity; *B. cepacia* L.S.2.4 increased Ni concentration in roots, while *H. seropedicae* LMG2284 decreased Ni concentration in roots and shoots of *Lolium perenne* |
| *Pseudomonas fluorescens* VI8L1, *Bacillus pumilus* VI8L2, *P. fluorescens* II8L4, *P. fluorescens* VI8R2, *Acinetobacter calcoaceticus* II2R3 | *Sedum alfredii*            | Zn and Cd    | Production of IAA, siderophores, fixation of nitrogen, solubilization of ZnCO₃, Zn₃(PO₄)₂ | Mobilized Zn in soil, thus increased soil Zn bioavailability; improved growth and Zn accumulation by *S. alfredii* |
| *Serratia marcescens* LKR01, *Arthrobacter* sp. LKS02, *Flavobacterium* sp. LKS03, *Chryseobacterium* sp. LKS04 | *Solanum nigrum* L.         | Zn, Cd, Pb, and Cu | Production of IAA, siderophores, ACCD, and solubilization of P | Decreased Cd phytotoxicity; improved plant growth and total Cd accumulation in host plants |
| *Serratia* sp. LRE07                  | *S. nigrum* L.              | Cd, Cr, Pb, Cu, and Zn | Production of IAA, siderophores, and solubilization of P | Bioaccumulation or removal of metals (Cd, Zn) in both single-ion and multi-ions systems |
| *Bacillus* sp. SLS18                  | *Sorghum bicolor* L.        | Cd and Mn     | Production of IAA, siderophores, and ACCD | Improved plant biomass production and its total metal uptake (continued) |
| Endophytic bacteria | Host plant | Metal stress | Plant growth-promoting traits | Mechanisms |
|---------------------|------------|--------------|------------------------------|------------|
| *Pseudomonas* sp. A3R3 | *Alyssum serpyllifolium* | Ni | Production of IAA, siderophores, ACCD, and solubilization of P; excreted cellulase and pectinase | Increased the biomass of *B. juncea* and Ni content in *A. serpyllifolium*; showed high level of colonization in tissue interior of both plant species |
| *B. pumilus* E2S2, *Bacillus* sp. E1S2, *Bacillus* sp. E4S1, *Achromobacter* sp. E4L5, and *Stenotrophomonas* sp. E1L | *Sedum plumbizincicola* | Cd, Pb, and Zn | Production of IAA, siderophores, ACCD, and solubilization of P | Bacterial inoculation increased water-extractable Cd and Zn contents in soil; improved plant growth and metal uptake |
| *Methylobacterium* *oryzae* CBMB20, *Burkholderia* sp. CBMB40 | *Lycopersicon esculentum* | Ni and Cd | nd | Biosorption considerable amount of Ni and Cd, thus reduced the metal toxicity; promoted plant growth and reduced accumulation of Ni and Cd in roots and shoots of tomato plants |
| *P. fluorescens* G10, *Microbacterium* G16 | *Brassica napus* | Pb, Cd, Zn, Cu, and Ni | Production of IAA, siderophores, ACCD | Increased water-soluble Pb in solution and Pb-added soil; increased biomass production and total Pb uptake |
| *Bacillus* sp. MN3-4 | *Alnus firma* and *B. napus* | Pb, Cd, Zn, Ni, and Cu | Production of IAA and siderophores | Exhibited bioremoval of Pb; increased root elongation of *B. napus* seedlings; reduced metal phytotoxicity and increase Pb accumulation in *A. firma* |
| Endophytes belonged to Firmicutes, Actinobacteria, Proteobacteria | *Elsholtzia splendens*, *Commelina communis* | Cu | Production of IAA, siderophores, ACCD, and arginine decarboxylase | Increased plant dry weights and Cu content in aboveground tissue of rapes |

(continued)
Table 11.4 (continued)

| Endophytic bacteria | Host plant | Metal stress | Plant growth-promoting traits | Mechanisms |
|---------------------|------------|--------------|-------------------------------|------------|
| *Microbacterium* sp. NCr-8, *Arthrobacter* sp. NCr-1, *Bacillus* sp. NCr-5, *Bacillus* sp. NCr-9, and *Kocuria* sp. NCr-3 | *Noccaea caerulescens*, *Thlaspi perfoliatum* | Ni | Production of IAA, siderophores, and ACCD | Enhanced growth and Ni translocation in plants |
| *Serratia nematodiphila* LRE07 | *Solanum nigrum* L. | Cd | nd | Promoted biomass production; increased higher photosynthetic pigments content of leaves |
| *Rahnella* sp. JN27 | *Amaranthus hypochondriacus* and *A. mangostanus* | Cd | Production of IAA, siderophores, ACCD, and solubilization of P | Enhanced plant growth and Cd uptake by both plant species |
| *Acinetobacter* sp. Q2BJ2, *Bacillus* sp. Q2BG1 | *Commelina communis* | Pb, Cu, Cd, and Ni | Production of IAA, siderophores, and ACCD | Increased plant dry weights; increased Pb contents in aboveground tissue of rapes |
| *Ralstonia* sp. J1–22–2, *Pantoea agglomerans* Jp3–3, *Pseudomonas thivervalensis* Y1–3–9 | *B. napus* | Cu, Pb, Cd, and Ni | Production of IAA, siderophores, ACCD, and solubilization of P | Increased the biomass of rapes and increased Cu content in above-ground tissues |
| *Burkholderia* sp. SaZR4, *Burkholderia* sp. SaMR10, *Sphingomonas* sp. SaMR12 and *Variovorax* sp. SaNR1 | *Sedum alfredii* Hance | Cd and Zn | nd | SaMR10 had little effect on phytoextraction, while SaMR12 and SaNR1 promoted plant growth and phytoextraction of Zn and Cd; SaZR4 only promoted Zn extraction |
| Endophytes belonged to Firmicutes, Proteobacteria, and Actinobacteria | *Pteris vittata* and *P. multifida* | As | Production of IAA | Possessed ability of both AsV reduction and AsIII oxidation |

IAA, indole-3-acetic acid; ACCD, 1-aminocyclopropane-1-carboxylate deaminase; P, phosphorus; nd, not determined

Sources: Adapted with permission from Ma et al. (2016)
| Source of endophytes | Bioactive compounds from endophytes | Cure against pathogen | Mode of pathogen transmission |
|----------------------|-------------------------------------|-----------------------|-----------------------------|
| *Boesenbergia rotunda, Streptomyces coelicoco* | Munumbicins | *Escherichia coli* | Ground meats, raw or under pasteurized milk |
| *Chloridium sp.* | Javanicin | *Pseudomonas sp.* | Contaminated water or surgical instruments |
| *Allamanda cathartica* | Munumbicins, Phomopsilactone | | |
| *Cladosporium sp.* | Cardiac glycosides, phenolic compounds | *Klebsiella pneumoniae* | Contaminated water and aerosols |
| *Cladosporium sp.* | Cardiac glycosides, phenolic compounds | *Proteus sp.* | Canned food products |
| *Cryptosporiopsis quercina* | Saadamycin | *Campylobacter jejuni* | Raw or uncooked poultry and milk |
| *Cytonaema sp.* | Cytonic acids A and B | *Human cytomegalovirus. Hepatitis virus* | Shellfish, berries, or contaminated water |
| *Diaporthe helianthi* | Fabatin, tyrosol | *Enterococcus hirae* | Nosocomial infection through hospitalized patients |
| *Fusarium proliferatum* | Beauvericin | *Clostridium botulinum* | Improperly processed, canned food |
| *Fusarium proliferatum* | Kakadumycin, beauvericin | *Listeria monocytogenes* | Raw or under pasteurized milk, smoked fish |
| *Fusarium sp., Cryptosporiopsis quercina* | Xularosides, munumbicins, Saadamycin, cryptocandin | *Candida albicans* | Contaminated sweet fruits and milk products |
| *Ganoderma boninense* | Rapamycin, cycloidodecanec, petalostemumol | *Bacillus subtilis* | Rice, pastas, raw milk, and meat products |
| *Hypericum perforatum, Diaporthe helianthi* | Hypericin, emodin, tyrosol | *Salmonella sp.* | Meat, eggs, and untreated tree nuts |
| *Nigrospora sp.* | Saadamycin | *Fusarium oxysporum* | Maize, cereals, groundnuts, and tree nuts |
| *Phomopsis sp., Cinnamomum mollissimum* | Munumbicins, Saadamycin | *Aspergillus niger* | Maize, cereals, groundnuts, and tree nuts |
| *Saccharothrix mutabilis, Streptomyces sp.* | Capreomycin, Munumbicins | *Mycoplasma (TB)* | Uncooked meat, eggs, or poultry |

(continued)
coronamycin, a complex of novel peptide antibiotics with activity against pythiaceous fungi and the human fungal pathogen Cryptococcus neoformans, was produced by a verticillate Streptomyces sp. isolated as an endophyte from an epiphytic vine Monstera sp. It was also active against the malarial parasite, Plasmodium falciparum.

Undoubtedly, one of the most revolutionary findings of endophyte studies was the isolation of taxol-producing endophyte Taxomyces andreanae (Stierle et al. 1993). The diterpenoid taxol was approved by the FDA as one of the most potent anticancer drugs, but the supply of this drug was limited for the destructive collection of yew tree, the main source of taxol. Later taxol (paclitaxol) was also reported to be produced by the endophyte Metarhizium anisopliae found in the bark of a Taxus tree and is one of the most promising anticancer agents (Gouda et al. 2016).

### Table 11.5 (continued)

| Source of endophytes | Bioactive compounds from endophytes | Cure against pathogen | Mode of pathogen transmission |
|----------------------|-------------------------------------|-----------------------|-------------------------------|
| Streptomyces hygroscopicus | Clethramycin | Cryptococcus neoformans | Lettuce harvested from tropical regions |
| Streptomyces lygroscopicus | Coronamycin, rapamycin | Saccharomyces cerevisiae | Bakery and fermented products |
| Streptomyces sp. | Kakadumycin A, hypericin | Shigella sp. | Contaminated food, water, and fecal waste |
| Streptomyces sp., Achyranthes bidentata, Phoma sp., Saurauia scaberrinae | Terephthalic acid | Staphylococcus aureus | Meat, eggs, and dairy products |
| Streptomyces sp., Kennedia nigricans | Munumbicins | Vibrio cholerae | Raw or undercooked shellfish, particularly oysters |
| Streptomyces tsusimaensis | Valinomycin | Corona virus | Food or water contaminated with infected fecal matter |
| Thottea grandiflora, Xylaria sp. | Streptomyces dihydroxynaphthol, glucopyranoside | Bacillus cereus | Uncooked meat and raw milk Contaminated body fluid or saliva |
| Xylaria sp. | Phenolic compounds | Streptococcus pyogenes | Contaminated water, raw milk, salads, and eggs |
| Xylaria sp., Ginkgo biloba, Fusarium proliferatum | Sordaricin 7 amino-4-methylcoumarin, Beauvericin | Yersinia enterocolitica | Swine meat and meat products, milk, and dairy products |

Sources: Adapted with permission from Gouda et al. (2016)
As a selectively cytotoxic quinone dimer, torreyanic acid is another important anticancer agent. Lee et al. (1996) reported the isolation of an endophyte strain *P. microspore* from *T. taxifolia* (*Florida torreya*) and the extraction of torreyanic acid from cultures of this endophyte. Camptothecin and its derivatives show strong antineoplastic activity. The fungus, which belongs to the family Phycomycetes, isolated from the inner bark of the plant *Nothapodytes foetida*, produced the anticancer drug lead compound camptothecin (Puri et al. 2005).

Endophytes are a potential source of novel secondary metabolites with antiarthritic, antimicrobial, anticancer, antidiabetic, anti-insect, and immunosuppressant activities (Devi et al. 2020; Kour et al. 2019a; Yadav et al. 2019). Bioactive compounds, such as camptothecin, diosgenin, hypericin, paclitaxel, podophyllotoxin, and vinblastine, are commercially produced by different endophytes colonizing respective plants which are agriculturally and pharmaceutically significant (Gouda et al. 2016; Godstime et al. 2014; Joseph and Priya 2011).

### 11.7 Conclusions and Future Perspectives

Promising plant growth-promoting activity and an ability to induce stress tolerance to host plants have drawn wide attention for developing not only culture dependent but also independent characterization of endophytic diversity. However, reports on successful application of endophytes in plants under field conditions are extremely scarce. Future studies should aim to explore the interrelationship between plant immunity and function of the microbial population of endosphere. Similarly, breeding of endophyte-colonized crops, genetic engineering of endophytes, maintenance, and adaptation to benefit plants at various growth stages of plants should be investigated. Further, endophytes impart resistance to hosts against pests, insects, nematodes, and plant pathogenic fungi and bacteria.

Similarly, host plants obtain tolerance to abiotic stress induced by drought, salinity, and toxic metals. Diverse bioactive compounds have been synthesized by microbial endophytes that may include antimicrobials (vanillin, essential oils), antifungals, antivirals (alkaloids), antioxidants (eugenol), anti-inflammatory (cineole), etc. Therefore, commercial processes can be developed to exploit the rich source of endophytic biodiversity to produce natural products for use in pharmaceutics, food, and cosmetics. Activity-based rapid screening technologies should be developed that may help in the selective isolation of beneficial endophytes. Establishing a target endophytic library for plant breeding may help to protect endangered medicinal plants from overexploitation. Endophytes can be envisioned to be the future of biofertilizers and biocontrol agents that can be promising alternatives to environmentally hazardous chemical fertilizers and pesticides resulting in a paradigm shift in agricultural best practices.

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