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Green guardians: Bacterial endophytes in protecting vegetable crops against pathogens

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Abstract: Vegetables are considered as the major source for opportunistic and emerging pathogens due to their diverse microbiome. Utilising bacterial endophytes and other bacterial agents to control a variety of economically important plant diseases is vital for achieving sustainable agriculture. Within internal plant tissues, bacterial endophytes form colonies without apparent injury. These bacteria provide several advantages for plant systems, including the direct stimulation of plant development through the creation of metabolites or phytohormones. Importantly, bacterial endophytes play a dual role by safeguarding their plant host through the biocontrol of pathogens and induction of the plant's innate immune system. This review offers a methodical and inclusive examination of the current state of endophytic diversity of bacteria, their methods of plant colonisation and their potential functions as protective agents against plant diseases. The review concludes by proposing diverse effective strategies for applying endophytic bacteria as a biological agent aiming to safeguard vegetable crop plants and enhancing the resilience of agricultural products.

Keywords: biological control agents; antagonist; formulations; plant diseases; vegetables

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Vegetables play a vital role in human health, serving as a significant source of essential nutrients such as vitamins, minerals, phytochemicals and dietary fibre. India has become the world's second-largest producer of vegetables, trailing only behind China, with a contribution of 12.3% to the global vegetable production. India holds the top position in the production of okra, chilis, peppers, onions, and beans, while it ranks second in tomato, potato, pea, cabbage, and cauliflower production (FAOSTAT 2022), losses of vegetables are estimated to range from 40–60%, depending on the type of vegetable, the stage of handling, and the mode of transport. Bacterial endophytes are bacteria that reduce the harmful effects of pathogens. The microbes are classified as plant growth-promoting bacteria (PGPB), a group that encompasses bacteria exerting beneficial effects on plants (Lugtenberg & Kamilova 2009). For example, they aid in the uptake of nutrients by plants, such as performing biological nitrogen fixation and facilitating the release of nutrients like phosphorus and iron. This is performed by synthesising organic acids and siderophores (Glick 2012). Pathogens that are present before harvesting can persist and have an impact on a product's quality after harvesting. For example, *Botrytis cinerea*, which causes grey mould disease, can infect over 200 varieties of plants and their by-products. Other significant microbes include *Colletotrichum* spp., responsible for anthracnose or blossom end rot diseases in most of vegetable crops (Sharma et al. 2009).

Numerous bacterial species are associated with different fruits and vegetables, as documented in various studies. Adesemoye et al. (2008b) found *Bacillus subtilis* and *Pseudomonas aeruginosa* on tomatoes and African spinach. Rekha et al. (2007) reported the presence of *Pseudomonas putida* on lettuce, while Phi et al. (2010) detected *B. subtilis* and *Paenibacillus polymyxa* on pepper. The presence of various bacterial species has been identified in association with specific crops, as reported in several studies. Madhaiyan et al. (2007) documented the presence of *Methylobacterium oryzae* and *Burkholderia* spp. on tomatoes, and Indian mustard was found to harbour *Kluyvera ascorbata* SUD165 (Burd et al. 2000). These findings highlighted the diverse microbial communities associated with different crops, underscoring the importance of understanding the interactions between bacteria and plants for agricultural and ecological considerations. The ongoing research in this area contributes valuable insights into the intricate dynamics of plant-microbe associations, aiding in the development of sustainable agricultural practices.

ENDOPHYTES

Endophytes are microorganisms associated with plants, residing within plant tissues without causing any damage or symptoms to their hosts (Hirsch & Braun 1992). The exploration of endophytes dates back to the mid-1800s when Anton de Bary coined the term "endophytes" to describe fungi dwelling inside host plant tissues (de Bary 1866). Derived from the Greek roots "endon", meaning within, and "phyton", meaning plant, "endophyte" literally translates to "within the plant". These endophytes can be categorised as facultative or obligatory. While facultative endophytes can thrive in various environments such as soil, artificial nutrient media, plant surfaces, and inside plants, obligatory endophytes cannot be cultured and require specific growth conditions (Christina et al. 2013). Facultative endophytes, in contrast to obligate ones, are readily isolable, making them widespread across plant species and potentially valuable for the development of natural commercial products (Conn & Franco 2004; Christina et al. 2013).

A summary of bacterial diversity in plants, obtained through both culture-dependent and microbiome sequencing techniques, shows a predominance of bacteria from the phylum Proteobacteria within the plant endosphere (Marques et al. 2015). Within the Proteobacteria phylum, γ-proteobacteria are often found to be more abundant in comparison to α- and β-proteobacteria (Hardoim et al. 2015). Additionally, Firmicutes, Actinobacteria, and Bacteroidetes are other prominent bacterial groups commonly identified in the plant endosphere (Tian et al. 2015; Furtado et al. 2019). This distribution of bacterial taxa highlights the dynamic and diverse nature of the microbial communities inhabiting plant tissues. In addition to the previously mentioned bacterial phyla, Acidobacteria, Planctomycetes, and Verrucomicrobia are less frequently observed in the plant endosphere. Culturable bacterial diversity within the plant endosphere often includes common genera such as *Pseudomonas, Bacillus, Micrococcus, Serratia, Burkholderia, Enterobacter, Rhizobium, Mycobacterium, Streptomyces* and among others mentioned in Table 1 (Afzal et al. 2019; Liu et al. 2020; Purushotham et al. 2020).

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Table 1. List of endophytes reported in various vegetable crops

Crop	Endophytic bacteria identified & mode of action	References
Tomato	*Bacillus subtilis; Pseudomonas aeruginosa;* (plant growth promotion)	Adesemoye et al. (2008a)
Tomato	*Methylobacterium oryzae* CBMB20; *Burkholderia* sp. CBMB40 (reduces the toxicity of Ni and Cd)	Madhaiyan et al. (2007)
Tomato	*Kluyvera ascorbata* SUD165 (decrease in nickel, lead, or zinc)	Burd et al. (2000)
Tomato, carrot, and lettuce	*Klebsiella pneumonia* (pathogenic bacteria)	Falomir et al. (2010)
Tomato and lettuce	*Pantoea agglomerans* (pathogenic bacteria)	Falomir et al. (2010)
Tomato	*Serratia rubidaea* (pathogenic bacteria)	Falomir et al. (2010)
Carrot	*Serratia marcescens* (pathogenic bacteria)	Falomir et al. (2010)
Tomato, carrot, and lettuce	*Klebsiella oxytoca* (pathogenic bacteria)	Falomir et al. (2010)
Cucumber	*Pseudomonas fuorescens* (plant growth promoting bacteria)	Nithya & Babu (2017)
Tomato	*Bacillus tequilensis* (plant growth promoting bacteria; nitrogen fixing)	Nithya & Babu (2017)
Onion, tomato and carrot	*Bacillus pumilus* (plant growth promoting bacteria; opportunistic pathogen)	Nithya & Babu (2017)
Carrot	*Paenibacillus polymyxa* (plant growth promoting bacteria)	Nithya & Babu (2017)
Carrot	*Paenibacillus illinoisensis* (plant growth promoting rhizobacteria (PGPR) and inhibit the activity of pathogens)	Nithya & Babu (2017)
Carrot	*Bacillus aerophilus* (bioremediation of imidacloprid, a synthetic insecticide)	Nithya & Babu (2017)
Carrot	*Microbacterium oleivorans* (biocontrol agents, reducing mycotoxin levels in peanuts, grapes, and cereals)	Nithya & Babu (2017)
Carrot	*Arthrobacter nicotianae* (biodegradation of agro-chemicals)	Nithya & Babu (2017)
Cucumber	*Stenotrophomonas rhizophila* (provides protects against biotic and abiotic stress)	Nithya & Babu (2017)
Cucumber	*Microbacterium schleiferi* [bioremediation of 1, 3, 5 – TMB (trimethylebenzene)]	Nithya & Babu (2017)
Cucumber	*Bacillus megaterium* (plant beneficial bacteria aid in nitrogen fixation and stimulate plant growth)	Nithya & Babu (2017)
Onion and tomato	*Bacillus aryabhattai* (plant growth promoting bacteria)	Nithya & Babu (2017)
Tomato	*Periconia macrospinosa* (improved mobilization and absorption of organic nutrients, leading to increased plant growth)	Yakti et al. (2018)
Cucurbits	*Bacillus* sp. (safeguard cucurbit plants from various soil borne pathogens and powdery mildew disease caused by *Podosphaera fuliginea*)	Khalaf & Raizada (2018)
Potato	*Clavibacter michiganensis* (biocontrol activities against *Erwinia carotovora)*	Reiter et al. (2002)
Potato	*Clavibacter michiganensis* (produced siderophores and indole-3-acetic acid (IAA), and exhibited antagonistic activity against *Rhizoctonia solani*, *Sclerotinia sclerotiorum*, and *Streptomyces scabies*)	Sessitsch et al. (2004)
Tomato, cucumber, carrot	*Enterobacter cloacae*	Falomir et al. (2010)
Carrot	*Pseudomonas fluorescens* (plant growth promoter)	Surette et al. (2003)
Eggplant	*Bacillus subtilis* Jaas ed1 (antifungal activity against *Verticillium dahlia*)	Lin et al. (2009)
Egg Plant	*Bacillius subtilis* (Antifungal activity against *Verticillium dahlia)*	Lin et al. (2010)
Egg Plant	*Pseudomonas mallei* (RBG4, ET17) and *Bacillus* spp. (RCh6) antimicrobial againts of *Ralstonia solanacearum*	Ramesh & Phadke (2012)
Tomato	*Streptomyces virginiae* Y30 and E36 (*R. solanacerum*)	Tan et al. (2011)
Tomato	*Bacillus* sp. *G1S3 and G4L1* (antimicrobial againts tomato bacterial wilt)	Fu et al. (2020)

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Table 1. to be continued...

Crop	Endophytic bacteria identified & mode of action	References
Tomato	*Bacillus* spp., *Proteus* spp., *Providencia rettegeri, Cupriavidus pauculus* and *Achromobacter piechaudi* (antagonistic activity against *R. solanacearum*)	Amaresan et al. (2012)
Tomato	*Bacillus pumilus* and *Bacillus amyloliquefaciens* (induce resistance against bacterial speck)	Lanna-Filho et al. (2017)
Radish	*Bacillus subtilis* YRR10 (inhibitory action against plant pathogenic fungi)	Seo et al. (2010)
Radish	*Klebsiella oxytoca (*promoting growth of endophytic bacteria)	Chen et al. (2017)
Chilli	*Pseudomonas fluroscens* EBS 20 *(*control damping off in nursery, Produce most salicylic acid, siderophore and hydrogen cyanide)	Muthukumar et al. (2010)
Radish	*Pseudomonas brassicacearum* YC5480 (control fungal pathogens, *Colletotrichum gloeosporioides, Fusarium oxysporum* and *Phytophthora capsici*)	Chung et al. (2008)
Black nightshade (*Solanum nigrum*)	*Serratia nematodiphila* LRE07, *Enterobacter aerogenes* LRE17, *Enterobacter* sp. LSE04 *and Acinetobacter* sp. LSE06 (1-aminocyclopropane-1-carboxylate deaminase ACC deaminase, indole acetic acid, siderophore and phosphate solubilizing activity)	Chen et al. (2010)
Tomato	*Bacillus subtilis* HYT- 12-1 (production of Indole acetic acid (IAA); phosphate solubilization; siderophores production; nitrogen fixation and ACC deaminase activity)	Xu et al. (2014)
Chilli	*Bacillus velezensis (*control *C. gloeosporioides)*	Nurbailis et al. (2023)
Cucurbits	*Paenibacillus polymyxa* hg18 (biocontrol agent for controlling *Fusarium* wilt in cucumber)	Cai et al. (2023)
Onion	*Bacillus velezensis* GFB08 (control foliar disease *Stemphylium* and *Colletotrichum*)	Wang et al. (2023)
Tomato	*Paecilomyces formosus* EDS 20 (growth-inhibiting activity against *Rhizoctonia solani*)	Arasu & Al-Dhabi (2023)
Onion	*Stenotrophomonas maltophila* (control purple blotch)	Saini et al. (2024)
Onion	*Bacillus thuringiensis* 23-045, 23-046, 23-052, and 23-055 and *B. toyonensis* 23-056 (biological control of *Fusarium* basal rot in onion)	Shin et al. (2023)
Onion	*Burkholderia gladioli, Pseudomonas alliivorans, Pantoea agglomerans, Pantoea ananatis* and *Pantoea allii* (pathogenic to onion crop)	Khanal et al. (2023)

ENTRY AND COLONISATION OF ENDOPHYTES IN PLANT TISSUE

Bacterial endophytes grow in the rhizosphere and rhizoplane before entering the plant root. Endophytic strains exhibit unique colonisation patterns and regions (Singh et al. 2024). Endophytic bacteria like to infiltrate the plant tissue through numerous places, with the root zone and aerial components, such as the stems, leaves, flowers, and cotyledons, being the most common (Zinniel et al. 2002). Penetration into the host can occur through both passive and active processes. Passive penetration involves entering through cracks in root tips caused by harmful organisms (Hardoim et al. 2008) while active penetration, on the other hand, involves attaching and proliferating via extracellular polymeric substances (EPSs), lipopolysaccharides (LPSs), structural components, quorum sensing, and the movement and multiplication of endophytes within plant tissues (Duijff et al. 1997; Dörr et al. 1998; Böhm et al. 2007). Plant-microbe interactions must be compatible in order for endophyte colonisation to be successful. Upon invasion, the plant detects the endophyte and releases signalling chemicals (Rosenblueth & Martínez-Romero 2006; Compant et al. 2010; Brader et al. 2014).

The colonisation of endophytic bacteria within the host plant is a multifaceted process that encompasses several steps. When microbial communities and root exudates interact, colonisation takes place (de Weert et al. 2002; Rosenblueth & Martínez-Romero 2006). Plant roots release substantial quantities of exudates that impact the diverse microbial communities pres-

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ent in the rhizosphere (Singh et al. 2017; Singh et al. 2018). Root exudates, which are abundant in organic substrates, such as lipids, phenols, amino acids, carbohydrates, phytosiderophores, and flavonoids, enhance the contact between the microorganisms and the roots by acting as chemo attractants, which eventually helps to attract rhizosphere-dwelling bacterial endophytes and start their colonisation of host plant tissues (Yuan et al. 2018). There are numerous examples available that demonstrate the direct participation of root exudates in the first stages of microbial colonisation of host tissues; Oku et al. (2012) examined the function of amino acids found in tomato plant root exudates and observed how they functioned as chemoattractants during *Pseudomonas fluorescens* Pf0-1 colonisation. As shown in Figure 1, endophytic bacteria have the capability to migrate from the rhizoplane to the cortex or root system through either active or passive means. Gregory (2006) found that the root zone's endodermis restricts the colonisation of endophytic bacteria, resulting in only a few species acquiring entrance. James et al. (2002) found that certain endophytic bacteria enter the endodermis by secreting cell wall dissolving enzymes, whereas others enter passively after root phase disruption to generate secondary roots. The research indicates that endophytic bacteria employ various mechanisms to colonise plant internal tissues. Certain bacteria, such as *Herbaspirillum seropedicae* Z67, can enter rice roots xylem vessels by penetrating the pericycle past the endodermis (James et al. 2002). The analogous processes of penetration have been noted for the *Burkholderia phytofirmans* strain PsJN in grapes (Compant et al. 2005; Compant et al. 2008). However, this mode of entry is limited to a subset of endophytic species (James et al. 2002; Compant et al. 2005). Despite overcoming barriers, the induction of plant defence mechanisms by endophytic bacteria is crucial for the successful colonisation of internal tissues, often resulting in strengthened cell walls and the development of protective materials around xylem vessels (Rosenblueth & Martínez-Romero 2006).

MECHANISM OF DISEASE SUPPRESSION BY ENDOPHYTIC BACTERIA

Plant pathogen growth can be inhibited by bacterial endophytes that promote plant growth. This is

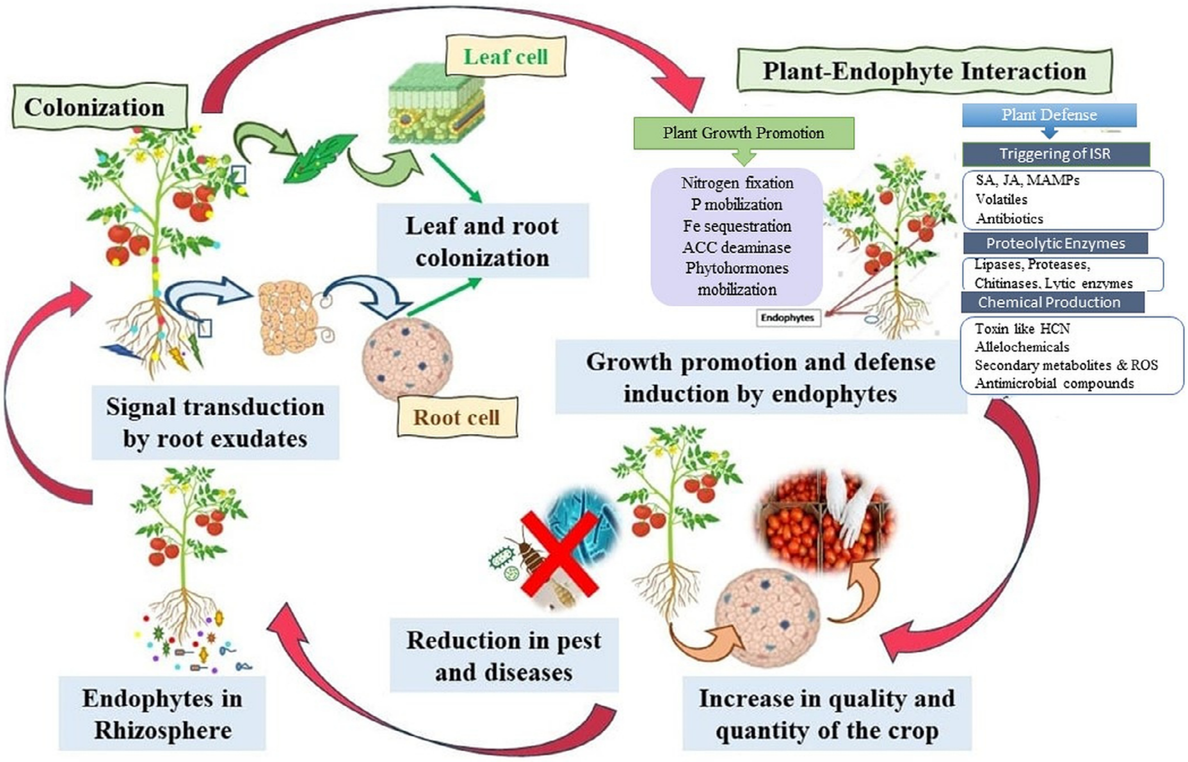

Figure 1. Endophytes and their interactions with host plants are detailed in the figure, highlighting the root exudates, communication, mobility, attachment, penetration, and target region (entry site) during colonization
(Image is created using Biorender.com)

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because they create a variety of enzymes and antibiotic compounds that act against phytopathogens and trigger the activation of the plant's innate defence mechanism as shown in Figure 2 commonly referred to as induced systemic resistance (ISR) (Pérez-Montaño et al. 2014). Endophytic bacteria can share the biocontrol techniques with other bacteria living in the rhizosphere, phyllosphere, or main soil. This makes it possible for scientists to investigate the special processes that the endophytic agents possessed with the following strategies.

Plant growth promotion (PGP). Endophytes hasten plant growth through various means. These primarily include phytostimulation, such as hormone production, followed by biofertilisation, including nitrogen fixation, phosphorus solubilisation, and siderophore formation to scavenge Fe^{3+} ions when Fe^{3+} is limited (Olanrewaju et al. 2017). Inducing stress tolerance is the third mechanism, and it can be achieved by controlling the release of stress hormones such as 1-aminocyclopropane-1-carboxylate deaminase. Lastly, endophytes contribute to rhizoremediation by protecting plants against environmental pollutants. Lugtenberg et al. (2013) conducted a comprehensive study documenting that various enzymes produced by bacteria are involved in the production of important plant hormones. These enzymes include those responsible for synthesising ethylene, cytokinins, gibberellins, and auxins. Among these hormones, auxins play a particularly crucial role in the development of lateral roots in plants. The study highlighted that the majority of bacteria found in the rhizosphere, which is the soil region close to the plant roots, have the capability to produce auxins. The production of auxins by rhizosphere bacteria is significant for the growth and health of plants, as it promotes the formation of lateral roots, enhancing the plant's ability to absorb water and nutrients from the soil. Kamilova et al. (2006) reported that enhanced radish growth has been observed through tryptophan-induced secretion of indole-3-acetic acid (IAA) by *Pseudomonas fluorescens* WCS365, making it a repeatedly recommended option for biological disease control. Additionally, Spaepen et al. (2014) observed that *Azospirillum brasilense SP245* enhanced the IAA production, which, in turn, enhanced the growth of the lateral roots and root hairs, ultimately resulting in the increased production of root exudates in *Arabidopsis thaliana*. Pliego et al. (2011) documented that numerous rhizosphere bacteria produce gibberellins, which are involved in cell division, cell elongation, and seed germination.

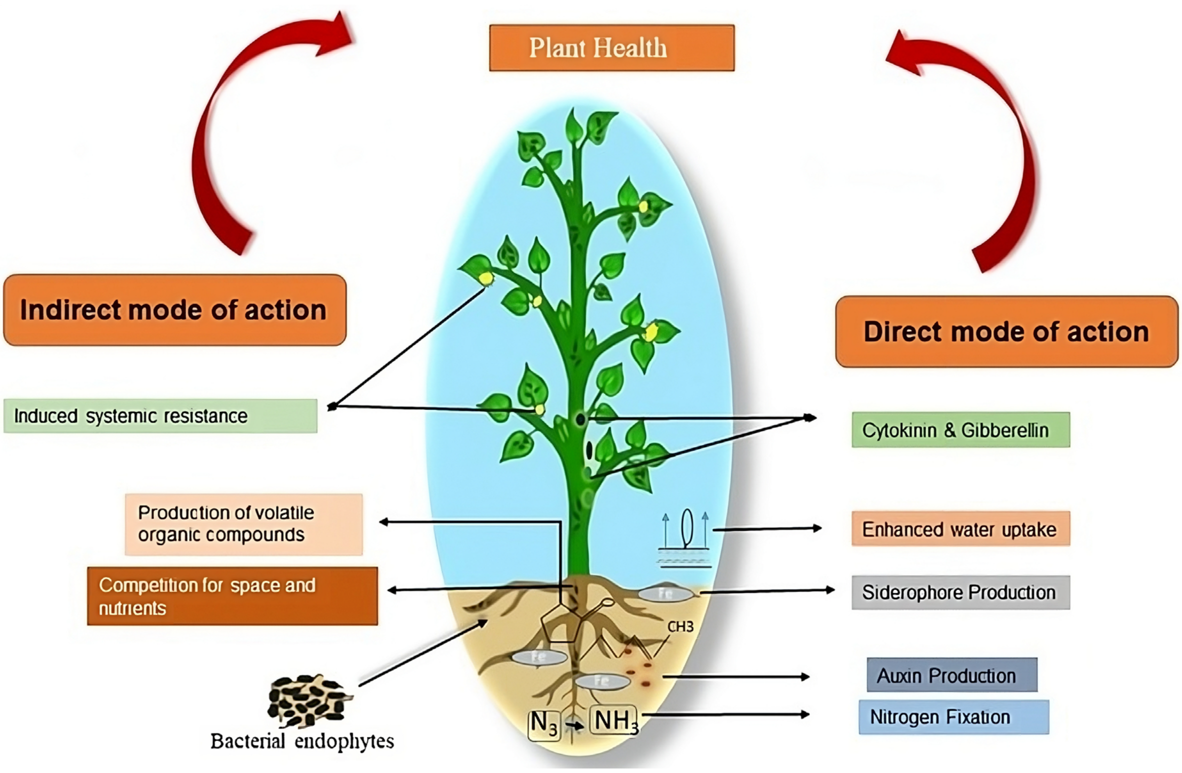

Figure 2. Different mechanisms of disease suppression by endophytes

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Acinetobacter calcoaceticus, a *Bacillus* species, and other rhizosphere-dwelling bacterial species secreted growth-promoting substances like cytokinin, gibberellins, acetoin, and 2,3-butanediol in a variety of crops, including cucumbers and Chinese cabbage, according to studies undertaken by researchers to evaluate the growth-promoting capabilities of root-dwelling bacteria (García et al. 2001; Kang et al. 2010; Kang et al. 2019).

Competition. The use of biocontrol agents creates competition between endophytic microbes and the existing soil plant pathogenic microorganisms. The success of endophytic bacteria depends on how well they colonise the roots over time, their capacity to withstand competition and how well they proliferate across the root tissues (Whipps 2001). Certain characteristics help these bacteria colonise roots effectively, such as different growth stages, the ability to attach to roots, movement capability, and using organic acids in the root exudates. Additionally, they generate a variety of components, including nucleotides, lipopolysaccharides, a type III secretion system (TTSS), and amino acids (Lugtenberg & Kamilova 2009). Plant growth-promoting bacteria (PGPB) residing in the rhizosphere have been recognised as crucial guardians against numerous diseases. Researchers found that the root's epidermis contains many nutrients that attract a wide range of microorganisms, including disease-causing ones. The competition for these nutrients between beneficial and harmful microorganisms often prevents disease-causing microorganisms from harming plants. Some reports suggest that flagella help PGPB migrate towards nutrient-rich root surfaces, where they efficiently use nutrients, primarily root exudates, to thrive (Turnbull et al. 2001).

Antibiosis. Antibiosis occurs when beneficial microbes emit secondary metabolites, such as antibiotics and volatile chemicals, to inhibit disease-causing germs (Fravel 1988). According to Haas & Défago (2005), antibiotics, such as volatile HCN, phenazines, and pyoluteorin, cause antibiosis. Dandurishvili et al. (2011) discovered novel antibiotics, including D-gluconic acid, 2-hexyl-5-propyl resorcinol, and volatile compounds like 2,3-butanediol, 6-pentyl-α-pyrone, and dimethyl disulfide (DMDS). They help accelerate antibiosis and are produced by endophytic microbes in tomato plants. Liu et al. (2019) reported that diseases caused by the fungus *Sclerotinia sclerotiorum* harm many important crops globally, and traditional fungicides are not very effective because the fungus can persist in the soil and spread through the air. Researchers have focused on biological control methods, and they have found that the microorganism *Streptomyces* sp. NEAU-S7GS2, isolated from soybean roots and soil, can significantly inhibit the fungus' growth and germination. In experiments, this microorganism reduced the disease incidence and severity in soybeans and promoted their growth. Detailed studies showed that NEAU-S7GS2 disrupts the fungus' structure and produces substances that help plants grow by breaking down soil nutrients. A genomic analysis revealed the genes responsible for these beneficial effects, making NEAU-S7GS2 a promising biocontrol agent and biofertiliser for agriculture. *Pseudomonas* and *Bacillus* are the two main bacterial genera whose ability to produce antibiotics has been extensively investigated. Some of these antibiotics include aerugina, rhamnolipids, ecomycins, cepacyamide A, pseudomonic acid, azomycin, and cepafungins. Additionally, antibiotics such as 2,4-diacetylfloroglucinol acid, phenazine-1-carboxylic acid, phenazine-1-carboxamide, pyroluteorine, pyrrolnitrine, oomycin A, viscosinamide, butyroaminectone, kyanoaminectone, zymicrolactone, and zymicrolactone have also been extensively researched (Santoyo et al. 2019). Pyoluteorin and pyrrolnitrin have been demonstrated to effectively suppress water stress diseases caused by damping off and root rot (Gu et al. 2022).

Induced systemic resistance (ISR). Plants have an ISR system that is activated by elicitors, or chemical signals, generated by helpful microbes (Pérez-Montaño et al. 2014). Ethylene and jasmonate are necessary for ISR signalling (Kannojia et al. 2019). The primary mechanisms through which these agents regulate the ISR in plants have been identified, even if the molecular details governing the interactions between beneficial microbes and plants are not yet fully understood. Among these are the roles played by phytohormones, pathogen- and microbe-associated molecular patterns (PAMPs and MAMPs), and a variety of elicitors, including siderophores, phytases, volatile organic chemicals, and miRNAs (Abdul Malik et al. 2020). ISR has been shown in tobacco plants, where resistance to *Phytophthora nicotianae* and *Rhizoctonia solani* in solanaceous crops was conferred by activating PR2 (encoding a β-1,3-glucanase) and PR3 (encoding a chitinase) in exposure to the volatile chemicals

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produced by *Bacillus* spp. (Kim et al. 2022). In addition to the Pathogenesis related genes, *Bacillus* spp. causes various defence mechanisms in plants, such as lignin build-up that alters the structure of the cell wall (Singh & Kalra 2016), and the generation of phytoalexins, auxins, flavonoids, and/or glucosinolates, among other secondary metabolites (Pretali et al. 2016). Consequently, ISR has been shown to be able to greatly lower the pathogenicity of a variety of plant pathogens, including fungus, bacteria, and viruses. This has been demonstrated that studies conducted on a wide range of crops, including beans, carnations, cucumbers, radishes, tobacco, and tomatoes (Kannojia et al. 2019).

It has been shown that using different bacterial strains, vegetable crops can develop induced systemic resistance to diseases. The *Pseudomonas fluorescens* strain 89B61 increased resistance to *Phytophthora infestans* in tomato plants (Yan et al. 2002), while *P. fluorescens* WCS 417 has been effective against *Alternaria* sp. and *Fusarium* sp. in tomato plants (Hoffland et al. 1996). Additionally, *P. fluorescens* Pf1 increased resistance to *Pythium aphanidermatum* in tomato and pepper plants (Ramamoorthy et al. 2002), and *P. fluorescens* 63-28 has shown efficacy against *Fusarium oxysporum f. sp. radicis-lycopersici* (M'Piga et al. 1997). *P. fluorescens* WCS 374 increased resistance to *Fusarium oxysporum* f. sp. *raphani* in a radish crop (Leeman et al. 1996). *Pseudomonas putida* 89B-27 showed resistance to *Fusarium oxysporum* f. sp. *cucumerinum* in cucumber plants, while *Serratia marcescens* has also demonstrated efficacy against the same pathogen (Liu et al. 1995). These findings illustrate the potential of certain bacterial strains in inducing systemic resistance against various diseases in vegetable crops.

Siderophore production. Siderophores are low molecular weight, iron-chelating molecules involved in antibiosis and nutrient competition that are produced by certain bacteria and plants (Gupta et al. 2015; Shanmugaiah et al. 2015). The PGPR has identified the synthesis of siderophores, such pseudobactin and pyoverdine, as a unique strategy for controlling hazardous phytopathogens that affect a variety of crops, including vegetables. When iron levels are low, they mostly aid the generating organism in acquiring iron. *Fusarium* wilt of peppers has been found to be controlled by the siderophore generated by *B. subtilis* CAS15 (Yu et al. 2011), whereas the siderophores produced by *Bacillus amyloliquefaciens* (DSBA-11 and DSBA-12) regulate the tomato bacterial wilt caused by *Ralstonia solanacearum* (Singh et al. 2015).

Lysis. Another important mechanism in the biological regulation of fungal infections is the parasitism of pathogenic fungi, which is made possible by the synthesis of hydrolytic enzymes. High concentrations of lytic enzymes, which have antifungal properties, are excreted by certain PGPR strains. For example, *B. subtilis* strain EPCO 16's chitinase and β-1,3-glucanase significantly reduced the growth of tomato-based *F. oxysporum* f. sp. *lycopersici* (Ramyabharathi et al. 2012). According to Dubey et al. (2014), *B. subtilis* BSK17 is known to produce β-1,3-glucanase and chitinase to support their competitive and antagonistic action against *Cicer arietinum*. According to Kumar et al. (2012), chitinase and β-1,3-glucanase are two important lytic enzyme classes that degrade the primary component of fungal cell walls, such as chitin and laminarin. Chitin is a long-chain polymer of N-acetylglucosamine, which forms a crucial part of the cell walls of most phytopathogenic fungi. The purified chitinases of *Streptomyces* sp. (Gomes et al. 2001), *Serratia plymuthica* (Frankowski et al. 2001) were highly antifungal. Numerous PGPR strains that exhibit significant antifungal activity, in addition, secrete important classes of hydrolytic enzymes like urease and amylase (Shrivastava et al. 2015), catalase (Patel & Pratibha 2014), *etc.* In order to slow down the growth of the infections, some antagonistic PGPR also release lipases and proteases (Pereg & McMillan 2015) and glucanases (Figueroa-López et al. 2016).

ROLE OF BACTERIAL ENDOPHYTES IN PLANT DISEASE MANAGEMENT IN VEGETABLE CROPS

Bacteria known as bacterial endophytes invade the internal tissues of plants without showing any outward signs of illness or symptoms (Ryan et al. 2008). They can originate from the rhizosphere, the phyllosphere, or the seed, and they can interact with the plant in different ways, such as symbiosis, mutualism, commensalism, or antagonism (Vásquez Rincón & Neelam 2021). Some of the endophytes that control diseases in vegetables are listed in Table 2.

Tran et al. (2007) demonstrated the effectiveness of *Pseudomonas fluorescens* in preventing tomato late blight (*Phytophthora infestans*)

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Table 2. Management of vegetable disease by bacterial endophytes

Bacterial endophytes	Pathogen	Vegetable crop	References
Alcaligenes faecalis subsp. *faecalis* str. S8	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	tomato	Aydi Ben Abdallah et al. (2016)
Pseudomonas fluorescens P142	Bacterial wilt by *Ralstonia solanacearum* (Biovar 2, Race 3)	tomato	Elsayed et al. (2020)
Arthrobacter sp. AM08, *Pseudomonas aeruginosa* AJ14, *P. mosselii* AB06, *Bacillus* cereus AP12, *B. thuringiensis* AK08 and *Serratia marcescens* AS09	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	tomato	Sriwati et al. (2023)
Paenibacillus polymyxa & *Bacillus zanthoxyli*	*Fusarium* wilt (*Fusarium oxysporum* f. sp.*cucumerinum*)	cucumber	Tan et al. (2024)
Bacillus subtilis 104 *Bacillus subtilis* 26D	Late blight by *Phytophthora infestans, Fusarium* wilt (*Fusarium oxysporum* f. sp. *eumartii*) and dry rot by *Fusarium*	potato	Lastochkina et al. (2020)
Bacillus amyloliquefaciens	Bacterial wilt (*Clavibacter michiganensis*)	tomato	Gautam et al. (2019)
Bacillus amyloliquefaciens	*Fusarium* wilt *(Fusarium oxysporum* f. sp. *lycopersici)*	tomato	Guleria et al. (2016)
Bacillus subtilis	Black Scruf (*Rhizoctonia solani)*	potato	Saber et al. (2015)
Bacillus subtilis	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *cucumerinum)*	cucumber	Jayapala et al. (2019)
Bacillus sp.	Anthracnose *(Colletotrichum capsica)*	chilli	Jayapala et al. (2019)
Staphylococcus epidermidis BC4 isolate and *Bacillus amyloliquefaciens* BL10	Bacterial wilt (*Ralstonia solanacearum)*	solanaceous crop	Nawangsih et al. (2011b)
Bacillus subtilis KA9 and *Pseudomonas fluorescens* PDS1	Bacterial wilt (*Ralstonia solanacearum*)	chilli	Kashyap et al. (2021)
Serratia strain B17B*, Enterobacter* strain E*, Bacillus* strains IMC8, Y, Ps, Psl and Prt	Phytophthora blight (*Phytophthora capsici*)	bell pepper	Irabor & Mmbaga (2017)
Pseudomonas brassicacearum, Paenibacillus peoriae Pa86, *Bacillus licheniformis* Bl17	Wilt disease (*Ralstonia solanacearum*)	potato	Bahmani et al. (2021)
Lysinibacillus sp.	Bacterial wilt disease (*Ralstonia solanacearum*)	chilli	Istifadaha et al. (2017)
Bacillus subtilis	Bacterial wilt disease (*Ralstonia solanacearum*)	chilli	Istifadaha et al. (2017)
Azotobacter chrococcum	Bacterial wilt disease (*Ralstonia solanacearum*)	chilli	Istifadaha et al. (2017)
Pseudomonas cepacea	Bacterial wilt disease (*Ralstonia solanacearum*)	chilli	Istifadaha et al. (2017)
Bacillus pseudomycoides NBRC 101232	Bacterial wilt disease (*Ralstonia solanacearum*)	chilli	Yanti et al. (2018)
Bacillus thuringiensis ATCC 10792	Bacterial wilt (*Ralstonia solanacearum*)	chilli	Yanti et al. (2018)
Bacillus mycoides strain 273	*Fusarium* wilt (*Fusarium oxysporum* f.sp. *capsici*)	chilli	Yanti et al. (2018)
Bacillus sp.	Anthracnose (*Colletotrichum capsici*)	chilli	Yanti et al. (2020)
Bacillus cereus	Anthracnose (*Colletotrichum capsici*)	chilli	Nurbailis et al. (2023)
Ochrobactrum pseudintermedium (CB361-80)	Angular leaf spot (*Pseudomonas syringae* pv. *lachrymans*)	cucumber	Akbaba & Ozaktan (2018)

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Table 2. to be continued...

Bacterial endophytes	Pathogen	Vegetable crop	References
Pantoea agglomerans (CC372-83)	Angular leaf spot (*Pseudomonas syringae* pv. *lachrymans*)	cucumber	Akbaba & Ozaktan (2018)
Alcaligenes faecalis sub sp. *faecalis* str. S8	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	tomato	Aydi Ben Abdallah et al. (2016)
Bacillus amyloliquefaciens FBZ24	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*)	tomato	Elanchezhiyan et al. (2018)
Pseudomonas fluorescens 63-28	Bacterial wilt (*Ralstonia solanacearum*)	tomato	Vanitha & Umesha (2011)
Staphylococcus epidermidis BL4, *Bacillus amyloliquefaciens* BL10	Bacterial wilt (*Ralstonia solanacearum*)	tomato	Nawangsih et al. (2011b)
Pseudomonas fluorescens, *Enterobacter cloacae*	Dry rot of potato (*Macrophomina phaseolina*)	potato	Al-Mughrabi (2010)
Enterobacter cloacae SM10	*Fusarium* wilt (*Fusarium oxysporum* f. sp. *spinaciae*)	spinach	Tsuda et al. (2001)

infection, along with a significant reduction in the spread of late blight lesions. Additionally, Zakharchenko et al. (2011) reported that plants colonised with a strain of *Pseudomonas aureofaciens* showed enhanced resistance to phytopathogens, such as *Phytophthora infestans*. Gravel et al. (2005) observed that bacterial bioagents, such as *Pseudomonas fluorescens, P. putida, P. marginalis, P. corrugata,* and *P. viridiflava,* effectively decreased the occurrence of damping-off, caused by *Pythium aphanidermatum* and *Pythium ultimum*. Ajay & Sunaina (2005) discovered that the antagonist *Bacillus subtilis* B5 effectively inhibited the growth of *Phytophthora infestans*. Luo et al. (2010) proved that, in both greenhouse and field settings, the *B. subtilis* strain significantly reduced the frequency and severity of wilt in brinjal (*Ralstonia solanacearum*). Ferrigo et al. (2017) identified the endophyte *B. subtilis* SR63 as one of the most effective strains against *Agrobacterium* sp. This strain has been identified as a valuable biocontrol agent for managing crown gall disease (*Agrobacterium tumifaciens*). Safdarpour & Khodakaramian (2017) showed that endophytic bacterial isolates from tomato explants had an antagonistic action against *Ralstonia solanacearum* that cause tomato bacterial wilt disease. *Pseudomonas mossellii* FS67, *P. fluorescens* FS167, and *P. brassicacearum* FS184 were the names given to these isolates. Specifically, in greenhouse conditions, the incidence of bacterial wilt disease was significantly reduced by the *P. mossellii* and *P. fluorescens* strains. Nawangsih et al. (2011a) found that the endophytic bacterial strains *Staphylococcus epidermidis* BC4 and *Bacillus amyloliquefaciens* BL10 isolated from healthy tomatoes significantly decreased the occurrence of bacterial wilt disease (*Ralstonia solanacearum)* in tomatoes as compared to the control group. Istifadaha et al. (2017) demonstrated that endophytic microbial strains such as *Lysinibacillus* sp. and *Bacillus subtilis*, along with nitrogen-fixing bacteria (*Azotobacter chrococcum*) and phosphate-solubilising bacteria (PSB) (*Pseudomonas cepacia*), individually and in combination as bio-fertilisers, effectively inhibited the bacterial wilt disease (*Ralstonia solanacearum*) incidence in chili plants by up to 80%. Akköprü et al. (2018) showed that the effects of *Xanthomonas euvesicatoria*-induced bacterial spot disease on the growth of pepper and tomato plants were mitigated by four endophytic bacterial strains*: Ochrobactrum* sp. CB36/1, *Pantoea agglomerans* CC37/2, *Bacillus thuringiensis* CA41/1, and *Pseudomonas fluorescens* CC44.

For the purpose of inhibiting or controlling the specific phytopathogen, the application technique becomes vitally important after a viable antagonist has been found. Microbial antagonists are generally used in two different phases when it comes to vegetables: pre-harvest and post-harvest (Singh & Singh 2009). Crops are frequently infested by pathogens in the field, and latent infections play a major role in the crops' degradation during storage and transit (Singh & Singh 2009). Vegetables experience an accelerated ageing and degradation process after harvest, when they become more vulnerable to pathogen colonisation. This can result in physical deterioration, weight loss, wrinkling, colour changes, rotting, and a reduction in the nutritional value. Therefore, endophyte application,

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both pre- and post-harvest, plays a significant role in the vegetable yield and exports.

METHODS OF ENDOPHYTE DELIVERY

The formulation of bioinoculants involves creating a consistent blend of selected beneficial strains with a suitable carrier, ensuring stability and protection of the strains during transportation and storage. The carrier serves as a medium for the dormant microbes, offering protection and a conducive environment for the microbial community. An ideal bioformulation should demonstrate effectiveness, environmental friendliness, rapid biodegradability, high retention water capacity, and appropriate shelf life (Malusá et al. 2012; Sahu et al. 2018). The biofertilisers' effectiveness and durability are improved by this formulation procedure. In rare cases, formulations may include cell protectants alongside the desired microorganisms to extend the spores' shelf life under adverse conditions (Bhattacharyya et al. 2020). Various types of formulations are developed based on their efficacy and survival rates.

Quality carriers have many desirable qualities, including being lump-free, easy to process, able to absorb moisture, easily sterilisable, affordable, widely available, and having a strong intrinsic pH buffering capacity. Solid carriers like soil (peat, coal, clay, and inorganics), organic materials (composts, soybean meal, wheat bran, and sawdust), or inert materials (vermiculite, perlite, kaolin, bentonite, and silicates) are used in dry formulations. Conversely, mineral oils, organic oils, humic acid, molasses, oil-in-water suspensions, and landfill leachates can all be used to create liquid formulations (Malusá et al. 2012; Bargaz et al. 2018).

Solid formulations. The extensive use of solid bioformulations, such as dusts, wettable powders (WPs), water-dispersible granules (WDGs), micro granules (MGs), and granules (GRs) (Ijaz et al. 2019), are available in the market. The active agent, carrier, and binder are usually present in these formulations as dry particles that are divided into coarse particles (10–100 μm) and MGs (100–600 μm) according to the particle size. Active element concentrations in GR formulations typically range from 5– 20% (Brar et al. 2006). GRs are frequently formed using substrates such as cornmeal baits, wheat GRs (Navon 2000), gelatin or acacia gum (González-Maldonado et al. 2023), and diatomaceous earth (Batta 2008), pine bark biochar (Araujo et al. 2020), tea leaf biochar (Azeem 2021), organic matrix-entrapped materials (cow dung, rice bran, neem leaf, and clay soil) (Kumar 2015), and alginate/starch blends (Rohman 2021). Prebiotic and suitable beneficial endophytes are combined to create formulations. Some important steps in the formulation process include increasing the shelf life and guaranteeing microbiological viability. A great deal of formulas use inert carriers like talc or charcoal. For instance, to treat leaf diseases, a formulation of *Pseudomonas fluorescens* was mixed with talc and 1% carboxymethyl cellulose. Another example is a formulation made of alginate that contained *Bacillus subtilis* and *Pseudomonas corrugate*, which is easy to make, dries quickly, and can be kept in storage for up to three years (Pankaj et al. 2008).

Compost serves as an excellent natural carrier for beneficial endophytes, offering nutrients in a biodegradable and environmentally friendly manner. Typically derived from plentiful natural waste materials, compost not only aids in the survival of soil microbes, but also promotes plant growth. Utilising composting has been recognised as a cost-effective method to reduce the amount of solid waste sent to landfills, as noted by Malusá et al. (2012). Chakravarty & Kalita (2011) reported that a vermicompost and farmyard manure combination enhance the shelf life period of *Pseudomonas fluorescens* against bacterial wilt in brinjal (*Ralstonia solanacearum).* Islam et al. (2004) documented elevated microbial activity in farmyard manure, attributed to the heightened rates of CO_2 evolution and increased dehydrogenase activity. This phenomenon proved to be instrumental in the mitigation of bacterial wilt (*Ralstonia solanacearum)* in tomato plants. Sundaramoorthy et al. (2012) revealed that the effectiveness of a talc-based bio-formulation against *Fusarium solani* in chili plants was evaluated. The bio-formulation contained a PGPR strain of *Pseudomonas fluorescens* (Pf1) and PGPE strains of *Bacillus subtilis* (EPCO16 and EPC5), together with additional calcium carbonate and carboxymethyl cellulose. The endophytic bacterial strains significantly decreased the occurrence of *Fusarium* wilt. Furthermore, a formulation for a seed coating was created using vermicompost as a carrier material and included *B. subtilis* OTPB1. When the formulation was tested on tomato plants among these

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crops, *Alternaria solani* and *Phytophthora infestans* lesion sizes on undamaged tomato leaves were significantly reduced. Basheer et al. (2019) stated that research was undertaken on the effectiveness of the plant probiotic endophytic *Bacillus* sp. CaB5, which was previously isolated from *Capsicum annuum*, in a formulation that was based on talc. The composition consists of carboxymethyl cellulose, calcium carbonate, and sterile talc. The findings showed that the formulation treatment improved the cowpea (*Vigna unguiculata*) and lady's finger (*Abelmoschus esculentus*) disease reduction and seed germination. Bharathi et al. (2004) reported that *Pseudomonas fluorescens* (Pf1) and *Bacillus subtilis* were found to be useful in boosting the vigour and germination of seeds. The study assessed talc-based formulations of rhizobacteria that promote plant development in greenhouse and outdoor environments. These formulations were tested against chilli fruit rot and dieback caused by *Colletotrichum capsici*. The results indicated promising potential for utilising these bacteria in combating such plant diseases. Reflinaldon et al. (2023) have found that the solid formulation containing the *B. pseudomycoides* strain SLBE1.1SN with rice straw as the carrier material, exhibited the highest efficacy in controlling whitefly in chilli. Şenol Kotan et al. (2023) used the *Pseudomonas chlororaphis* isolates MF-1, C-37 A, and *Bacillus subtilis* isolates TV-6 F, TV-17C to construct bacterial formulations on a solid carrier. They looked at how well these formulations worked as biocontrol agents against the fungus *Fusarium oxysporum* f. sp. *radicis-cucumerinum*, which causes the cucumber disease *Fusarium* root and stem rot.

Liquid formulation. Prebiotics included in beneficial endophyte formulations, such as glycerol, vermicompost wash, indole acetic acid IAA, and malic acid, contribute to this effort. Studies have demonstrated that a formulation comprising PGPMs like *Bacillus licheniformis, Bacillus sp., Pseudomonas aeruginosa*, and *Streptomyces fradiae* shows strong microbial survival even after 120 days in storage. Manikandan et al. (2010) revealed that a liquid formulation of *Pseudomonas fluorescens* strain Pf1, modified with glycerol, is a useful biocontrol agent for managing *Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*) in tomatoes. Sharma et al. (2022) optimised an oil-in-water based liquid formulation of *Bacillus siamensis* that demonstrated a significant reduction in the damping-off disease. Additionally, the seed treatment with this formulation enhanced the seed germination, resulting in a high yield. Sampath et al. (2016) developed a liquid formulation of *Bacillus subtilis* strain EPCO16 with the aim of improving both the shelf life and efficacy of the biocontrol agent. Compared to the talc-based formulation, the liquid formulation of *B. subtilis* EPCO16 exhibited greater efficacy against *Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*), ultimately resulting in an enhanced fruit yield in tomatoes.

Application strategy of endophytes. For products based on microbes, farmers are not ready to spend money on specialised machinery. Therefore, prepared inoculants ought to be applied with ease utilising common agricultural equipment and basic methods. One way to perform inoculation is by applying it to the soil or plant material. The soil application, while more time efficient for farmers, typically requires a higher quantity of inoculant. For the soil inoculation, either solid or liquid formulations can be utilised, though farmers may mix them before application, especially with liquid formulations. Additionally, the use of fertilisers containing organic matrices, insoluble phosphates, and selected P-solubilising microorganisms can enhance the nutrient availability, particularly phosphorus, benefiting the plant tolerance to soil pathogens. The application techniques differ based on the crop type. Since our focus is mostly on vegetables, which are considered annual crops, the inoculation can be applied in-furrow, as a seed dressing, or as a coating. Another method is to spread the inoculum either by itself or in conjunction with seeds over the surface of the soil. On the other hand, root dipping or seedling inoculation can be used for the initial inoculation of vegetable crops cultivated in nurseries (Chen et al. 2010). Sundaramoorthy et al. (2012) evaluated the effectiveness of the rhizobacterial strain *Pseudomonas fluorescens* (Pf1) and the endophytic bacterial strains *Bacillus subtilis* (EPCO16 and EPC5) in reducing the severity of the *Fusarium solani* that caused chili wilt disease. The disease was successfully controlled when these PGPR and PGPE strains were applied through soil application, seed treatment, or seedling root dip. Sundaramoorthy et al. (2012) revealed that the four beneficial bacterial strain *Brevibacillus brevis, and the Bacillus subtilis* strains KL-077, BS-1, and BS-2 were all successful in promoting tomato growth and combating *Ralstonia solanacearum* that

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caused wilt infection. They worked well whether applied through seed treatment + soil drench, soil drench alone, or foliar spray. Fu et al. (2020) aimed to identify an endophytic strain of *Bacillus* species capable of controlling tomato bacterial wilt (*Ralstonia solanacearum*) through a foliar spray application. The study found that the *Bacillus* sp. strains G1S3 and G4L1 notably reduced the occurrence of tomato bacterial wilt. In a glasshouse, further pot trials were carried out to evaluate the biocontrol effectiveness of the foliar spray application. Manikandan et al. (2010) reported that a liquid formulation was used as seed treatment and seedling dip to check how effective the endophytes are against *Fusarium* wilt (*Fusarium oxysporum* f. sp. *lycopersici*) of tomatoes. Mane et al. (2014) proved that applying *Pseudomonas fluorescens* by foliar spraying after seed treatment was successful. It was discovered that by using this method, early blight (*Alternaria solani*) in tomatoes could be prevented considerably while the yield was increased. Xue et al. (2009) documented that soil drenching with antagonistic strains of *Acinetobacter* sp. and *Enterobacter* sp. resulted in a reduction of bacterial wilt (*Ralstonia solanacearum*) incidence in tomato plants. Abeysinghe (2009) discovered that the brinjal plant resistance against *R. solani* was greatly increased by combining seed bacterisation with *B. subtilis* CA32.

NANOTECHNOLOGY USAGE IN ENDOPHYTES

Jain et al. (2021) demonstrated the efficacy of nano-fertilisers, revealing that controlled-release fertilisers can mitigate the adverse effects associated with the overuse of traditional chemical fertilisers, thereby enhancing the soil quality. Conventional methods of applying PGPBs as fertilisers proved inefficient, with approximately 90% of the bacteria lost during application due to external environmental factors like heat and UV radiation, consequently inflating the application costs. Nano encapsulation technologies have emerged as a promising solution to safeguard PGPBs, prolong their viability, enhance the dispersion in fertilisers, and facilitate the controlled release. For instance, the utilisation of nanocapsules composed of alginate with silicon nanoparticles and carbon nanotubes, housing strains like *Pseudomonas fluorescens* VUPF5 and *Bacillus subtilis* VRU1, markedly augmented the root length and proliferation in the commercial pistachio rootstock UCB-1 (Moradipour et al. 2019). Sodium alginate (NaAlg) nanocapsules containing *Bacillus subtilis* VRU1 effectively colonised beans with this PGPB strain and demonstrated control over pathogens such as *Rhizoctonia solani* (Moradipour et al. 2019; Saberi Riseh et al. 2021). Consequently, the creation of encapsulated bioformulations that contain PGPB are becoming a more often used tactic. Encapsulation offers improved storage conditions for PGPBs and enhances their efficacy in plant applications. Alginate, being biodegradable and environmentally friendly, is commonly utilised for encapsulating PGPBs (Saberi Riseh et al. 2021). However, further investigation is warranted to assess the impact of encapsulation on bacteria and their targeted release in organic crop production systems.

A promising approach to enhance the crop productivity involves the use of multifunctional biological formulations with prolonged effects, amalgamating the benefits of biofertilisers, fungicides, and bactericides, all based on PGPBs. Preparations centred around bacteria from genera such as *Bacillus, Azotobacter*, and *Pseudomonas* are particularly promising. Nanoparticles derived from these bacteria may also merit special attention for crop protection and productivity (Giri et al. 2023). Pour et al. (2019) revealed the development of *Pseudomonas fluorescens* (vupf5 and t17-4 strains) encased in alginate-gelatin to lower the incidence of *Fusarium solani* in potatoes.

COMMERCIALISED PRODUCTS AND THEIR TRADE NAMES

Numerous commercialised bioformulated products are widely utilised as biostimulants, biocontrol agents, and fertilisers throughout Europe, North America, and Asia as mentioned in Table 3. A variety of biofertilisers and biostimulants comprising advantageous bacteria, such as *Bacillus polymyxa*, *Bacillus subtilis*, *Bacillus megaterium*, *Azotobacter vinelandii* and *Rhizobium leguminosarum*, are available in one such product, Inómix Phosphore, from the T. Stanes & Company Ltd. (India) in Indian markets, which includes microbial strains such as *Pseudomonas fluorescens*, *Bacillus megaterium*, and, which aids in the phos-

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Table 3. Commercial endophytes and their trade names

Trade names	Endophytes	Company/Institution
National		
AtEze	*Pseudomonas chlororaphis* 63-28	Turf Science Laboratorie
Biocon	*Pseudomonas fluorescens*	Tockalai Experimental Station, Tea Research Association, Jorhat, Assam, India
Bio-jet, spot less	*P. aureofaciens* strain TX-1	Eco Soil Systems, FL, USA
Biolep	*Bacillus thuringiensis* var. *kurstaki*	Biotech International Limited, New Delhi, India
Bio-save 100, Bio-save 1000	*P. syringae* ESC-10	EcoScience Corp, Orlando, FL, USA
Bio-save 110	*P. syringae* ESC-11	EcoScience Corp, Orlando, FL, USA
Bioshield	*Pseudomonas fluorescens*	POABS Biotech, Kuttoor, Kerala, India
Cedomon	*P. chlororaphis*	BioAgri AB, Sweden
Epic	*Bacillus subtilis*	Gustafson Inc., Dallas, USA
Esvin Pseudo	*P. fluorescens*	Esvin Advanced Technologies Limited, Tamil Nadu, India
Frostban, Blightban A506	*P. fluorescens* A506	Plant Health Technologies, Pune, India
GB34	*B. subtillus* strain GB34	Gustafon, USA
Intercept	*Pseudomonas cepacia*	Soil Technologies, Fairfield, IA, USA
International		
Kodiac, Companion	*B. subtillus* strain GB 03	Growth Products, USA
Pant Biocontrol Agent-2	*P. fluorescens*	G. B. Pant University of Agriculture Technology, Pantnagar, India
P-Suraksha	*Pseudomonas* sp.	International Panaacea Limited, New Delhi, India
Rhizo-Plus KFZB	*B. subtilis* FZB24	Biotechnik GmBH, Germany
System 3	*B. subtilis* GB03	Helena Chemicals Co., Memphis, TN, USA

phate availability. ABiTEP GmbH in Germany offers the biofertilisers Symbion-N, Symbion-P, and Symbion-K, containing various microbial strains such as *Azospirillum, Rhizobium, Acetobacter, Azotobacter, Bacillus megaterium* var. *phosphaticum, and Frateuria aurantia*. Another product, Rhizovital 42 (FZB24f), from ABiTEP GmbH, comprises *Bacillus amyloliquefaciens* spp. *plantarum*, facilitating the improved phosphate availability in the soil. These bioformulated products play crucial roles in sustainable agriculture practices by enhancing the soil fertility, promoting plant health, and reducing the reliance on chemical inputs. CataPult, Nodulest 10, and Agrilife Nitrofix are trade names of biofertilisers. These products employ microorganisms such as *Bradyrhizobium japonicum*, *Azotobacter chroococcum*, *Azotobacter vinelandii*, *Acetobacter diazotrophicus*, *Azospirillum lipoferum*, *Rhizobium japonicum*, *Pseudomonas striata*, *Bacillus polymyxa*, and *Bacillus megaterium*. The assigned functions of these microorganisms include nitrogen fixation, phosphate solubilisation, mineral nutrition, and silicate weathering (Cobos 2005; Lara 2008; Moreno-Sarmiento et al. 2007).

Ester (2022) reported RhizoMyco and RhizoPlex as biofertilisers offering diverse benefits for plant health and growth. RhizoMyco is a combination of growth-promoting agents and eighteen different species of endo- and ectomycorrhizal fungi. Similar mycorrhizal species were included in RhizoPlex, which functions as an endomycorrhiza inoculant and is enhanced by a specially blended mixture of proprietary bacterial cultures and stress-relieving components. Both products contribute to the phosphate availability and support root and shoot development, endorsed by Novozymes (www.novozymes.com), a European company. JumpStart and Tag Team (enriched with LCO (lipochitooligosaccharides) or rhizobial strains for legumes) boosts the nitrogen fixation, particularly in leguminous crops, were reported on by Mehnaz (2016). These products collectively offer a holistic approach to improve the soil health and promote sustainable agricultural practices.

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The Flozyme Inc. company in USA offers a range of biofertiliser products, Inogro is one of the biofertiliser comprises a blend of over 30 carefully selected microbes, specifically chosen for their soil rehabilitation capabilities and their capacity to enhance the productivity. The product has higher nutritional levels, quicker and earlier germination, quicker maturation, and greater stress resistance. Noteworthy greenhouse trials have showcased remarkable yield improvements, such as a staggering 301% increase for rice and an exceptional 400% enhancement for tomatoes, as reported by Celador et al. (2018).

Mehnaz (2016) outlined various bio formulations from around the globe, one of which is Bio Power Lanka, a company based in Sri Lanka. They provide a diverse array of agricultural bio- products, such as Bio Gold a liquid solution made up of native isolates of friendly bacteria including *Azotobacter chroococcum* and *Pseudomonas fluorescens*. This multipurpose solution can be applied in a variety of ways to both agricultural and horticultural crops, including foliar spraying, drip irrigation, spraying the root zone, and using it as a seed inoculant. Its broad applicability and diverse application methods make Bio Gold a convenient and effective solution for enhancing the growth and productivity of crops across different agricultural crops. *Bacillus megaterium*, a phosphate-solubilising microbe, is available in the liquid formulation as Bio Phos® (India).

AgriLife has created 15 biofertilisers, each specifically designed to meet the needs of agriculture. These biofertilisers include vesicular arbuscular mycorrhizae (VAM), manganese-solubilising fungus, potassium, ferrous, sulfur, silica, and zinc mobilising bacteria, in addition to nitrogen-fixing and phosphate-solubilising bacteria. For instance, P Sol B is a phosphate-solubilising biofertiliser enriched with *Pseudomonas striata* (NCIM 2847), *Bacillus polymyxa* (NCIM 2188), and *Bacillus megaterium* (NCIM 2087). It is convenient to apply these biofertilisers into the soil, or onto the seedlings or seeds. Another notable product is AgriVAM, formulated with spores and fragments of vesicular-arbuscular mycorrhizal (VAM) (*Glomus* species), suitable for application to the soil, seeds, nursery beds, and during planting. Fe Sol B, containing autotrophic, acidophilic *Acidithiobacillus ferrooxidans*, is designed to release iron oxidase, facilitating iron metabolism. It can be efficiently applied to seedlings and soil or via drip irrigation. Si Sol B includes *Bacillus* spores and can be applied to seeds, seedlings, and the soil, as well as by drip irrigation. S Sol B features *Thiobacillus thiooxidans*, an autotrophic, acidophilic bacterium, and is designed for application to seedlings and the soil, is also suitable for irrigation. This information was published on the Agrilife website by Devanur (2015).

CONCLUSION AND FUTURE PERSPECTIVES

In today's world, it is critical to boost the agricultural output while maintaining soil fertility in order to meet food demands and ensure a healthy environment for future generations. However, the presence of numerous pests and pathogens in crops causes an overall decrease in the agricultural yields, resulting in massive crop losses each year. To reduce crop output losses and control diseases, a variety of effective approaches should be implemented. Endophytes are environmentally friendly, non-toxic, easy to apply, and cost-effective, thus farmers can employ them instead of fertilisers in sustainable agriculture. More research is required to understand the biochemical, molecular, and genetic mechanisms of endophytes, which are essential to the stress resistance of different crops. The omics method can aid in understanding the roles of the complex plant microbiome and provide information on competent bacteria in terms of stress tolerance and plant productivity. Hence, there is need to consider these lacunae for the commercialisation of products with beneficial endophytes and the consortia of endophytes will be a good option for the effective biocontrol-based management to overcome the residual effects of fungicides. Endophytes and their metabolites must be studied at the multi-omics level since they have the potential to aid in the biological management of plant diseases.

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