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Endophytic Bacteria from Vetiver as Emerging Biocontrol Agents against Banana Fusarium Wilt: A Review

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ABSTRACT

Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *cubense* (*Foc*), particularly Tropical Race 4 (*Foc*TR4), remains one of the most destructive diseases affecting global banana production. The susceptibility of Cavendish cultivars, including 'Grand Nain', and the long-term persistence of the pathogen in soil have rendered conventional control strategies largely ineffective. In response, increasing attention has been directed toward sustainable approaches such as biological control using plant-associated microorganisms. Among these, bacterial endophytes have emerged as promising candidates due to their ability to colonize internal plant tissues and confer protection against pathogens through multiple mechanisms. Vetiver (*Chrysopogon zizanioides*), a perennial grass known for its resilience to environmental stress and extensive root system, serves as a potential reservoir of functionally diverse microbial endophytes. This review synthesizes current knowledge on vetiver-associated bacterial endophytes and evaluates their potential as biocontrol agents against Fusarium wilt in banana. Key mechanisms discussed include the production of antimicrobial compounds, secretion of cell wall-degrading enzymes, induction of systemic resistance, competition for nutrients and ecological niches, and enhancement of plant growth and stress tolerance. Despite promising findings from related systems, direct evidence supporting the efficacy of vetiver-derived endophytes against *Foc* in banana remains limited, with most studies confined to In vitro or non-banana models. Critical challenges include inconsistent field performance, limited understanding of host–endophyte compatibility, and the absence of standardized evaluation protocols. Future research should focus on strain selection, molecular characterization, formulation development, and field validation to bridge the gap between laboratory findings and practical application. Harnessing vetiver-associated endophytes offers a novel and sustainable strategy for managing Fusarium wilt and improving the resilience of banana production systems.

Keywords: Vetiver grass; plant–microbe interactions; *Fusarium oxysporum* f. sp. *cubense*; Banana

INTRODUCTION

Banana (*Musa spp.*) is one of the most important fruit crops globally, serving as a staple food and a major source of income for millions of farmers in tropical and subtropical regions. However, its production is severely constrained by Fusarium wilt, also known as Panama disease, caused by *Fusarium oxysporum* f. sp. *cubense* (*Foc*). The emergence and rapid spread of the highly virulent Tropical Race 4 (*Foc*TR4) pose a significant threat to Cavendish cultivars, including 'Grand Nain', which dominate global export markets [14, 38]. The pathogen invades the plant through the roots, colonizes the vascular tissues, and leads to systemic wilting, ultimately resulting in plant death. Its ability to persist in soil for decades and its wide host adaptability make management extremely difficult [8, 38].

Currently, control strategies for Fusarium wilt are based on visual assessment for the early appearance of symptoms, removal of diseased plants, and strict quarantine measures to limit pathogen spread. Ongoing intensive research efforts have identified resistant somaclones and potential biocontrol agents, such as vesicular–arbuscular mycorrhizae (VAM), against this pathogen [22, 49]. Some farmers also use synthetic fungicides to manage banana diseases; however, the repeated application of these pesticides results in adverse effects, particularly toxicity to applicators and the environment [16, 33].

There has been increasing interest in the use of biological control agents (BCAs) for managing various plant diseases, including Fusarium wilt in banana, as a promising alternative to synthetic inputs. Biocontrol strategies involving the selection and application of endophytes have become an integral component of integrated disease management in several agricultural and horticultural crops [40]. Identifying and exploiting endophytic bacteria associated with disease resistance and susceptibility may provide a practical and sustainable strategy to enhance current management approaches.

Chrysopogon zizanioides, commonly known as vetiver grass, is widely used in phytoremediation efforts, including soil erosion control, slope stabilization, and the restoration of contaminated lands [9]. A study by Vu et al. successfully isolated sixteen bacterial endophytes from the roots of vetiver grass, suggesting its potential application in biofertilizer production for enhanced plant growth [54]. Similarly, Munakata et al. reported that 46% of endophytic bacterial isolates from vetiver roots exhibited significant inhibitory effects against *Fusarium graminearum*, a major pathogen of cereal crops [30]. However, despite the growing body of research on endophytes and biological control, there remains limited information on the application of vetiver-derived bacterial endophytes specifically for the management of Fusarium wilt in banana. This represents a critical knowledge gap, particularly in the context of developing sustainable and environmentally friendly strategies to combat *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 (*Foc*TR4).

Therefore, this review aims to synthesize current knowledge on root-associated bacterial endophytes of *Chrysopogon zizanioides* and evaluate their potential as biocontrol agents against Fusarium wilt in banana. Relevant literature was collected from databases including Scopus, Web of Science, and Google Scholar. Peer-reviewed articles published in English were included, with emphasis on studies related to disease management and plant–microbe interactions, while irrelevant and duplicate records were excluded. This review further highlights the mechanisms of action of endophytic bacteria, explores the role of vetiver as a reservoir of beneficial microbes, and identifies key research gaps and future directions for their application in sustainable banana production systems.

Biology of Fusarium Wilt in Banana

The pathogenic soil-dwelling fungus "*Fusarium oxysporum* f. sp. *cubense* Tropical Race 4" is recorded as the most prevalent disease attributed to the Fusarium wilt of banana [22]. This disease represents one of the earliest major global plant disease epidemics, having spread extensively during the first half of the twentieth century. The epidemic originated in Central America and led to the collapse of the susceptible 'Gros Michel' cultivar, which at that time dominated the global banana export trade before being replaced by Cavendish cultivars [50]. Approximately 10% of the land designated for export production in Mindanao is affected by Fusarium wilt, and the disease continues to spread with varying levels of severity [5].

Three races of *Fusarium oxysporum* f. sp. *cubense* (Foc) have been recognized based on their banana host range: *Foc* Race 1, Race 2, and Race 4. Race 4 is further subdivided into Tropical Race 4 (*Foc*TR4) and Subtropical Race 4 (*Foc*STR4), both of which are capable of infecting 'Cavendish' cultivars. Among these, *Foc*TR4 is considered the most virulent and destructive due to its broad host range. It can infect Cavendish bananas as well as cultivars susceptible to Races 1 and 2, and it exhibits greater tolerance to high-temperature conditions compared with other *Foc* races [10].

Foc is a common soil inhabitant that produces three types of asexual spores: macroconidia, microconidia, and chlamydospores. Macroconidia are formed from monophialides on branched conidiophores within sporodochia. They are typically four- to eight-celled, sickle-shaped, thin-walled, and delicate, with foot-shaped basal cells and attenuated apical cells (Figure 1a). Microconidia are one- or two-celled, renal to oval in shape, and produced on short monophialides (Figure 1b). In contrast, chlamydospores are thick-walled asexual spores formed singly or in pairs, and may also occur in clusters or short chains (Figure 1c). These structures are highly resistant to desiccation and other unfavorable environmental conditions, allowing the pathogen to survive in soil for extended periods, often for decades [15, 41].

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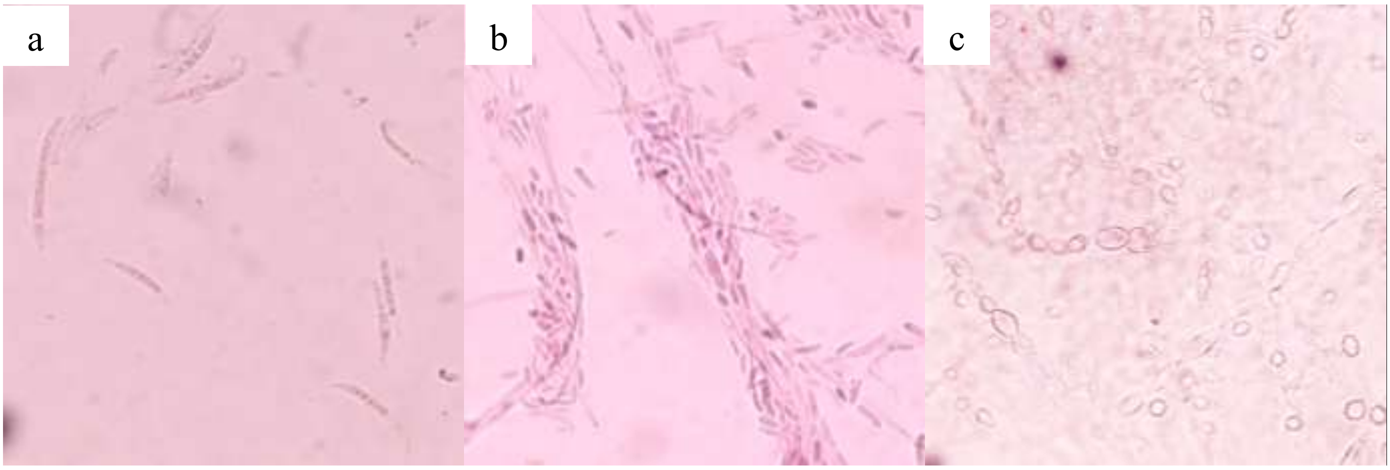

Figure 1. Morphological characteristics of *Foc*TR4: (a) macroconidia, (b) microconidia, and (c) chlamydospores.

Infection of banana by *Foc* is initiated through interactions with primary and secondary root exudates [57]. Following root penetration, the fungus produces microconidia and toxins that accumulate in the xylem and move upward within the plant, facilitating colonization of adjacent vessels [6]. This process leads to characteristic symptoms, including wilting, leaf yellowing, splitting and vascular discoloration of the pseudostem, ultimately resulting in plant death (Figure 2) [12]. Infected plants often die before fruit development, leading to significant yield losses in the field. In less severe cases, plants may exhibit stunted growth and reduced productivity [1, 25].

Figure 2. Field symptoms of banana Fusarium wilt: (a) leaf yellowing, (b) pseudostem splitting, and (c) vascular discoloration.

Endophytic Bacteria as Biocontrol Agents

Bacterial endophytes are microorganisms that play a role in colonizing plant tissues without causing harm and offer potential as biocontrol agents against plant pathogens [29]. These endophytic bacteria facilitate the plant growth and bolster disease resistance through its various mechanisms, such as the phytohormones production, induction of systemic resistance, and a secretion of microbial compounds that inhibit the growth of phytopathogens [3, 4]. Endophytic bacteria found in weeds, medicinal plants, and *Capsicum frutescens* represent a promising resource for investigating their antagonistic properties against *Foc* strains in banana plants. These endophytic bacteria have been found to produce antifungal compounds that inhibit the growth of *Foc*. *Alcaligens* sp., *Stenotrophomonas maltophilia*, and the *Bacillus subtilis* have been also reported to exert a strong inhibitory effect on the growth of *Foc* [39].

In the study of Xiang et al. suggested a possible endophytic bacterium in managing the Fusarium wilt in bananas. The EB1, *Bacillus velezensis* isolated from the banana plant was found to strongly antagonize against *Foc* isolates and induct disease resistance in the tissue-cultured plantlets [58]. Likewise, Xu et al. exhibit HQB-1, *Burkholderia* sp. obtained from banana soil rhizosphere, and showed a wide range antifungal property through its production of phenazine-1-carboxylic acid. VB7, *Bacillus amyloliquefaciens* also demonstrated the ability to suppress *Foc* growth [59], while enhancing the plant growth and stimulate the defense enzyme activity in banana plantlets in In vitro [53]. Nakkeeran et al. corroborates that these bacterial endophytes promotes the banana growth through the different mechanisms, including the solubilization of phosphate and indole acetic acid and siderophores production [31].

Moreover, the endophytic *Serratia marcescens* isolated from *Hevea brasiliensis* that was inoculated to the banana plants that led to an increase of chitinase and glucanase production, which essentially reduced the disease severity of *Foc* Race 4 by up to 79 percent in the nursery conditions and 70 percent in the field conditions [47]. Furthermore, *Burkholderia* sp. and *Herbaspirillum* sp., derived from pineapple roots and stem. These endophytes potentially fix atmospheric nitrogen into a consumable form by plants [56], and an *Acremonium* sp. that is isolated from *Kandelia candel* [26], have demonstrated a mechanism to promote plant growth and help the uptake of nutrient in banana plants.

Vetiver Grass as a Microbial Reservoir

Vetiver (*Chrysopogon zizanioides*) is widely recognized for its exceptional adaptability to diverse and often extreme environmental conditions, including drought, waterlogging, salinity, and heavy metal contamination. This resilience is largely attributed to its extensive and dense root system, which can penetrate deep into the soil profile and create a stable and nutrient-rich microenvironment that supports diverse microbial communities [13, 52]. The rhizosphere and internal root tissues of vetiver serve as ecological niches for a wide range of microorganisms, including bacteria and fungi with potential functional roles in plant growth promotion and stress tolerance.

The ability of vetiver to thrive in contaminated and degraded environments has made it a model plant in phytoremediation studies. Its roots are known to associate with microorganisms capable of degrading organic pollutants and tolerating high concentrations of heavy metals, suggesting the presence of highly adaptable and metabolically versatile microbial populations [13]. These conditions exert selective pressure that favors the enrichment of beneficial microbes, including endophytic bacteria with enhanced capabilities for survival, colonization, and production of bioactive compounds. Consequently, vetiver is considered a promising reservoir of functionally diverse endophytes that may be harnessed for agricultural applications.

Several studies have reported the isolation of bacterial endophytes from vetiver roots, including genera such as *Bacillus*, *Pseudomonas*, *Enterobacter*, and *Microbacterium*, which are commonly associated with plant growth promotion and biological control [7, 44]. These endophytes have demonstrated the ability to produce phytohormones, solubilize nutrients, and synthesize antimicrobial compounds that can inhibit plant pathogens. Moreover, their adaptation to stressful environments may enhance their persistence and efficacy when introduced into agricultural systems, particularly under field conditions where environmental variability often limits the performance of microbial inoculants.

In addition to their functional traits, vetiver-associated microbial communities are influenced by the plant's unique root architecture and exudation patterns, which provide carbon sources and signaling molecules that, facilitate microbial colonization and interaction. The dense fibrous root network increases the surface area available for microbial attachment, while root exudates selectively recruit beneficial microorganisms that contribute to plant health and soil stability [19]. These interactions highlight the role of vetiver not only as a passive host but also as an active mediator in shaping its associated microbiome.

Vetiver-Derived Endophytes for Disease Supression

The ability of vetiver to thrive under diverse environmental stresses suggests that its associated microbiota possess adaptive traits that may be advantageous for agricultural use, particularly in the suppression of soil-borne pathogens. Among these, bacterial endophytes isolated from vetiver roots have demonstrated notable antimicrobial activity, indicating their potential as biological control agents (see Table 1).

Table 1. Vetiver-associated microbial endophytes and their reported functional roles

Microbial Genus	**Source (Vetiver Tissue)**	**Functional Traits**	**Reported Target/Effect**	**Mechanism of Action**	**References**
Bacillus spp.	Root endophytes	Antifungal activity, enzyme production, ISR induction	Inhibition of soil-borne fungi (*Fusarium*, *Rhizoctonia*)	Lipopeptides (iturin, surfactin), chitinase, ISR	Compant et al. [11]; Bharti et al. [7]
Pseudomonas spp.	Root/rhizosphere-associated	Antibiotic production, siderophore production	Suppression of fungal pathogens	Phenazines, siderophores, niche competition	Kloepper et al. [24]
Enterobacter spp.	Root endophytes	Plant growth promotion, nutrient solubilization	Enhanced plant vigor, indirect disease suppression	IAA production, phosphate solubilization	Lodewyckx et al. [27]
Microbacterium spp.	Root tissues	Stress tolerance, plant growth support	Improved plant resilience under stress	Nutrient cycling, metabolic support	Hardoim et al. [19]
Streptomyces spp.	Root-associated microbes	Strong antifungal metabolite production	Broad-spectrum pathogen inhibition	Antibiotics, volatile compounds	Compant et al. [11]
Mixed consortia (endophytes)	Root microbiome	Synergistic interactions	Enhanced suppression of pathogens	Multi-mechanistic (ISR + antibiosis + competition)	Ryan et al. [43]

A recent study by Vu et al. identified sixteen bacterial endophytes recovered from the root tissues of vetiver grass, *Chrysopogon zizanioides*. The results indicated that through phenotypic analyses and 16S rRNA gene sequencing, the bacterial strains were identified as four bacterial species, including *Klebsiella variicola* B1, *Enterobacter cloacae* B4, *Enterobacter cloacae* B6, and *Enterobacter asburiae* B11. On the other hand, a phytase and phosphatase, which degrade phytate and phosphate, respectively, were produced by the *K. variicola* B1 and *E. cloacae* B4 strains. *Enterobacter asburiae* B11, also isolated from the roots, reported to produce a more indole acetic acid (IAA), which is potentially a plant growth regulator (PGR). This phytohormone (IAA) in the auxin class, providing an important role in tissue-culture banana, which promotes and enhanced the cell division, elongation, and differentiation of the plants during *In vitro* micropropagation [54]. Ho et al. isolated a bacterium *Burkholderia cenocepacia* strain, which was obtained from the roots of *C. zizanioides* and demonstrated efficacy against *Foc* isolates. Co-cultivation of banana tissue-culture plantlets with this strain resulted in a reduction of up to 86% in the occurrence of Fusarium wilt in the field settings. Hence, the non-indigenous bacterial endophytes also inhibit the growth of pathogenic *Foc* isolates in bananas by inducing an immune response [21].

Munakata et al. stated that the vetiver grass is promoted by its robust root system, mitigating the pollution of dioxin at Bien Hoa airbase, which decreases the amounts of toxic compounds in the contaminated soil [30]. Furthermore, Ahluwalia et al. studied the endophytic bacteria that live in the roots of plants having a significant contribution to the enhancement and development of the plant host. In addition, these microorganisms colonize the plant endophytically and elevate their tolerance to high salinity and drought stress. This may facilitate the nutrient absorption and synthesis of biostimulants in the plant development [2].

Mechanisms of Action against Fusarium Wilt Direct Antagonism through Antimicrobial Compounds

One of the primary mechanisms by which endophytic bacteria suppress *Fusarium* spp. is through the production of antimicrobial metabolites. Genera such as *Bacillus* and *Pseudomonas*, commonly isolated from plant tissues, are known to produce a wide array of bioactive compounds including lipopeptides (e.g., iturin, surfactin, fengycin), phenazines, and other antibiotics that inhibit fungal growth [18, 34]. These compounds disrupt fungal cell membranes, interfere with cellular metabolism, and inhibit spore germination [55]. In addition, some endophytes produce volatile organic compounds (VOCs) that can suppress pathogen growth even without direct contact [45], Yang et al. identified specific VOCs from endophytic fungi *Sarocladium brachiariae* that damaged plasma membranes of *F. oxysporum f. sp. cubense* and disrupted fusaric acid production [60]. Such direct antagonistic interactions are particularly important in limiting the early stages of *Fusarium* infection in the root zone.

Production of Cell Wall-Degrading Enzymes

Endophytic bacteria can also inhibit fungal pathogens through the secretion of extracellular enzymes that degrade structural components of fungal cell walls. Enzymes such as chitinases, β-1,3-glucanases, and proteases target chitin and glucans, which are essential components of fungal cell walls, leading to cell lysis and reduced pathogen viability [11]. Rumandani et al. confirms that endophytic *Bacillus* spp. (including *B. subtilis*, *B. mojavensis*, and *B. velezensis*) produce hydrolytic enzymes — glucanase, cellulase, and chitinase — that inhibit *Foc* growth and induce systemic resistance in plants [42]. This enzymatic activity enhances the biocontrol potential of endophytes and complements the action of antimicrobial metabolites. The combined effect of enzymatic degradation and antibiosis contributes to a stronger and more sustained suppression of *Fusarium* spp.

Induced Systemic Resistance (ISR) in Host Plants

In addition to direct inhibition, endophytic bacteria can enhance the plant's own defense mechanisms through induced systemic resistance (ISR). ISR is a physiological state in which the plant's defense pathways are primed, allowing for a faster and stronger response upon pathogen attack [24, 37]. Nguyen et al. directly demonstrated that both *Bacillus subtilis* PTA-271 and *Pseudomonas fluorescens* PTA-CT2 prime JA and ET signaling pathways in Arabidopsis, with ISR relying on enhanced expression of SA, JA, and ET marker genes upon pathogen challenge [32]. Kloepper et al. also confirmed that ISR elicited by several *Bacillus* strains is dependent on jasmonic acid, ethylene, and the regulatory gene NPR1 [24]. In banana, the endophytic *Bacillus subtilis* TR21 upregulated the jasmonate and brassinosteroid biosynthesis pathways in banana root tissues and improved resistance to *Foc*, thereby reducing disease severity and delaying symptom development [46].

Competition for Nutrients and Ecological Niches

Another important mechanism is the competition between endophytes and pathogens for nutrients and colonization sites within the plant. Efficient colonization of root tissues by beneficial endophytes can limit the availability of space and resources required for pathogen establishment. Mon et al. covers antagonistic mechanisms of rhizosphere microbes and endophytes against *Foc* in banana, including colonization competition among *Bacillus*, *Trichoderma*, and *Pseudomonas* species [28]. Thangavelu & Gopi demonstrated this in the field with combinations of endophytic and rhizospheric bacteria completely suppressed Fusarium wilt in banana 'Grand Nain', with the antagonists colonizing roots, corms, pseudostems, and petioles within 15 days — effectively occupying the niche before *Foc* could establish [48].

Enhancement of Plant Growth and Stress Tolerance

Endophytic bacteria can indirectly reduce disease impact by promoting plant growth and improving stress tolerance. Many endophytes produce phytohormones such as indole-3-acetic acid (IAA), solubilize phosphate,

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and enhance nutrient uptake, resulting in more vigorous plants that are better able to withstand pathogen attack [19]. Ting et al. demonstrated that endophytic isolates, particularly *Serratia* UPM39B3, promote growth and enhance tolerance to Fusarium wilt in banana plantlets. Inoculated plants, even when infected, showed significantly greater height, pseudostem diameter, root mass, and leaf number compared with untreated controls. These findings highlight the dual role of specific endophytes as both growth promoters and disease-tolerance agents, offering a promising strategy for managing Fusarium wilt through improved vegetative vigor [51].

Root Colonization and Barrier Formation

Effective root colonization by endophytic bacteria can act as a physical and biological barrier against pathogen entry. By occupying infection sites and forming stable populations within root tissues, endophytes can hinder the penetration and spread of *Fusarium* into the vascular system. Pan et al. used scanning and transmission electron microscopy to show that endophytic *Burkholderia cepacia* colonized the intercellular spaces of banana root tissues and simultaneously colonized the surface of *F. oxysporum* f. sp. *cubense* Race 4 hyphae, causing mycelial deformation [35]. Paparu et al. provided the first in situ quantification of endophyte colonization in banana, showing nonpathogenic *Foc* colonized roots (56%) and rhizomes (93%), with hyphae predominantly in the hypodermis but crucially not in vascular tissues — occupying precisely the outer layers through which *Foc* must pass to reach the vasculature [36]. He et al. used fluorescent-labeled *Bacillus* strains and confocal microscopy to confirm that *B. subtilis*, *B. velezensis*, and *B. amyloliquefaciens* colonize internal cells of banana roots and exhibit chemotaxis toward *Foc*TR4 hyphae within the plant, suggesting active seeking and engagement with the pathogen at infection sites. This barrier effect is particularly important for soil-borne pathogens like *Foc*, which rely on root entry to initiate infection [20].

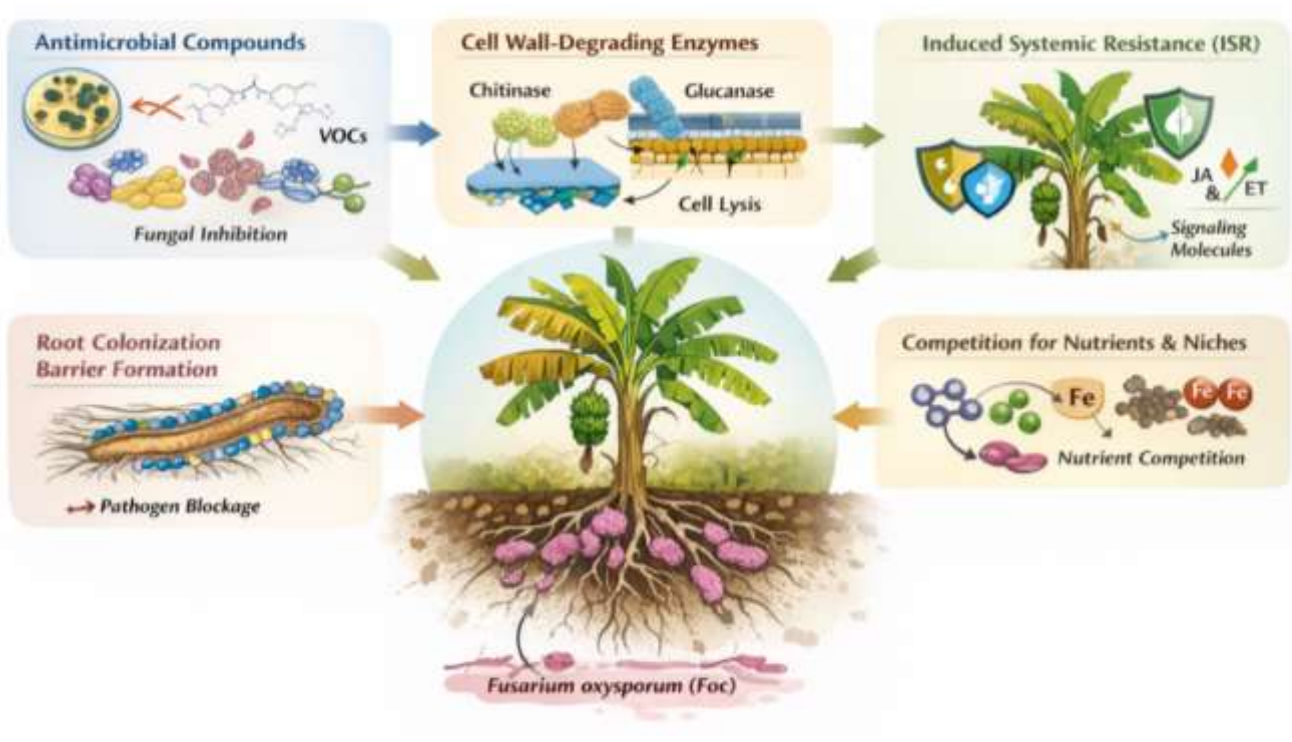

Figure 3. Diagram summarizing the mechanism of action.

Challenges and Research Gaps

Despite the increasing recognition of bacterial endophytes as promising biocontrol agents, the application of vetiver (*Chrysopogon zizanioides*)-derived endophytes for the management of Fusarium wilt in banana remains insufficiently explored. A major limitation is the lack of direct evidence linking vetiver-associated endophytes to the suppression of *Fusarium oxysporum* f. sp. *cubense* (*Foc*), particularly under greenhouse and field conditions. Most existing studies are limited to In vitro assays or involve different host–pathogen systems, which may not accurately reflect the complexity of the banana–*Foc* pathosystem. This gap underscores the need for comprehensive In vivo and field-based evaluations.

Another significant challenge is the inconsistent performance of microbial inoculants under field conditions. Environmental factors such as soil type, climate variability, and interactions with native microbial communities can influence the survival, colonization, and efficacy of introduced endophytes. Strains that exhibit strong antagonistic activity in controlled environments often fail to maintain their effectiveness in the field, highlighting the need for selecting robust and adaptable isolates.

The limited understanding of host–endophyte compatibility also constrains practical application. Endophytes isolated from vetiver may not readily colonize or persist within banana tissues, and their functional expression may vary depending on the host plant. Studies addressing cross-host colonization, persistence, and functional stability of vetiver-derived endophytes in banana are still lacking and represent a critical research need. In addition, there is a lack of standardized methodologies for isolation, screening, and evaluation of endophytes, which makes it difficult to compare results across studies and identify the most effective strains. Harmonized protocols that integrate laboratory screening, greenhouse validation, and field trials are essential for advancing research and ensuring reproducibility.

From a practical perspective, the development of stable formulations and efficient delivery systems remains a major challenge. Issues related to shelf life, carrier materials, and application methods (e.g., root inoculation, soil drenching, or nursery-stage application) must be optimized to ensure consistent field performance. Furthermore, scaling up production while maintaining microbial viability and efficacy is necessary for commercialization.

CONCLUSION AND RESEARCH PROSPECTS

Vetiver (*Chrysopogon zizanioides*)-associated bacterial endophytes represent a promising and underexplored resource for the biological control of Fusarium wilt in banana. Their demonstrated functional traits—including antimicrobial activity, production of cell wall-degrading enzymes, induction of systemic resistance, and enhancement of plant growth—highlight their potential as multifunctional agents in sustainable disease management. These attributes are particularly relevant in addressing the persistent challenge posed by *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 (*Foc*TR4), a pathogen that is difficult to control using conventional approaches.

However, despite strong theoretical and experimental support from related systems, the application of vetiver-derived endophytes in the banana–*Fusarium* pathosystem remains limited. Current evidence is largely based on In vitro studies or indirect findings, with insufficient validation under greenhouse and field conditions. Bridging this gap is essential to establish their practical efficacy and reliability. Future research should prioritize the isolation and characterization of highly effective strains, followed by rigorous In vivo and field evaluations to confirm their performance under diverse environmental conditions.

In addition, advancing the application of vetiver-derived endophytes will require a deeper understanding of host–microbe interactions, particularly their ability to colonize and persist within banana tissues. The integration of molecular tools such as metagenomics, transcriptomics, and genome-based functional analyses will be critical in elucidating the mechanisms underlying their biocontrol activity and in identifying key traits associated with effective disease suppression. These approaches may also facilitate the design of microbial consortia with complementary functions, thereby enhancing overall efficacy.

From a practical standpoint, efforts should be directed toward the development of stable formulations and efficient delivery systems suitable for field application. Optimization of inoculation strategies—such as nursery-stage application, root dipping, or soil drenching—will be essential to maximize colonization and long-term effectiveness. Furthermore, alignment with regulatory frameworks and generation of robust efficacy data will be necessary to support the registration and commercialization of these biological agents.

Vetiver-derived bacterial endophytes hold significant potential as components of integrated disease management strategies for Fusarium wilt in banana. Their successful deployment will depend on a multidisciplinary approach that combines microbiology, plant pathology, molecular biology, and agronomy. By bridging fundamental research with applied innovations, these endophytes could contribute to the development of resilient, environmentally sustainable banana production systems in the face of evolving disease pressures.

Data Availability

The data supporting this study are derived from previously published literature, reports, and publicly accessible sources cited throughout the manuscript. All relevant information can be accessed through the references provided, ensuring transparency and enabling readers to verify and further explore the sources used in this study.

Ethical Approval

This study is a review of existing literature and did not involve any direct experimentation on human participants or animals; therefore, ethical approval was not required.

Conflict of Interest

The authors declare no conflicts of interest related to this study.

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