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Plant Growth Promotion and Biocontrol Potential of Endophytic and Rhizosphere Bacteria Associated with Black Pepper (*Piper nigrum* L.)

Abhija, S.P., Abhija Sebastian, Aarcha Dinesh, Gouri Nandan, Hema Suresh and Nysanth, N.S.*

Dept. of Microbiology, College of Agriculture, Padannakkad, Kasaragod, Kerala (671 314), India

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Corresponding Author

Nysanth, N.S.

: nysanth.ns@kau.in

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Abstract

Black pepper (*Piper nigrum* L.), known as the "king of spices," is one of the world's oldest and economically important spices. Native to the Malabar Coast of India, it is now cultivated in several tropical countries. However, its production and productivity are severely constrained by several diseases, which represent one of the major challenges to sustainable cultivation. Among these, Foot rot, caused by *Phytophthora capsici* and slow decline disease, associated with soil-borne pathogens such as *Fusarium* spp. and *Meloidogyne* spp., are major constraints. These diseases cause root damage, stunted growth, wilting and eventual plant death. Although chemical pesticides are commonly used for disease management, excessive use poses environmental and health risks. Beneficial endophytic and rhizosphere bacteria hold considerable potential as plant growth promoters, enhancing growth through nutrient solubilization, nitrogen fixation, phytohormone and siderophore production, while suppressing phytopathogens through antimicrobial activity and induction of plant defense responses, without adverse environmental effects.

Keywords: Biocontrol, Black pepper, Endophytic bacteria, Rhizosphere bacteria

Introduction

Black pepper (*Piper nigrum* L.), popularly known as "black gold," belongs to the family Piperaceae and is believed to have originated in the sub-mountainous tracts of the Western Ghats of India. Black pepper is one of the oldest and most widely consumed spices in human history and is highly preferred due to its characteristic pungency and distinctive aroma. It is extensively used as culinary spice and condiment and a main component of traditional Ayurvedic medicine owing to its diverse therapeutic properties. Piperine, essential oils and oleoresins are the major constituents contributing to its quality and high commercial value. In addition, it exhibits strong antimicrobial, antioxidant and anticancer properties. These biological activities further contribute to the significant nutritional, medicinal and economic importance of black pepper.

Black pepper cultivation is largely constrained by several fungal, oomycete, bacterial and nematode-associated diseases. Among these, *Phytophthora* foot rot, commonly known as quick wilt, caused by the filamentous oomycete pathogen, *Phytophthora capsici* Leonian, is the most destructive and widespread diseases of black pepper. The pathogen primarily infects the collar and root regions, followed by rapid tissue necrosis, leaf yellowing and wilting, defoliation and cause eventual death of the plant. Conventional chemical management strategies to control foot

rot disease often provide inconsistent results and their repeated application pose severe environmental concerns and the development of reduced pathogen sensitivity. Moreover, effective and durable host resistance to quick wilt remains inadequately characterized in black pepper. These challenges emphasize the need for sustainable approaches, including the exploration of host associated beneficial microorganisms for disease suppression.

Slow decline disease, another major challenge to black

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pepper production, is caused by a complex involving *Fusarium* spp. and root-knot nematodes (*Meloidogyne* spp.). The characteristic symptoms include yellowing, stunted growth, marginal and tip drying of leaves, wilting and root gall formation. In the end, root deterioration and gradual decline lead to death of infested plants. Slow decline disease is controlled using biological methods involving microbes to inhibit nematodes based on their products such as enzymes, volatiles and other natural compounds.

Plant Growth-Promoting Bacteria in Black Pepper

Plants are naturally connected with diverse microorganisms that inhabit different plant compartments and play vital roles in plant growth, health and adaptation to environmental stresses. Of these, beneficial bacteria colonizing the rhizosphere and internal parts of plants have attained great attention because of their potential to trigger plant growth as well as suppress various phytopathogens. In black pepper, these bacterial communities represent an important but comparatively underexplored biological approach for sustainable crop cultivation and disease management.

Rhizosphere bacteria actively colonize the narrow zone of root-adhered soil enriched with root exudates under the direct influence of plant roots. This region is a nutrient-rich environment that supports diverse microbial populations. Beneficial bacteria inhabiting rhizosphere region, known as plant growth-promoting rhizobacteria (PGPR), have been known to enhance growth and yield of black pepper through several direct and indirect mechanisms. Direct mechanisms *viz*. nitrogen fixation, solubilization or mobilization of nutrients including phosphorus and potassium and synthesis of phytohormones, including indole-3-acetic acid (IAA), cytokinins and gibberellic acids and 1-aminocyclopropane-1-carboxylate (ACC) deaminase production, which lowers stress-induced ethylene levels and enhance stress tolerance in plants against various abiotic stress conditions such as salinity, drought and heavy-metal stress. Indirectly, they improve overall plant health by producing siderophores and antimicrobial metabolites, competing with phytopathogens for nutrients and space and inducing plant defense responses.

Endophytic bacteria, in contrast, colonize the plant tissue internally without any apparent symptoms or harm under normal conditions. They may reside in roots, stems, leaves and other plant tissues and can establish close associations with the host. Their habitat provides an important advantage, helping intimate interactions with the host and potentially contributing to improved nutrient acquisition, growth promotion, stress tolerance and protection against invading pathogens. Many endophytic bacteria have been identified from different tissues, predominantly roots, stems and leaves of black pepper, indicating the occurrence of diverse internal bacterial community.

The multifunctional nature of endophytic and rhizosphere bacteria keeps them particularly relevant for black pepper cultivation (Figure 1). Exploring the diversity, functional traits and interactions of both rhizosphere and endophytic bacteria with black pepper is therefore needed for formulating effective microbial-based strategies for plant growth and disease management in black pepper.

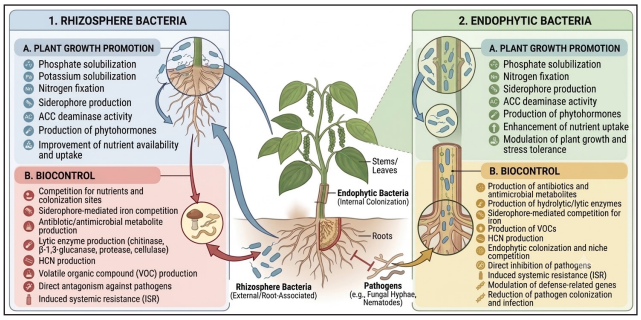


Figure 1: Plant growth-promoting and biocontrol mechanisms of rhizosphere and endophytic bacteria associated with black pepper

Diversity and Functional Roles of Endophytic Bacteria in Black Pepper

Endophytic bacteria internally colonize different tissues of black pepper including roots, stems, leaves and other aerial parts. The composition and functions of endophytic bacterial communities may vary between these compartments. Root endophytes closely interact with soil and rhizosphere bacterial populations, whereas bacteria residing in stems and leaves may represent a more selective community capable of surviving and multiplying within plant tissues. This tissue-specific distribution indicates that different plant compartments may provide distinct ecological niches for bacterial colonization.

Among numerous endophytic bacterial genera, *Bacillus* and *Pseudomonas* are considered as the predominant members because of their significant role in plant growth enhancement and biological control. Other genera such as *Rhizobium*, *Enterobacter*, *Serratia*, *Arthrobacter* spp., *Micrococcus* spp. and *Curtobacterium* have also been found to be important members of black pepper-associated endophytic bacterial communities. They independently or synergistically contribute to plant health through a range of plant growth-promoting (PGP) and antagonistic activities (Kollakkodan *et al.*, 2021; Ngo *et al*., 2020). Their plant growth-promoting traits include phosphorus and potassium solubilization, nitrogen fixation, phytohormone synthesize, siderophore production and enhanced nutrient acquisition. Furthermore, they act as biological control agents through the production of antimicrobial metabolites, volatile compounds and hydrolytic enzymes, as well as through competition for nutrients and colonization sites. Certain bacterial endophytes were found to induce systemic defense responses in the host and make the host resistant against invading pathogens. These activities benefit the host by suppressing destructive soil- and plant-associated pathogens, including *Phytophthora capsici* and *Fusarium* spp. Thus, the multifunctional role of black pepper-associated endophytic bacteria, combining nutrient mobilization, growth stimulation, pathogen antagonism and activation of plant defense, emphasizes their potential as microbial resources for reducing dependence on chemical inputs and developing integrated and sustainable disease-management strategies.

The major bacterial genera from black pepper, their sources or habitats, functional traits and potential target pathogens or problems are summarized in table 1.

Table 1: Plant growth-promoting and biocontrol activity of endophytic bacteria in black pepper

Bacterial group	Habitat/ Sources	Major function
Bacillus velezensis PCSE10	Stem	Stimulate plant growth and suppress *Phytophthora* foot rot.
Bacillus subtilis EBDC16, *Bacillus cereus* EBCS30	Root	Improve plant growth and synthesize antifungal compounds.
Rhizobium radiobacter PCRE10	Root	Biocontrol activity against *Phytophthora* foot rot.
Bacillus siamensis EB.CP6, *Bacillus velezensis* EB.KN12, *Bacillus methylotrophycus* EB.KN13	Root	Biocontrol activity against *Phytophthora* foot rot.
Priestia sp. T2.2, *Lysinibacillus* sp. C5.11	Root	Plant growth promotion and rooting of stem cuttings of black pepper.
Bacillus megaterium DS9	Root	Biocontrol activity against root-knot nematode *Meloidogyne* spp.

Beneficial Rhizosphere Bacteria in Black Pepper

The rhizosphere is known to occupy dynamic bacterial communities with multitude of functions. Rhizosphere bacterial communities are structured by soil properties, host genotype, environmental factors, cultivation practices and growth stage of the plant. Bacterial genera, *Pseudomonas*, *Bacillus* and *Burkholderia* associated with black pepper rhizosphere have been reported as promising bioagents for enhancing growth and biocontrol activity (Lau *et al*., 2020; Nysanth *et al*., 2022). The predominant bacterial groups associated with the black pepper rhizosphere and their functions are summarized in table 2.

Table 2: Plant growth promoting traits of black pepper-associated rhizosphere bacteria

Bacterial group	Major function
Pseudomonas spp. KBPf16	Nematicidal activity
Streptomyces spp. IISRBPAct1	Biocontrol activity against *Sclerotium rolfsii* and *Phytophthora capsici*
Bacillus sp., *Pseudomonas* sp., *Brevibacillus* sp., *Burkholderia* sp.	Inhibition of *Fusarium solani*
Streptomyces albulus, *Streptomyces albogriseus*	Growth promotion and biocontrol of soil-borne pathogens *viz*., *Sclerotium rolfsii* and *Phytophthora capsici*
Azospirillum sp.	Nitrogen fertilization and phosphate solubilisation

Compared with endophytic bacteria, rhizosphere bacteria interact more directly with the surrounding soil environment and roots, where they can actively colonize the root surface and respond to nutrients released through root exudation. The growth-promoting and antagonistic functions of rhizosphere bacteria are broadly comparable to those described for endophytic bacteria. Nevertheless, their close interaction with surrounding soil may offer further chance for nutrient cycling and suppression of soil-borne pathogens. The direct biocontrol activity of bacterial isolates from both niches against *Fusarium* spp., as demonstrated by dual-culture assays, is presented in figure 2.



Figure 2: Direct antagonism of endophytic and rhizosphere bacteria from black pepper against *Fusarium* spp. in a dual-culture plate assay: a) Control; b) *Bacillus* sp. obtained from the rhizosphere of black pepper; c) *Bacillus* sp. isolated from root of black pepper

Conclusion

Beneficial endophytic and rhizosphere bacteria represent promising biological tools for sustainable black pepper production. Their multiple plant growth-promoting traits, *viz*. nitrogen fixation, nutrient mobilization and phytohormone and siderophore production, can increase nutrient acquisition and plant growth, while antimicrobial activity, competition and induction of plant defense contribute to suppression of devastating plant pathogens such as *Phytophthora capsici* and *Fusarium* spp. Their role in improving plant growth through both direct and indirect mechanisms has gained considerable attention towards their use as bioinoculants in sustainable crop production. However, further information on ecological functions and molecular-level interactions is essential for understanding their potential applications in sustainable agriculture.

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