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REVIEW ARTICLE

Induction of fungal disease resistance in rice mediated by bacterial endophytes

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Abstract

Rice crops are being affected by destructive pathogens that cause disease. The climatic variations make the plants more vulnerable to different biotic stresses. Severe limitations are experienced in rice-growing regions due to fungal diseases such as blast and sheath blight. Synthetic chemicals are used extensively to treat plant diseases, which are more harmful to animals, plants and humans. Endophytes are adaptable, beneficial microorganisms that offer environmentally friendly solutions for disease control by symbiotic or mutual associations and live within and between plant cells, helping to increase nutrient availability in plants. The endophytes improve plant growth by production of plant hormones such as indole-3-acetic acid, auxin and gibberellic acid. This also induces systemic resistance by activating the ethylene, jasmonic acid and salicylic acid cycle to increasing peroxidase (PO), polyphenol oxidase (PPO), phenylalanine ammonia-lyase (PAL) and superoxide dismutase (SOD) during abnormal physiological processes which happens during pathogen infestation. It also produces secondary metabolic substances such as iturin, surfactin, zwittermycin A, 2,4 diacetyl phloroglucinol, etc., that have antibacterial and antifungal properties, which help to manage plant diseases. Utilizing bacterial endophytes as bio inputs on a large scale aids in the eco-friendly management of plant diseases, thus increasing productivity. This review paper highlights bacterial endophytes' role in managing rice's emerging fungal diseases by induction of systemic resistance, plant growth promotion, siderophore production, antibiosis, biostimulant and nutrient solubilization activities.

Keywords: antibiosis activity; bacterial endophytes; biostimulation activity; induced systemic resistance; PGPR activities; rice fungal disease

Introduction

Rice (*Oryza sativa* L), with a chromosome count of 2n = 24, is the leading staple food for approximately 60 % of the global population (1). India is ranked 111th out of 125 countries in rice production globally, after China, contributing around 25 % to the total production worldwide. Approximately 520.4 million metric tons of rice is consumed, with an additional 20 % increase in production needed to meet daily food demands. India is ranked 111th out of 125 countries in the Global Hunger Index report, with a score of 28.7 %. The report showed a significant issue of food insecurity among the current population in India. The major causes of food insecurity is due to biotic and abiotic stresses. Annual crop loss due to biotic and abiotic stress is 15 % and 50 % in global rice production (2). The major threats to rice cultivation are pests and diseases. Among those diseases are more problematic. Diseases such as blast (*Pyricularia oryzae*), brown spot (*Helminthosporium oryzae*), sheath blight (*Rhizoctonia solani*), sheath rot (*Sarocladium oryzae*), false smut (*Ustilaginoidea virens*), bacterial leaf blight (*Xanthamonas oryzae* pv *oryzae*), bacterial streak (*Xanthomonas oryzae* pv *oryzicola*), panicle blight (*Burkholderia glumae*), Rice yellow dwarf and Rice Tungro virus affects the crop more frequently. Fungi are the most severely devasted pathogen in the rice crop (3). Rice blast and sheath blight are the primary crop problems among the fungal diseases. Annual yield loss of sheath blight is up to 50 % and rice blast is up to 10 % to 30 % (4). Nowadays, global climate change has given immense attention to crop failure. Understanding the pathogen's interaction and management strategy made it further challenging. It modifies the pathogen distribution and alters the resistance of plants against pathogens and makes the plant more susceptible to diseases (5). To take preventive measures, the leading growing countries have started using excess synthetic chemicals to improve crop health and increase production. This front-line defence faced negative impacts on the environment viz., pest resurgence, pathogen resistance, residual effect of the plant, ill effect to soil microbes, pollution of groundwater, river water, excess nutrients deposited in catchment area causing eutrophication and death of water animals and intoxication of food made harmful to human as well as animals (4, 6). In recent years, scientists have been employing host-associated microorganisms to manage plant diseases, offering an environmentally friendly and safe approach (7).

Beneficial biocontrol agents are potentially used to control plant pathogens. In 1866, de Barry identified the non-pathogenic microorganism residing within the plant tissue, and named as an endophyte and gave the first definition as "Any organism that lives within plant tissue" (8). Endophytes, either bacteria or fungi sustained inside a plant with or without harm to the plant. Rice plants have complex microbes that play an essential activity in growth and development during their cultivation. Endophytic microbes are essential in modern agriculture for their plant growth promotional activities by uplifting nutrient uptake, producing phytohormones like IAA and eliciting protection from phytopathogens using secondary metabolites (6).

Endophytes are a stationary approach for mitigating biotic and abiotic stresses. They effectively utilize their bioactive chemical compound to prevent plant diseases, enhance plant growth and promote plant development. This created an opportunity to decrease pesticide usage and achieve sustainable agricultural production (8). This effective method of extending the lifespan of goods, combating drought, enhancing resistance to pathogens in adverse conditions, revitalizing polluted soil with lead contamination and increasing soil fertility leads to year-round crop cultivation (9). The goal of biological control is to uphold balance in agricultural systems. The host's susceptibility to pathogens is lessened because of the regulatory impact of non-pathogenic microorganisms. This review indicates that endophytic microorganisms have the potential to effectively manage plant diseases by targeting both host-specific and non-host-specific pathogens through their mutual relationship, leading to sustainable crop cultivation (10).

Overview of major fungal disease on rice

Rice sheath blight

Rice sheath blight is caused by *Rhizoctonia solani*, teleomorph stage (*Thanetophorus cucumeris*) was first reported in Japan in 1910 (11). In India sheath blight was reported in Gurdaspur in 1963 and faced significant consequences in rice production cultivation followed by Punjab, Haryana, Jammu and Kashmir, eastern Uttar Pradesh, Uttarakhand, Chhattisgarh, Bihar, West Bengal, Odisha, Andhra Pradesh, Tamil Nadu, Karnataka, Kerala, Madhya Pradesh, Assam, Manipur and Tripura (12). The disease appeared at the tillering stage, initially, it seemed to be a green to brownish lesion above soil level (Fig. 1), the latter spot enlarged and spread vertically to the entire plant and horizontally to nearby plants by runner hyphae. Under favourable conditions, it produces profusely branched silky brown colour mycelium and dark brown irregularly shaped sclerotia. The constant growing of rice using high-yielding strains and large amounts of nitrogen fertilizers promotes the development of pathogens and the widespread spread of diseases in extensive areas. The dark brown hard sclerotia are produced as a resting structure during abnormal conditions and serve as an inoculum for the next season (13).

Rice blast disease

Rice blast or rotten neck is one of the most severe diseases caused by *Magnaporthe oryzae* anamorph named *Pyricularia oryzae* in all rice-growing areas. In 1637, Soong Ying-Shin first reported 'rice fever disease in China and Imochi-byo reported in Japan in 1704 (14). In India, the disease occurrence was first reported in the Tanjore district in Tamil Nadu in 1918 (15). It was followed by Maharashtra, Himachal Pradesh, Andhra Pradesh, and subsequently other parts of rice-growing areas (16). It expresses three types of symptoms: leaf blast, nodal blast, and panicle blast. Managing is challenging due to the heterothallic mycelium constantly producing new races. It causes yield losses of 70-80 %. Within 15 to 20 days, the pathogen rapidly expanded and destroyed the region designated for growing rice, resulting in a complete loss of up to 100 %. Extended periods of rain, such as drizzle, dew and limited sunshine, caused disease outbreaks, leading to increased conidial growth and the spread of primary inoculum from one field to another. The infested debris is the source of inoculum for disease development and distribution in further seasons (17).

Bacterial endophytes

Bacterial endophytes are omnipresent in the living plant host. Plant microbes are categorized as symbiotics, pathogenic, saprotrophic, epiphytic, opportunistic and competent, similar to a phytopathogen (18). In 1866, de Barry identified the non-pathogenic microorganism in the plant tissue and named it an endophyte. He gave the first definition, "Any organism that lives within plant tissue (19). Petrini gives suitable definitions for endophytes, stating that "endophytes are microorganisms that live or inhabit and colonize in the internal tissue of plant without causing any harmful effect to the host" (20). Endophytes are endosymbionts, which include bacteria, fungi, algae, actinomycetes and viruses (21). Endophytes have been found in roots, shoots, ovules, endosphere of mature seeds, flowers, leaves, meristematic tissues, sprouts and germ-free micropropagated plants (22, 23). A record of bacteria found in various sections of rice plants includes *Pantoea* in the seeds, *Rhizobium* and *Burkholderia* in the roots and *Methylobacterium* in the shoots (24-26). The bacterial endophytes such as *Pseudomonas fluorescens, Xanthomonas sacchari* and *Staphylococcus* sp. were also reported in milled rice seeds (27). It was also

Fig. 1. Rice sheath blight symptom.

identified in *Flavobacterium* sp., *Mycobacterium* sp. and *Xanthomonas* sp. salt-tolerant and salt-sensitive cultivars (28). It colonizes roots by being attracted to plant root exudates in the rhizosphere, which contain various nutrients (29). Microorganisms are signaled by chemotaxis responses, including aerotaxis receptors and cytoplasmic receptors, allowing them to enter plant tissues and provide benefits (30). A wide range of bioactive substances synthesized by endophytes, such as alkaloids, steroids, terpenoids, peptides, polyketides, flavonoids, quinols and phenols, have extensive industrial applications (31). Soil is the selective carrier material for seed and plant microbiota. The microbiome associated with seeds is dormant along with the seed resting stage. The seed starts germination, the microbes actively colonize in root tip for utilization and multiplication through the excreting of plant nutrition. Similar to bacteria assisting with nutrient uptake in plants, plant exudates help to maintain the microbial community in the rhizosphere (32). Endophytes can be transferred vertically and horizontally (33). Vertical transmission occurs from one generation of plant seeds to the next. The *Stenotrophomonas maltophilia, Mycobacterium absessus* and *Ochrobactrum* sp found in rice seed endophytes have been shown to transmit across two generations, with 3.5 x 10^5 CFU in the first generation and 4.5x 10^3 CFU in the second generation (34). Seed-borne endophytes *Bacillus amyloliquefaciens* transmitted in subsequent generations (8). Horizontal transmission occurs when a vector carries pathogens from one plant to another nearby through soil or insects. During pollination, both *Apis mellifera* and *Osmia bicornis* change or transfer endophyte communities (35). Plant parts have a lower population compared to the rhizosphere due to specific nutrients and compatibility (36). Microbial communities assist in changing plant physiology in abnormal conditions and help them defend and boost induced systemic resistance in the face of biotic stress (37). Endophytic colonization and the composition of bacterial communities in plants are affected by various factors, such as plant genetics, growth stage, soil characteristics, climate and farming methods (38). It is becoming more significant each day in agriculture due to its ability to release secondary bioactive metabolites. The metabolites support plant growth by improving soil nutrients like nitrogen absorption, phosphate breakdown, ammonia use and siderophore creation in plant habitats (39). Moreover, they function as growth regulators akin to auxin, gibberellin and indole-3-acetic acid, aiding plants' resistance development (40). These bacteria secrete various secondary compounds such as cyclic lipopeptides, bio-surfactin, 2, 4-di-acetyl phloroglucinols, pyoluteorin, phenazines, bacillomycins, fengycin, lipopeptides, pyrrolnitrin, celluloses, hydrogen cyanide, polyketide synthase and non-ribosomal peptide synthases to combat phytopathogens (41, 42). ROS plays a significant role in pathogen defense, with different reactions seen in biotrophic and necrotrophic organisms in response to high levels of ROS. Endophytes are effective organisms for regulating ROS levels by utilizing antioxidants to combat biotic stress (43).

Vertical and horizontal transmission of endophytes

Endophytes can be transferred both vertically and horizontally (33). Vertical transmission occurs from one generation of plant seeds to the next. The *Stenotrophomonas maltophilia, Mycobacterium absessus* and *Ochrobactrum* sp found in rice seed endophytes have been shown to transmit across two generations, with 3.5 x 10^5 CFU in the first generation and 4.5x 10^3 CFU in the second generation (34). Seed-borne endophytes *Bacillus amyloliquefaciens* transmitted in subsequent generations (8). Horizontal transmission occurs when a vector carries pathogens from one plant to another nearby plant through soil or insects. The horizontal mode refers to transmitting either bacterial endophytic microbe via air, soil and environment. During pollination, both *Apis mellifera* and *Osmia bicornis* change or transfer endophyte communities in the host plant (35).

Mechanism of action

Endophytes improve plant growth and vitality through two classified categories: Direct and Indirect mechanisms. Direct pathways impact observable factors such as plant growth, yield and biomass through activities like nitrogen fixation, phosphate solubilization, nutrient competition, ammonia utilization, ACC deaminase and promotion of plant growth hormones (Fig. 2). In contrast, indirect pathways, such as pathogen suppression through antibiosis, induced systemic resistance, hydrogen cyanide production, lysis activity and siderophore production, do not have visible effects on these parameters (44).

In direct mechanism

Siderophore production

Iron, copper, zinc, magnesium and nickel are vital for the survival of every living being. Iron is necessary for the metabolic processes of all living organisms and cannot be replaced (45). Competition in soil environments arises frequently because of the limited supply of iron ions for the soil microbial community and plants (46). Iron is the primary nutrient that restricts the growth of plants and microbes due to its ferric insolubility (45). Siderophore production functions as a form of biocontrol, showing hostile impacts on parasitic pathogenic fungi in iron resource competition (47). Bacteria belonging to genera such as *Bacillus, Pseudomonas* and *Enterobacter* are known to chelate siderophores under conditions of iron limitation (48). Endophytic microbes release low molecular weight compounds known as "siderophores", which have higher affinity with Fe^{3+} and the iron complex with specific protein in the outer membrane facilitates iron (Fe^{3+}) into the plant cell and also makes rich availability of iron in the rhizosphere region (49). All microorganisms have produced unique proteins that regulate iron and can bind to iron compounds. *Pseudomonas fluorescens* produces a unique hydroxamate iron-chelating protein called "pyoverdines" that strongly binds to iron, depriving iron for *R solani* in paddy (50). *B. velezenins* produces siderophore bacillibactin, which reduces to inhibits the activity of *R. solani* and *P. oryzae* (51). The endophytic *Streptomyces sporocinereus OsiSh-2* competes with *M. oryzae* for iron nutrients (52). At the same time, *Bacillus subtilis* uses iron chelate against *R. solani* the Hydroxamate siderophore of *Pseudomonas putida* suppresses blast disease and *B. velezensis LS123N* employs the siderophore mechanism to control disease in rice (53-55).

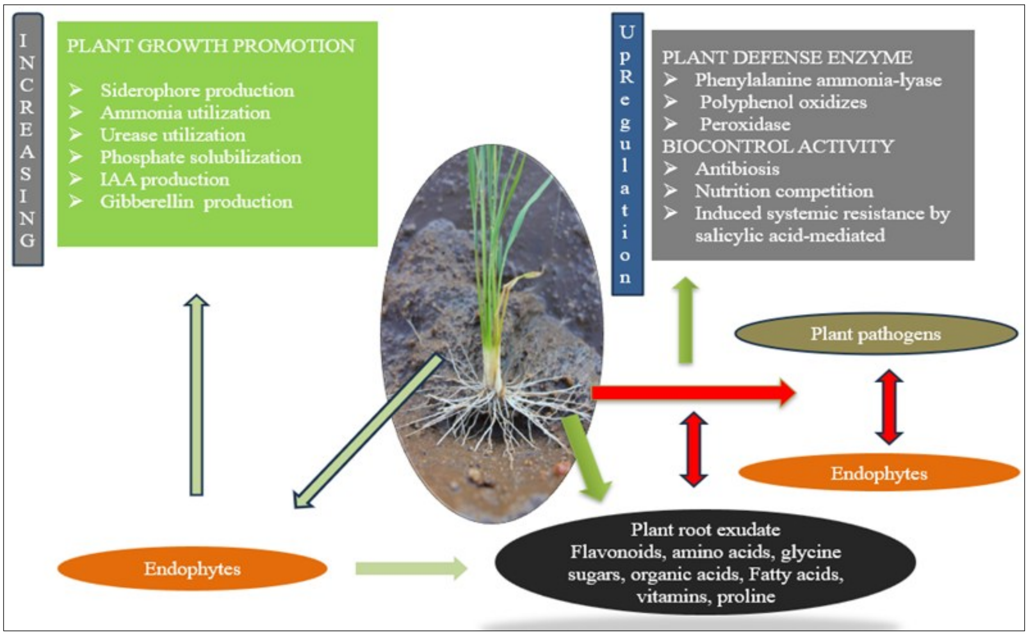

Fig. 2. Biocontrol mechanism of endophytes.

Antibiosis

Antibiotics comprise various small molecules crucial for inhibiting the development and metabolism of pathogens and enhancing plant defense mechanisms (Table 1, 2). Six antibiotic groups, including pholoroglucinols, pyrrolnitrin, pyoluteorin, phenazines, cyclic lipopeptides and hydrogen cyanide, efficiently manage plant diseases with volatile and non-volatile chemicals (56, 57). To prevent plant diseases from spreading, lipopeptide compounds possessing antibiotic and antifungal properties form pores in cells to extract internal contents and harm bacterial and fungal pathogens (58). The bioactive substances such as malabaricone, rosmarinic acid and acimalabaricone cascade the pathogen's virulence, fight pathogen resistance, disrupt biofilm formation and make the pathogen avirulent (59). *Serratia* sp and *Pseudomonas putida* generate secondary inhibitory compound hydrolytic enzymes to reduce the incidence of *R. solani* and *Verticillium dahlia* (60). When exposed to sheath blight, *Bacillus amyloliquefaciens* produces potent secondary metabolites (61). Endophytic enzymes such as glucanase, protease, cellulose, pectinase, chitinases, amylases, lipases, pectinases, phosphatases, hemicellulases, chitinases and 1, 3-glucanases, serve to protect them from plant pathogens (62). These enzymes kill fungal spores, spore germination and germ tubes and bacteria may parasitize disease-causing fungi (63, 64). The endophytic bacterium *B. bassiana* produces hydrolytic enzymes like pectinase, cellulase, lipase, α-amylase and xylanase, which can lower the occurrence of *R. solani* (65). *Bacillus* sp lyse the fungal hyphae of *R. solani* using lytic enzymes such as beta-1,3-glucanase and chitinase (66). Fluorescent pseudomonads produce hydrogen cyanide to suppress soil-borne pathogens (67). *Lysinibacillus sphaericus* potentially controls the mycelial growth of *R. solani* using the strong antifungal activity of 1, 2-Benzenedicarboxylic acid butyl 2-Ethylhexyl ester (68).

Induced Systemic Resistance (ISR)

ISR is a captivating occurrence found in plants, triggered by environmental factors like pathogen attacks, beneficial microorganisms, pathogenic proteins and elevated phenolic compounds, causing a systemic resistance response in the entire plant (83). When microbes begin interacting with plants, the plants detect microbial-associated molecular patterns through proteins of bacterial flagellin, lipopolysaccharide, beta -1,3-glucan and ergosteroids, activating plant defence mechanisms. When *Pseudomonas syringae* interact with plants, they create flagellin (flg22) and N-hydroxypipecolic (NHP) acid. This activation produces phytoalexins like camalexin, salicylic acid, stigmasterol and the NHP precursor pipecolic, inducing acquired resistance in specific plant tissue (84). During microbial association, plant cells experience a rapid increase in phenylalanine ammonia-lyase (PAL),

Table 1. Bacterial endophyte against *R. solani*

Pathogen	Endophytes	Mode of action	Reference
R. solani	*B. stratospheric, B. cereus, B. subtitles, B. thermophilus, B. pumilus, E. cloacae, K. pneumoniae*	Strong antagonistic and antimicrobial capabilities using surfactin, iturin and bacillomycin.	(52)
R. solani	*Bacillus subtilis* var. *amyloliquefaciens*	Generate powerful lytic action and antifungal effects similar to surfactin, iturin, bacillomycin and azalomycin F, along with significant inhibition of mycelium.	(69)
R. solani	*Bacillius wiedmannii* sp, *B. altitudinis* sp, *B. aryabhattai* sp, *B. indicus* sp, *B. tequilensis, F. phosphorivorans* sp	High antifungal antibiotic activity	(4)
R. solani	*Lysinibacillus sphaericus*	Production of a highly volatile compound, such as 1, 2-Benzenedicarboxylic acid butyl 2-Ethylhexyl ester, exhibits antifungal effects through mycelial disruptions and shrinkage	(68)
R. solani	*Bacillus amyloliquefaciens*	Propanamine, N, N, 2-trimethyl, 1(2H)-Naphthalenone, 3,4-dihydro-6,7 -dimethyl, Diethyl Phthalate, Dichloroacetic acid tridecyl ester, Hexadecen-1-ol trans-9, Glycine N-(N-glycyl-L-leucyl) and 2,6,10-	(61)

Table 2. Bacterial endophytes against *P. oryzae*

Pathogen	Endophytes	Mode of action	Reference
P. oryzae	*Bacillus licheniformis and Stenotrophomonas rhizophila*	High HCN production through suppression of blast disease	(70)
P. oryzae	*Bacillius subtilis*	Produced antimicrobial compound Butyl alcohol 1-D1 is a Biosurfactant	(71)
P. oryzae	*Microbacterium testaceum*	Complete inhibition of mycelial growth and produced volatile compounds Hexadecanoic acid	(72)
P. oryzae	*B.siamensis, B. amyloliquefaciens, B. subtilis*	Produces antifungal activity against pathogen by using Butyl alcohol 1-D1 and 2,3-Butanediol and increases high phenol activity	(73)
P. oryzae	*Bacillius velezensis*	High antifungal antibiotic activity and high inhibition	(74)
P. oryzae	*Bacillus altitudinis sp, Fictibacillus phosphorivorans sp, Cuprividus metallidurana sp*	High antifungal antibiotic activity and high inhibition	(4)
P. oryzae	*Bacillus safensis* B21	High antifungal antibiotic activity and high inhibition	(75)
P. oryzae	*Bacillus velezensis* and *Pseudomonas putida*	Iturin A2 and Iturin A6 Inhibit hyphal growth and increase membrane permeability. significant inhibition on the pathogenic growth.	(76)
P. oryzae	*Bacillus velezensis* and *Pseudomonas putida*	Up regulating defense enzyme and phenol content. Inhibition of mycelial growth and produced high antibiotic activity	(73)
P. oryzae	*Streptomyces albidoflavus strain Emeranaa*	Produced antimicrobial compounds against rice blast like Benzaldehyde,3-methoxy-4- [(trimethylsilyl)oxy]-, Omethyloxime, 2,4-Di-tert-butylphenol	(71)
P. oryzae	*Streptomyces albidoflavus OsiLf-2*	Created antimicrobial substances, enzymes that break down cell walls, siderophores and lytic enzymes, along with hydrogen peroxide (H2O2) and a-mannosidase activity to induce plant immunity against pathogens through Damage Associated Molecular Pattern (DAMP) to develop resistance to diseases.	(77)

polyphenol oxidizes (PPO) and peroxidase (PO) levels. PAL catalyzes the conversion of phenylalanine into cinnamic acid, a precursor for phenol and phytoalexins biosynthesis, leading to resistance to biotic stress by inducing salicylic acid (SA). It provides broad-spectrum protection by triggering the plant's natural defense system as its first line of protection against various plant pathogens. Infected plants increase their levels of JA and ET as an active sign. Besides, instigated foundational protection includes jasmonate and ethylene motioning inside the plant and these hormones fortify the host plant's resistance reactions against an assortment of plant pathogens. The endophytic *Pseudomonas putida* secreted lipopolysaccharide and exopolysaccharide while interacting, which led to resistance against *P. oryzae* infection in rice seedlings and an increase in defence enzymes like peroxidase, polyphenol-oxidase activities and total phenols (54). *Pseudomonas* sp and *Bacillus subtilis var amyloliquefaciens* induce systemic resistance against *Rhizoctonia solani*, *Bacillus* sp activity enhances the levels of peroxidase, polyphenol oxidase and phenol content during the interaction with *P. oryzae* in the host, *Bacillus megaterium* triggers the salicylic acid-dependent pathway to create resistance to the spikelet rot disease rice pathogen (69, 85, 86).

Direct mechanism

Plant Growth-Promoting activity

Biostimulant activity: Endophytic microorganisms are abundant in producing different growth hormones such as auxin, indole acetic acid (IAA), gibberellic acid (GA), cytokinin, ethylene, strigolactones, brassinosteroids and jasmonates (8). These hormones function as messengers and coordinators within the entire plant system (Table 3). *Rhodococcus, Bacillus, Azotobacter, Alcaligenes, Pseudomonas, Azospirillum, Klebsiella, Enterobacter, Herbaspirillum, Rhizobium, Burkholderia, Pantoea* and *Acetobacter* are the most common genera involved in producing plant growth regulators (78). IAA is important in differentiating meristematic tips, cell elongation and the growth of lateral and adventitious roots, while GA helps with seed germination and slows down plant aging (79). Additionally, cytokinin controls cell division and ethylene controls reactions to environmental stress, impacting cell expansion in root structure by supporting lateral root growth and development, thereby improving nutrient and water absorption (80). During pathogen infection, *Bacillus*, *Microbacterium*, *Micrococcus* and *Pseudomonas* species are renowned for synthesizing auxin and GA, promoting seedling growth and plant vitality (81). Bacteria

Table 3. Bacterial endophytes as plant growth promoters

Endophytes	PGPR activities	Reference
Enterobacter cloacae	Phosphorous solubilization, nitrogen fixation, auxin, ammonia production and gibberellic acid	(70)
B. velezens and *P. putida*	IAA production, ammonia production, siderophore production, ACC deaminase production and phosphate solubilization	(76)
Pseudomonas sp	Protease production, denitrification activity, urease production, cellulase production, ACC-deaminase production, phosphate solubilization and IAA production	(93)
Microbacterium testaceum *Klebsiella pneumoniae, Leclercia adecarboxylata, Enterobacter* sp	Production of IAA, ammonia and hydrolytic enzymes	(72)
Bacillius amyloliquefaciens	Phosphate solubilization, nitrogen fixation, IAA, siderophore production	(52)
Acidovorax sp, Xanthomonas sp	Phytohormone production like GA3, IAA	(8)

living inside plants produce nitrogen and α-ketobutyrate using ACC deaminase and ammonia. This helps plants grow better in low-nitrogen conditions and more tolerant to salt concentration (77). Endophytes modulate the ethylene levels in plants by producing the 1-aminocyclopropane-1- carboxylate deaminase, a critical trait that enables interference with the host plant's physiology and creates induced systemic resistance (82).

Nutrient solubilization

Phosphate solubilization : Nitrogen, phosphorus and potassium are essential to plant growth and yield nutrients. Phosphorus is crucial in regulating plant growth and development by being a necessary nutrient for root growth (87). Fe^{2+} makes it in an unavailable form. Soil phosphorus is unavailable diffusion (88). The phosphate-solubilizing microbes *Bacillus, Klebsiella* and *Enterobacter* sp. solubilize residual P by acidification, chelation and iron exchange reactions into soluble forms in rice (8). It will improve soil health and quality and help prevent plants from pathogen attacks (89). Organic acid production is an essential factor for releasing phosphorus in bound form. The symbiotic relationship of the phosphate-solubilizing *Bacillus* spp. Secretes gluconic, isovaleric itaconic, isobutyric, lactic acids, acetic acids and exopolysaccharides to convert the soluble form of phosphorus (90). *Pantoea dispersa* produce salicylic and benzene acetic acids for more effective P solubilization in field crops (91). In addition, enzymes including phosphatase, C-P lyases, phosphonates and phytases, help to convert organic phosphorus to available phosphorus. *Dyella ginsengisoli* produces beta 1,3 glucanase enzyme, which solubilizes inorganic phosphate in canola to increase length root growth (92).

Nitrogen fixation : Rice is a non-leguminous crop, which was in high demand scare of the fixation of nitrogen to the plant. Nitrogen is the major demanding nutrient for crop performance and it can largely independently depend on the chemical fertilizer. The researcher found continuous application of nitrogen fertilizer to the field, represses the nitrogenase enzyme activity of biological nitrogen-fixing bacteria (94). The biological nitrogen fixation of endophytic bacteria helps to assimilate nitrogen into the plants. Inoculating rice seedlings with nitrogen-fixing endophytic bacteria has significantly enhanced rice's biomass and grain yield. Endophytic diazotrophic *Lysinibacillus sphaericus, Klebsiella pneumoniae* and *Bacillus cereus* were identified nif genes and the endophytes increased the fixation of nitrogen to the plant and also inhibited the activity of *R. solani* (95). *Burkholderia cepacian* and *Citrobacter* sp increased the nitrogen concentration in the rice plant (96). *Herbaspirillum* sp was identified potential endophytic diazotrophic bacteria that helps fix nitrogen in wild paddy plants (97).

Potassium solubilization : Endophytes play a significant role in potassium solubilization, crucial for enhancing plant nutrient uptake. Certain endophytic bacteria can mobilize potassium from insoluble sources in the soil, converting it into forms that plants can readily absorb. These endophytes produce organic acids and enzymes that break down potassium-bearing minerals, facilitating the release of potassium ions. The use of potassium-solubilizing endophytes in agriculture has the potential to enhance crop yields, especially in potassium-deficient soils, making them a valuable tool for sustainable farming practices. *E. cloaceae* solubilize the potassium and make available to easy uptake of plants and high inhibitory activity against *Xanthomonas oryzae pv oryzae* (98). *Enterobacter hormaechei, Citrobacter braakii, Pseudomonas putida, Erwinia iniecta* and *Pantoea agglomerans* were increasing the solubilization of potassium ions in the sodic-saline soil their enhancing the growth and yield under the field condition. *Pantoea ananatis* helps with both the solubilization of phosphate and potassium in saline soil (99). The endophytic bacteria *Pantoea* sp, *Pseudomonas* sp and *Pseudomonas* sp help solubilize the potassium ions and as vigorous inhibitory activity against *P. oryzae* (100).

Conclusion

Over the last few decades, there has been a significant increase in the use and consumption of artificially produced fertilizers and pesticides. Continuously using synthetic chemicals can cause the soil to become infertile, decrease its production and productivity and lead to the development of resistance to pests and pathogens. Because of the sterile soil's inability to produce crops at its full potential, there is a decrease in crop yield and an increase in environmental pollution, affecting humans, animals and microorganisms. Continuously using harmful chemicals can lead to resistance, resurgence and the development of highly virulent pests and pathogens. The endophytic microorganism deploys a biological weapon to enhance crop health by utilizing regional-specific microorganisms, managing the most harmful pathogen through secondary active metabolites and strengthening the plant's uptake of nutrients. The current utilization of biological control aids in reducing the reliance on hazardous chemicals and managing harmful elements as nations opt for eco-friendly methods to regulate organisms and alleviate various stresses.

Limitation

Several vital limitations hinder the study of endophytes. Firstly, the immense diversity of endophytes presents challenges in accurate identification and characterization. Many species remain unknown or poorly understood, complicating our understanding of their ecological roles. Secondly, isolating and culturing endophytes is often tricky, as many do not thrive under standard laboratory conditions, leading to a bias toward easily cultured species and underrepresenting others. Environmental variability further complicates research, as endophyte populations can change significantly based on soil type and climate factors. This variability makes drawing general conclusions about their functions across different ecosystems challenging.

Additionally, the host specificity of endophytes means that interactions can vary widely among plant species, limiting the applicability of findings from one system to another. Moreover, understanding the functional roles of endophytes such as their contributions to plant growth and disease resistance requires extensive research and many of their mechanisms remain unexplored. The intricate relationships between endophytes and other microorganisms also pose challenges; these interactions can influence plant health in complex ways that are not yet fully understood. These limitations underscore the need for more comprehensive and interdisciplinary approaches to endophyte research.

Prospects

The prospects of endophytes are promising, particularly in agriculture, biotechnology and environmental sustainability. As research advances, the potential to harness endophytes to enhance crop resilience, improve soil health and promote sustainable agricultural practices becomes increasingly viable. By identifying and utilizing beneficial endophytes, scientists can develop biofertilizers and biopesticides, reducing reliance on chemical inputs and fostering eco-friendly farming methods. Additionally, endophytes hold promise in bioremediation efforts, as they may help detoxify contaminated environments. As our understanding of their ecological roles deepens, endophytes could be crucial in addressing global challenges such as food security and environmental degradation.

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Authors' contributions

KK and KS collected the literature, data and drafted the manuscript. IN and TR formatted the article according to the journal. RN, PG and SKS contributed to the editing and revision. NHS and SS contributed to plagiarism compliance and checking. All authors read and approved the final manuscript

Compliance with ethical standards

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