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Exploring the bioefficacy of Endophytic Bacteria against Important Plant Pathogens

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ABSTRACT

The biological management of plant diseases has developed into a separate scientific and technological discipline, and in recent years, this change has happened quickly. A form of bacterium known as a bacterial endophyte may colonize any portion of a plant without causing any symptoms or harm to the host plant. Endophytic bacteria have been discovered by several researchers, and there is growing evidence that they can stop a variety of plant diseases from growing and functioning. Endophytes have a variety of benefits including growth-increasing and disease-hampering properties. Researchers' interest in this field is growing as a result of its potentially to be utilized as an alternative to synthetic fungicides. This review's main objectives are to chart the development of endophytic bacterial research and give scientists access to current knowledge that will spur further investigation. Endophytic bacteria are employed to control plant diseases including wilt, rot and post-harvest damage, as well as nematode infestation. Endophytic bacteria are also used to control nematodes and postharvest diseases. With an emphasis on endophytic bacteria, this review explains the diverse mechanisms of bacterial endophytes to shield the plant from biotic infection.

Keywords: Antibiotics, Bacteria, Endophytes, Management, Phytopathogens

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INTRODUCTION

Plant diseases create tremendous biotic stress in plants, causing farmers to lose a lot of money and tainting food by creating toxins while it is kept. Farmers' purposeful determination to combat illness resulted in the development of a variety of pesticidal molecule, the use of which destroys the environment and eventually, harms human health. Plant health management has gotten more difficult as certain plant diseases have developed resistance to these treatments (Dun-chun *et al*., 2016). Bio-control of plant diseases has become more important in addressing these concerns. Plant growth-promoting rhizobacteria (PGPR) have long been investigated by many scientists and rhizosphere treatments for biocontrol have mostly focused on them. Due to the expanding range of ways that microorganisms may be used to boost plant development and lower disease-causing pathogens, researchers have lately turned their attention to those that colonize interior tissues with laser beams (Saeed *et al*., 2021). Researchers have recently focused a lot of emphasis on the function of bacterial endophytes among these microorganisms in plant disease management. Endophytic bacteria were defined by Wilson (1995) as prokaryotes that seek to colonize the vascular tissues without causing any damage to the host plant. Endophytes are "endo-symbionts" that live inside plant tissues without causing injury or illness and may be discovered using aseptic procedures, according to researchers. Previous studies showed the beneficial relations between plants and microorganisms and scientists believed that fungi that weren't often recognized for causing illnesses in agricultural plants had the power of microbial endophytes (Clay, 1988). The seeds of horticultural as well as agricultural crops might be used to isolate bacterial species (Kirchhof *et al*., 1997).

According to studies, endophytic bacteria can be found in plant parts. When describing the habitat of endophytes, Andrews (1992) stated that, unlike microorganisms dwelling in and above the rhizosphere, endophytes may exist in a fully isolated environment. Endophytic bacteria, according to Arnold and Lutzoni (2007), may reside in the rhizosphere, twig, leaves, petals, seeds and fruits of agricultural plants.

Endophytes have a variety of benefits, according to a growing body of literature. Kang *et al*., (2007) described endophytes growth-increasing properties, whereas Senthilkumar *et al*., (2007) performed endophytes' disease-hampering properties. Bakker *et al*., (2007) investigated the work of endophytes in strengthening crop defense mechanisms against various plant disease. Endophytes have been shown to generate anti-herbivory compounds as well as catalyze biological nitrogen fixation in plants (Martínez *et al*., 2003) and improve their mineral absorption (Malinowski *et al*., 2000). Backman *et al*., (1997) conferred specific bacteria colonizing a specific crop species, changing populations as seasons change, the order in which they colonized and their capability to mobilize within cells and encourage systemic resistance as endophytes as antimicrobials against multiple plant diseases.

Endophytes

A quick description of 'Endophytes' is provided here to help you comprehend the subsequent sections of the review. Endophytes are micro-organisms that be inherent asymptomatically in the plant for at least a portion of their lifespan (Solis *et al*., 2016). Endophytes thrive within their hosts intracellularly, systemically or locally without creating apparent infection or disease signs (Schulz *et al*., 2015). According to Busby *et al*., (2016), endophytism is characterized by "inconspicuous infections, diseased host tissues that are at least temporally symptomless and demonstrated microbial colonization inside host tissues". All plants are thought to have endophytes, and the biodiversity of these microorganisms relies on a range of factors, including the type of host plant, plant canopy, nutrient availability, the adequacy of the local environment and interactions between bacteria and fungi that are carried by the soil (Yan *et al*., 2015). Endophytes are potential biocontrol agents because they can change interactions with infections and pests. An endophyte called *Acremonium alternatum* boosts tomato resistance to the powdery mildew disease *Leveillula taurica* and shields beans from the moth *Plutella xylostella*. An isolated fungal endophyte from cotton plants called Phomopsis sp. prevented caterpillar herbivory on cotton plants. Sometimes an endophyte species can act as a biocontrol agent, and other times it might promote the growth of the host plant, which has additional benefits. Neotyphodium species promote host plant growth, fitness and stress tolerance while safeguarding it against infections and pests (Solis *et al*., 2016). Furthermore, pathogenic *Sclerotium rolfsii* was decreased and sunflower biomass output was boosted by endophytic *Penicillium citrinum* and *Aspergillus terreus* (Harman *et al*., 2021). How endophytes minimize diseases and pests is the next important question. We will explore how endophytes maintain their interaction with their hosts before diving into several biocontrol techniques.

Interaction between plants and endophytes

The concept of "balanced antagonism" between endophytes and their host explains why they colonize without exhibiting any symptoms (Schulz *et al*., 2015). Fungal virulence factors will be totally overcome by plant defence systems, preventing the fungus from colonising plant tissues. If fungal virulence elements could interfere with plant defence systems, a plant-pathogen connection would result in plant disease (Suryanarayanan *et al*., 2016).

When they are impacted by internal or external conditions that make them express pathogenic factors, certain endophytes turn into pathogens (Kusari *et al*., 2012). *Colletotrichum magna* strains that are pathogenic and endophytic have been demonstrated to transform their life styles by interfering with certain genetic loci or closely related genes that cause anthracnose disease in cucurbitaceous crop (Rai and Agarkar, 2016). A non-pathogenic mutant strain of *Colletotrichum magna* (Path-1) produced from a pathogenic strain (CmL2.5) colonizes the roots and stems of cucurbit plants asymptomatically and inhibits the virulent form of the fungus, according to experiments (Rai and Agarkar, 2016). High humidity or a shortage of nutrients may be to blame for this frequent occurrence of Colletotrichum switching lifestyles, which alters the host's vulnerability in the presence of natural circumstances (Fisher and Petrini, 1992; Rai and Agarkar, 2016).

Some endophytes produce small quantities of antifungal and antibacterial chemicals to prevent competitors (both pathogenic and endophytic bacteria and fungi) and maintain a competitive balance (Suryanarayanan *et al*., 2016). The insecticidal metabolite rugulosin generated by endophytic Phialocephala species from *Picea glauca* (white spruce) poisons *Choristoneura fumifurana* (spruce bud worm). Secondary metabolites regulate the antagonistic connections between competitors, plant hosts, and endophytes (Hashem *et al*., 2023). Estrada *et al*., (2012) found that endophytic *Fusarium verticillioides* in maize might lower pathogenic *Ustilago maydis* aggressiveness while simultaneously destroying protective systems.

The compounds in the plant are effective against *U. maydis*. Pathogen reduction may also come through multipartite healthy relations between endophytes, competitors and host plants. Secondary metabolites will impair their ability to develop and survive (Suryanarayanan *et al*., 2016). In conclusion, interactions between plants and endophytes are complex and control the balance of host defence, fungal virulence and secondary metabolites.

Metabolites and activities of endophytes

The potentiality of microbial endophytes to yield a variety of crucial compounds for pharmacology, including antiviral, antifungal, antibacterial, antitumor and anticancer medications, is well documented. Several endophytes can produce plant hormones and growth factors (Kandel *et al*., 2017; Chaudhary *et al*., 2022). Abiotic stress tolerance, siderophores, nematocidal, insecticidal and agricultural chemicals are some of their other potential products. A variety of extracellular enzymes, including the phosphatase enzyme, which transforms insoluble phosphate into soluble phosphates for easier digestion by plants, have been shown to be secreted by endophytes (Sharma *et al*., 2021). Endophytes create chemicals that can be employed in the production of biofuels and the degradation of sophisticated organic and inorganic pollutants that are produced during industrial operations (Burragoni and Jeon, 2021). The advantages of endophytes are listed below, along with some prospective uses for them in various industries.

Endophytes potential in agriculture

Endophytes, according to published studies, are a good source of metabolites and desirable functionalities that might benefit an organic agricultural system. Some endophytes might be employed as bio-pesticides against plant pathogens because of their antibacterial, nematicidal and insecticidal capabilities.

Biopesticidal properties of Endophytes

A systemic weed commensal fungal endophyte *Epichloe typhina* releases mycotoxic properties in extracts of Phleum pratense, a perennial grass native to much of Europe. Bacteria generated chitinase, which is known to dissolve chitin polymers, which are a key component of a fungal cell wall. Bacillus cereus strain was recognized as

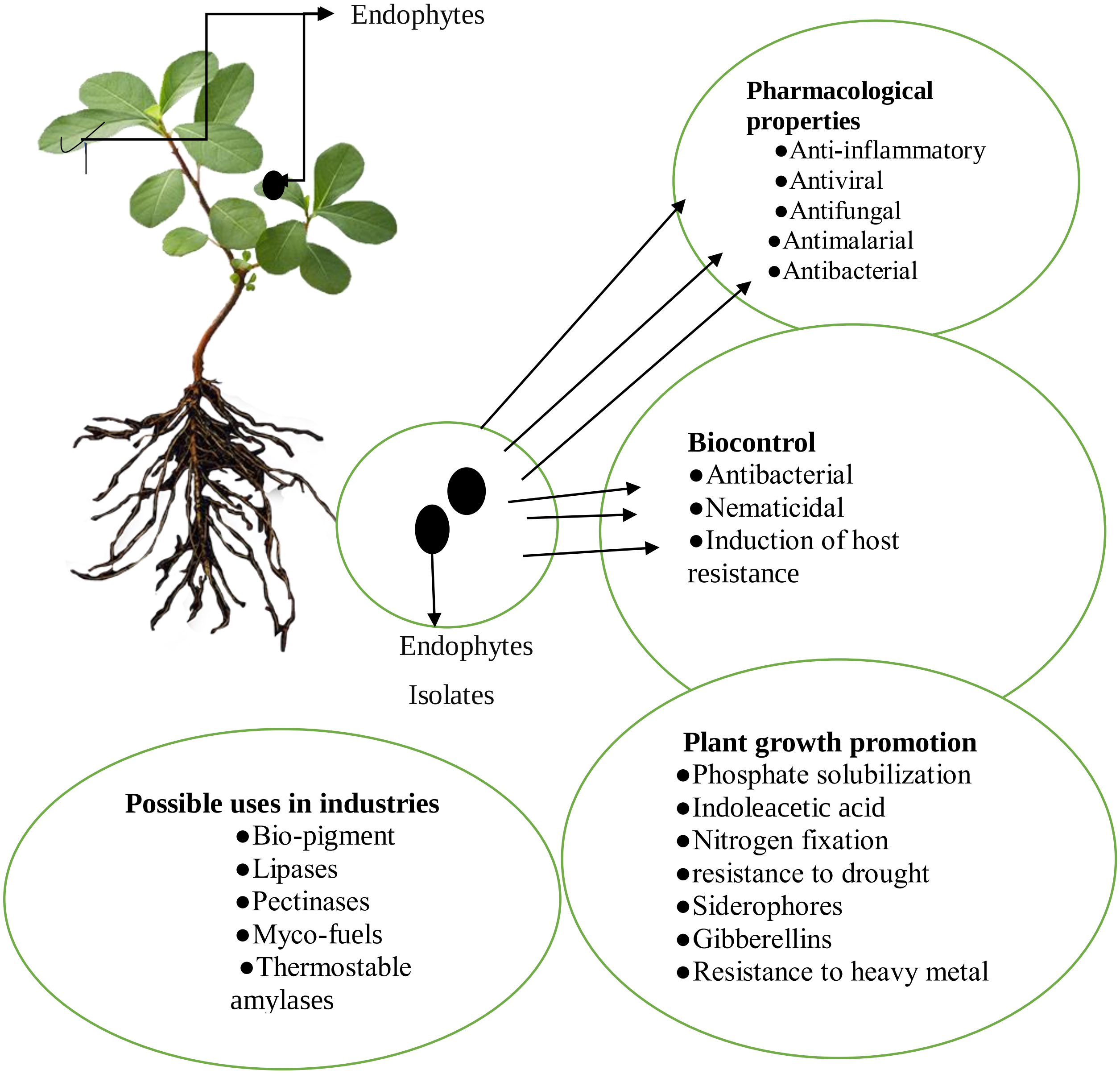

Fig.1. Endophytes and their diverse properties (Source: Unpublished photographs from the authors)

bacterial endophyte, was previously perform a defense mechanism against *Rhizoctonia solani* (Pleban *et al.*, 1997). A strain of *Neotyphodium* sp. (AR601) that produces substantial amounts of alkaloids such as loline and ovaline and is injected into the turf tall fescue cultivar 'Jackal' has shown bird deterring capacity (Pennell, 2010). By generating pathogenesis-related proteins, some endophytes have been confirmed to reliably produce effective resistance in plants against common phytopathogens. Fungal endophytes isolated from the tree leaves were shown to produce chitinase and chitosanase, which may help

Table 1. Mechanism involved in the mode of action of bacterial endophytes

Broad mode of action	Mechanism involved	References
Root colonization through competition	Various growth stages, the capability to adhere to roots and circulate around without inhibition, and the efficient utilization of the organic acids released from root exudates, the generation of a range of chemicals, together with amino acids, and the type III secretion system are all characteristics of this species.	Lugtenberg and Kamilova ,2009
Antibiosis and antibiotics suppressing pathogens	Pharmaceuticals such as phenazines, pyoluteorin, pyrrolnitrin, and the volatile HCN are produced.	Pierson and Pierson, 2010; Dandurishvili *et al.*, 2011; Henry *et al.*, 2011; Savadogo *et al.*, 2011; Ramkumar *et al.*, 2013; Zhang *et al.*, 2013; Torres *et al.*, 2016
	There is the production of D-gluconic acid, 2-hexyl-5-propyl resorcinol, and the volatiles 2,3-butanediol, 6-pentyl—pyrone, and DMDS.	
	Lipopeptides with disease-controlling abilities include surfactin, fengycin, polymyxin, bacitracin, and the iturin group.	
	Pyrrolnitrin, pyrrologlucinol, phenols, and volatile organic compounds such benzothiazole, pyrazine (2,5-dimethyl), and phenolic derivatives are produced.	
Signal interference	Exo-enzyme synthesis requires the deactivation of AHL molecules.	Dandurishvili *et al.*, 2011
Ferric iron ion competition	Siderophores are synthesized in order to trap ferric ion.	Whipps, 2001
Competition for nutrients and niches (CNN)	CNN follows the same method as competitive root colonization.	Malfanova, 2013
Detoxification and degradation of virulence factors	Fusaric acid detoxifies toxins released by pathogens.	Uroz *et al.*, 2003
	By destroying autoinducer signals, which prevent the expression of several virulence genes, the ability to sense quorum is achieved.	
	Resistance produced by salicylic acid, c-LPs, pyocyanins, siderophores, and other substances	

host plants defend against many plant pathogens by activating host defenses and enhancing resistance (Zheng *et al.*, 2017).

Antimicrobial properties of endophytes

Some endophyte species have been found to form antimicrobial compounds (Jha *et al.*, 2023). For their antibacterial properties, endophytic microbes from plants have also been taken into consideration (Wang *et al*., 2019; Xu *et al*., 2020). Phomopsichalasin was extracted from Phomopsis sp., isolate no. MF6031, which was attained from the twigs of Salix gracilostyla var. melanostachys was shown to have antibacterial action against *Bacillus subtilis*, *Salmonella gallinarium* and *Staphylococcus aureus* as well as antagonistic activity against *Candida tropicalis* (Horn *et al*., 1995). In one more investigation, a Colletotrichum spp. isolated from internal stem cells of *Artemisia annua* L. was found to exhibit antifungal, antibacterial and fungistatic activities (Lu *et al*., 2000).

Direct inhibition on plant pathogens

Several recent research has initiated that endophytes may defend the host plants from diseases or may decrease the destruction triggered by pathogenic microorganisms (Ganley *et al*., 2008; Meja *et al*., 2008). Despite the fact that certain research suggests potential endophyte mechanisms for limiting pathogen damage, our understanding of the exact control of endophyte, pathogen and plant is still in its infancy. In this part, we will talk about the processes as direct effects, indirect effects by increasing plant defence and ecological effects. During direct influence, endophytes actively conquer plant diseases by generating antibiotics and lytic enzymes (Fadiji and Babalola, 2020). Conversely, direct interactions amongst bacterial endophytes and biotic plant diseases can be challenging and hostile depending on the species involved (Afzal *et al*. 2019).

Indirect effects of on host plant resistance

In reaction to severe environmental circumstances such as drought, cold, salt stress or during biotic infections, plants generate a number of defence mechanisms. In response to diverse stimuli, rapid structural and biochemical changes occur, such as cellular necrosis, hypersensitive response and phytoalexin synthesis. Over time, two forms of innate resistance develop to withstand pathogen infestation: non-specific (generic) resistance and particular resistance (Kira'ly *et al*., 2007). The previous one is efficient compared to a wide range of pathogenic microbial species, whereas the latter can tolerate infection by a few pathogenic strains. In fact, resistance improvement and secondary metabolite synthesis boost plant defence against endophytes.

Plant Disease Management

Endophytic bacteria have arisen as an attractive, promising and ecologically friendly biological control technique because they can efficaciously decrease biotic disease incidence and severity by blocking the vascular development of the target pathogen (Constantin *et al*. 2019; de Lamo *et al*. 2018). These endophytes infiltrate plant portions without causing harm. On a variety of hosts, they either directly or indirectly promote plant growth and/or also act as biocontrol agents by inducing resistance (Constantin et al. 2019).

Wilt-Causing Pathogens by Bacterial Endophytes

Wilt is a widespread disease caused by fungal and bacterial strains that can cause major financial losses for farmers. Fusarium and Verticillium are two significant fungal species that produce wilt, and they are difficult to treat since they are soilborne diseases. The pathogenic agent's soil-borne origin and capability to infiltrate the vascular system of infected plants, as well as the rise of new and vigorous pathogen physiological races, make disease treatment difficult. Chemical wilt treatments are generally unsuccessful due to the pathogen's extensive host range and ability to live in soil for lengthy periods of time. As a result, biological wilt management has become more significant, encouraging many scientists to do research on discovering appropriate endophytic bacteria to control wilt infections. Endophytic microorganisms may constitute a potentially appealing and ecologically safe option for wilt pathogen biocontrol because endophytes may better restrict disease occurrence and severity by inhibiting systemic fungal progress (Aydi-Ben-Abdallah *et al*., 2020). Endophytic bacteria by their diverse mode of action have been revealed in a quantity of studies to check the growth of wilt-producing pathogens (Table 2).

Managing Root Rot by Endophytic Bacteria

Pathogens that cause root rot are particularly challenging to control because they may persist in the plant debris/soil up to many years until the environmental conditions are conducive for them and a susceptible host plant can be produced (Conner *et al*., 2014). The primary method for controlling these infections still involves the use of agrochemicals, but this method has repeatedly led to the emergence of resistance and had a negative impact on the environment. Although frequently employed to address root rots, seed coating with fungicides has had little impact on the pathogens' control (Xu and Kim, 2014). Endophytic bacteria have been praised to manage root rot pathogens because they share a niche with the disease, secrete antifungal metabolites, and aid flora in acquiring nutrients and preparing for plant defence (Muthukumar and Bhaskaran, 2007). Root tissues are colonized by endophytic bacteria, which can defend their host plants from invasion by soil-borne pathogens (Mercado-Blanco *et al*., 2004; Rybakova *et al*., 2016) because endophytes are initially seen in root hairs during the initial stages of their colonization, and afterwards move in the root cortex (Prieto *et al*., 2011; Castanheira *et al*., 2017; Rangjaroen *et al*., 2017). Plants benefit from endophytic bacteria invading interior plant tissue in many different ways, with the production of plant growth regulators, osmo-protectants (Beneduzi *et al*., 2012), exopolysaccharides (Berg *et al*., 2013), antifungal metabolites (Gond *et al*., 2015) and regulation of plant physio-biochemical components (Hashem *et al*., 2016). Regardless of how crucial the endophyte-plant interaction is, little is known about how pathogens, endophytes, and legumes interact in adverse environmental conditions. Management of various rot causing pathogens by endophytic bacteria is summarized in Table 3 mentioned below.

However, only a few endophytic biological control agents have been approved for practice in sustainable agriculture and are currently commercially accessible. This calls for greater research on the exploration and expansion of biocontrol organisms, particularly the utilization of endophytes.

Bacterial Endophytes for storage pest

Latest findings have documented the antagonistic behaviors of a wide variety of bacterial endophytes that are found on the outer most layer of fruits and vegetables. On the surface of the fruit, several bacterial species and actinomycetes can influence the development of postharvest diseases (Huang *et al*., 2021). Three primary bacterial phyla—*Proteobacteria*, *Actinobacteria* and *Bacteroidetes*—dominate the various microbial communities found within or on the host plant surface (Hacquard *et al*., 2015). The most common biocontrol bacteria discovered on fruit surfaces include *Bacillus* spp., *Burkholderia, Citrobacter, Pseudomonas* and *Paenibacillus,* (Huang *et al*., 2021). By displaying antibiosis, *Pantoea dispersa* prevented sweet potato from developing black rot (Jiang *et al*., 2019). *Streptomyces* species, a Gram-positive bacterium was recently discovered to be able to stop the infection caused by various bacteria and fungi, including *Burkholderia glumae*, a bacterial rice pathogen (Degrassi and Carpentieri-Pipolo 2020).

Notably important tasks are screening microbial antagonists against diverse phytopathogens (Kumari *et al*., 2022). For BCA screening, bacterial strains that may produce antibiotic or volatile chemicals as well as enzymes that can disrupt or lessen the pathogen virulence factors are favored (Zimand *et al*,. 1996; Kapat *et al*., 1998; Kumari *et al*., 2022). Table 4 enlists the endophyte-produced bioactive compounds that may be employed to combat biotic infections after harvest.

Endophytic in nematodes management

Since the middle of the 1990s, bacterial endophytes have been revealed to be antagonistic to phytopathogenic nematode (Hallmann *et al*., 1997; Siddiqui and Mahmood, 1999; Bhat *et al*., 2023). Plant pathogens are opposed by the greater number of Gram-negative endophytic bacteria and by only few species of Gram-positive bacterial endophyte (Kobayashi and Palumbo, 2000). Gram-negative endophytes include *Burkholderia cepacia*, *P. fluorescens* and *Agrobacterium radiobacter*, whereas Gram-positive endophytes include Bacillus spp. Acrhomobacter, Acinetobacter, Agrobacterium, Bacillus, Brevibacterium, Microbacterium, Pseudomonas, Xanthomonas and other species have also been discovered to have the capacity to suppress phytopathogenic nematodes (Yadav *et al*., 2017; Harni *et al*., 2023).

Table 2. Role of bacterial endophytes in wilt disease management

Sr No.	Pathogens causing wilt	Endophytic bacteria have been shown to reduce wilt incidence	Mode of action	References
1	*Verticillium dahliae F. oxysporum f. Sp. lycopersici F. oxysporum f. Sp. radicislycopersici*	*Pseudomonas sp.* strain PsJN *P. fluorescens* WCS417r B. pumilus SE-34 *Bacillus amyloliquefaciens* BO7 B. amyloliquefaciens RWL-1	Endophytic bacteria colonize tomato plants and thicken their cortical cell walls as structural barrier. Siderophores and plant defence hormones like jasmonic acid, and salicylic acid are generated, enhancing ISR.	Vitullo *et al*., 2012; Shahzad *et al*., 2017
2	*F. oxysporum* f. Sp. *vasinfectum Verticillium dahliae*	*Aureobacterium saperdae*, *Bacillus pumilus*, *Burkholderia solanacearum*, *Phyllobacterium rubiacearum*, *Pseudomonas putida*, *Bacillus subtilis* KDRE01, *Bacillus megaterium* KDRE25	Antibiosis is performed by producing antibiotic components. Cotton wilt induced by mycelial growth inhibition and toxin production.	Lin *et al*., 2013
3.	*F. oxysporum* f. sp. *cubense* race 4 *Fusarium oxysporum* f. sp. *cubense*	*Burkholderia cepacia* is a kind of bacteria. Strains 84 and 4B of *Pseudomonas putida*. Strains of *Bacillus cereus*, *Acromobacter* spp., strains of *Bacillus flexus Rhizobium* spp., W19 *Bacillus amyloliquefaciens*	Colonize the hyphae and macrospores of the fungal pathogens by inducing mycelial deformities. It has been demonstrated that siderophores and secondary metabolites like surfactin, iturin, and bacillomycin D produce a thick biological layer that prevents pathogen development.	Smith *et al*., 2003; Thangavelu and Gopi, 2015
4	*Fusarium oxysporum*	BECS7, BECS4 and BECL5 *Pseudomonas fluorescens (Pf1) Bacillus subtilis* (EPCO16 and EPC5), *Pseudomonas* spp.	Pathogen suppression by hydrolytic enzyme synthesis	Amaresan *et al*., 2014
5	*F. Avenaciarum F. sambucinum F. oxysporum*	*Bacillus* spp.	*In vitro* antibiosis	Sturz *et al*., 1999
6	*C. fagacearum*	*Pseudomonas denitrificans* and *P. putida*	*In vitro* antagonism and competitive colonization of microbes	Brooks *et al*., 1994

Table 3. Management of various rot causing pathogens by endophytic bacteria

Endophytic Bacteria	**Isolated from**	**Disease**	**Pathogen**	**Reference**
Actinoplanes missouriensis	Lupin roots	Root rot of lupin	*Plectosporium tabacinum*	El-Tarabily, 2003
Bacillus amyloliquefaciens	Stems, leaves, and roots of the *Eleusine indica* (weed)	Stem end rot of pitaya	*Alternaria alternata*	Trung *et al.*, 2021
Bacillus subtilis subsp. *subtilis* and *B. amyloliquefaciens*	Soybean roots	Charcoal rot of soybean	*Macrophomina phaseolina*	Torres *et al.*, 2016
Bacillus megaterium and *Enterobacter hormaechei* subsp. *xiangfangensis*	Mangroves and other vascular shrubs	Root rot of bean	*Fusarium solani*	Mutungi *et al.*, 2022
Bacillus subtilis and *Mesorhizobium cicero*	Nodules of chickpea	Root rot of chickpea	*Fusarium solani*	Egamberdieva *et al.*, 2017
Bacillus cereus and *Pseudomonas aeruginosa*	Rhizome of turmeric	Rhizome rot of turmeric	*Pythium aphanidermatum*	Vinayarani and Prakash, 2018
Bacillus mycoides isolates BP24 from	Sugar beet leaves	Black pod rot of cacao	*Phytophthora capsica*	Bargabus *et al.* 2002; Bargabus *et al.*, 2004; Melnick *et al.*, 2008
Bacillus pumilis	Germinating sugar beet seeds			
Bacillus cereus	Potato and tomato plants			
Burkholderia gladioli	Healthy corm of saffron	Corm rot of saffron	*Fusarium oxysporum*	Ahmad *et al.*, 2021
Bacillus, Lysinibacillus, and *Stenotrophomonas*	Tomato plants	Root rot of tomato	*Rhizoctonia solani*	Sahu *et al.*, 2019
		Collar rot of tomato	*Sclerotium rolfsii*	
Pseudomonas viridiflava	Apoplastic fluids attained from canola leaves	Black rot of canola	*Xanthomonas campestris* pv. *Campestris*	Romero **et al.**, 2019
		Stem rot of canola	*Sclerotinia sclerotiorum*	
Burkholderia cepacia and *Pseudomonas aeruginosa*	Symptomless oil palm root tissues	Basal stem rot of oil palm	*Ganoderma boninense*	Sapak *et al.*, 2008
Paenibacillus polymyxa	Spermosphere of the Styrian oil pumpkin	Fruit rot of Styrian oil pumpkins	*Didymella bryoniae*	Fürnkranz *et al.*, 2012

Table 4. Role of bioactive compounds secreted by endophytic bacteria against post-harvest diseases

Endophytic bacteria	**Secretion of bioactive compound**	**Role against post-harvest pathogens**	**References**
Bacillus subtilis	Iturin A, lipopolysaccharide	Antifungal activity	Ek-Ramos *et al.*, 2019
Bacillus sp.	Surfactin, fengycin	Used against bacterial diseases	Jasim *et al.*, 2016
Bacillus amyloliquefaciens CEIZ-11	Lipopolysaccharide	Antifungal activity	Zouari *et al.*, 2016
Bacillus strains and *Enterobacter*	3-Methylbutan-1-ol	Manage postharvest infection of *Botrytis cinerea* on tomato fruit, as well as control grey mold during storage and transit	Chaouachi *et al.*, 2021
Bacillus sp. and *Exiguobacterium acetylicum*	α-Farnesene	Reduces the postharvest infection of litchi fruit caused by *Peronophythora litchii*	Zheng *et al.*, 2019
Bacillus pumilus TM-R	Ethanol	Antifungal activity against post-harvest pathogens	Morita *et al.*, 2019
Pseudomonas aeruginosa	Phenyltetradeca-2,5-dienoate	Antibacterial activity	Pratiwi *et al.*, 2017
Pseudomonas donghuensis P482	Dimethyl sulphide, S-methyl thioacetate, methyl thiocyanate, dimethyl trisulphide, 1-undecan and HCN	Against post-harvest losses caused by *Rhizoctonia solani*	Ossowicki *et al.*, 2017
Pseudomonas fluorescens strain WR-*1*	Volatile organic compounds (VOCs)	Both antibacterial and antifungal activity	Raza *et al.*, 2016
Pseudomonas putida BP25	Volatile organic compounds (VOCs)	Antifungal activities against *Phytophthora capsici*	Sheoran *et al.*, 2015
Streptomyces lavendulae SPS-33	2-Methyl-butanol and 3-methyl-1-butanol	Check the infection of *Ceratocystis fimbriata* causes postharvest losses in sweet potato	Li *et al.*, 2020

Table 5. Effect of endophytic bacteria against phytopathogenic nematodes (PPN)

Endophytic Bacteria	**Crop**	**Plant Pathogenic Nematode (PPN)**	**Effect of Endophyte on PPN**	**Reference**
Pantoe agglomerans, Cedecea davisae, Enterobacter intermedius, Pseudomonas putida and *Pseudomonas Fluorescens*	Tomato	*Meloidogyne incognita*	As a seed treatment, it reduces nematode infestation.	Munif *et al.*, 2000
Agrobacterium radiobacter, Bacillus pumilus, B. brevis, B. megaterium, B. mycoides, B. licheniformis, Chryseobacterium balustinum, Cedecea davisae, Cytophaga johnsonae, Lactobacillus paracasei, Micrococcus luteus, Micrcoccus halobius, Pseudomonas syringae and *Stenotrophomonas maltophilia*	Tomato	*Meloidogyne incognita*	Number of galls and egg masses were reduced.	Mekete *et al.*, 2009
Pseudomonas spp., *Bacillus* spp., *Methlobacterium* spp.	Okra	*Meloidogyne incognita*	The quantity of adult females, egg masses, eggs per egg mass, and root gall index were all reduced.	Vetrivelkalai *et al.*, 2010
Rhizobium etli	Tomato	*Meloidogyne incognita*	35 days after nematode inoculation, the quantity of eggs per female was reduced.	Martinuz *et al.*, 2013
Pantoea agglomerans, Cedecea davisae, Enterobacter spp., *Pseudomonas putida*	Tomato	*Meloidogyne incognita*	When used as a root dip and soil drench, it reduced early root penetration by second stage juvenile along with the reduction in gall formation.	Munif *et al.*, 2013

Bacillus cereus, *Methylobacterium* sp., *Pseudomonas* sp.	Tomato	*Meloidogyne incognita*	Adult female population, egg masses, eggs per egg mass were all reduced.	Hu *et al.*, 2017; Vetrivelkalai, 2019
Bacillus subtilis (Talc based)	Banana	*Meloidogyne incognita, Pratylenchus coffeae, Radopholus similis, Helicotylenchus multicinctus*	Reduced nematode population	Jonathan and Umamaheswari, 2006
Streptomyces sp.	Banana	*Meloidogyne javanica*	J2s inhibition	Su *et al.*, 2017
Rhizobium etli	Potato	*Meloidogyne incognita*	Reduced number of galls on roots.	Hallmann *et al.*, 2001
Pseudomonas fluorescens, P. putida, P. syxantha, and *P. aurantiacea*	Potato	*Globodera rostochiensis*	Growth and multiplication of nematode population was reduced.	Trifonova *et al.*, 2014
Bacillus carotarum, B. cereus, and *Pseudomonas pseudoalcaligenes*	Potato	*Globodera rostochiensis*	J2 mortality increased by 67-97%; Reduces the amount of cysts by 51-65% and J2s by 48-76%	Istifadah *et al.*, 2018

Studies on endophytic bacteria invading plant roots and inhibiting nematode development are few. For this study, we show several instances of endophytes as biocontrol agents of phytopathogenic nematode in a range of crops and forests, despite the fact that regulatory rules may classify endophytes as bio-stimulants or soil supplements and others as biopesticides (Table 5).

Endophytes are a poorly explored group of microorganisms especially bacterial endophyte which are capable of producing bioactive compounds that can be utilized to combat numerous plant pathogens. Endophytic bacteria have been sources of bioactive and volatile compounds and have proven to be useful for different group of plant pathogens. In both the pre-harvest and post-harvest stages, endophytic bacterial and actinomycete strains have been widely used as BCAs against a variety of plant diseases. Therefore, the potential colonization efficacy of endophytes is a crucial characteristic for disease management. In conclusion this review explained how plants harbor diverse endophytic bacterial strains, colonizing their parts and some of them emitting volatile organic compounds (VOCs) with antifungal and/or plant growth promotion activity. Using these natural symbionts provides a chance to increase crop production while minimizing the use of hazardous pesticides against plant diseases. Finally, given the lack of research on endophytic diversity, there is a high likelihood of discovering novel and unique bacterial strains from unexplored wild/cultivated plants.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest

AUTHOR CONTRIBUTIONS

Conceptualization and writing of manuscript: Seweta Srivastava and Aspak; table making: Kanuri Komala Siva Katyayani and Dipshikha Kaushik; reviewing and editing: Seweta Srivastava and Meenakshi Rana; Figure drawing and Grammer editing: Shubham Kumar and Raghavendra Reddy Manda; Reference setting: Manash Shukla and Vinit Pratap Singh. All authors have read and agreed to the published version of the manuscript.

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