

ENDOPHYTIC MICROBIOME-MEDIATED STRATEGIES FOR SUSTAINABLE MANAGEMENT OF PLANT VIRAL DISEASES

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ABSTRACT

Plant viruses pose a serious threat to global crop production and food security; however, effective and durable management strategies to mitigating viral diseases remain limited. Rapid viral evolution, reservoir hosts, mixed infections, and climate change further complicate their management. Conventional strategies such as vector management and the development of resistant cultivars often provide incomplete and short-term protection. Endophytes, including bacteria, fungi, actinomycetes, and arbuscular mycorrhizal fungi that reside asymptotically within plant tissues are increasingly recognized as sustainable biocontrol agents against plant viral diseases. These microorganisms enhance host defence by inducing systematic resistance through priming salicylic acid, jasmonic acid, and ethylene signalling pathways, thereby promoting the accumulation of pathogenesis-related proteins and modulating antioxidant systems. In addition, several endophytes produce antiviral metabolites, including ribonucleases and other bioactive compounds, that directly interfere with viral replication, limit insect vector feeding and transmission, and reduce symptom development. Recent advances in symbiont-mediated RNA interference (SMR) using engineered endophytes to deliver double-stranded RNA (dsRNA) further expand the potential of endophytes for durable and systemic viral suppression. This review expands our current understanding of the direct and indirect mechanisms of endophyte-mediated viral inhibition and highlights future prospects for endophyte-based bioformulations and their integration into effective viral disease management strategies.

KEYWORDS: Plant virus, Endophytes, SMR, Induced systemic resistance, Integrated plant viral management

INTRODUCTION

Plant viruses are among the most significant biological constraints to agricultural productivity, causing substantial yield losses and threatening global food security.¹ more than 25 families of plant viruses affect crop production, with RNA viruses accounting for nearly 80% of these pathogens.² Their ability to mutate rapidly allows them to adapt and evolve rapidly, making disease management more challenging. This genetic plasticity enables frequent host-range expansion and the breakdown of resistance in cultivated varieties.³ Management of viral diseases remains difficult due to their mesobiotic nature and they cannot be controlled using conventional biopesticides.⁴ Current control strategies rely largely on prophylactic measures such as the use of virus-free planting material, resistant varieties/cultivars and management of the insect vectors.⁵ However, excessive dependence on insecticides is unsustainable due to environmental risks, development of resistance in vectors, and rapid vector population growth.³ In addition, host resistance is frequently overcome by emerging and evolving viral strains. This highlights the need for durable and sustainable alternatives for plant virus management.

Endophytes have emerged as a promising yet underexplored biological tool for plant virus management.⁶ The earliest definition of an endophyte was given by De Bary in 1866: “any organisms residing inside plant tissue, unlike epiphytes that are surface-associated”. Fig. 1 provides an overview of microorganisms that reside asymptotically within plant tissues, including diverse bacterial, fungal, and actinomycete communities that establish mutualistic interactions with their hosts. These organisms are widely recognized for their roles in plant growth promotion, stress tolerance, and improving plant health.⁷ Recent studies indicate that endophytes can protect plants against viral pathogens through multiple mechanisms, including the induction of systemic resistance, production of antiviral metabolites, and modulation of defence pathways.⁴ They usually have mutualistic interactions in which they receive nutrients and shelter

from the plant and provide defence benefits to the host. Their ability to colonise internal plant tissues and prolonged systemic protection makes endophytes a compelling component of sustainable plant disease management strategies.⁸ Endophytes shape plant-virus dynamics through two routes. Indirectly, they prime the plant's own defence responses, thereby enhancing resistance or tolerance. Directly, they suppress viral replication through the production of antiviral metabolites. Some endophytes also reduce virus spread by affecting insect vectors or by competitively displacing other microbes that exacerbate viral infections. A dedicated section highlights physiological and molecular insights such as gene expression, hormone signalling, and metabolomic changes that underpin these interactions. Recent field experiments have further demonstrated the potential of fungal endophytes for virus management. In tomato, seed treatment with the endophytic fungi *Hypocrea lixii* F3ST1 and *Trichoderma asperellum* M2RT4 was evaluated against whitefly-mediated transmission of tomato infectious chlorosis virus (TICV) and tomato chlorosis virus (ToCV) under field conditions. The study showed that endophyte application influenced the whitefly vector and reduced virus transmission, demonstrating that endophytic fungi can contribute to viral disease suppression through both plant-associated and vector-mediated mechanisms.⁹ Finally, we address practical considerations for applying endophytes in the field, current constraints and knowledge gaps, and outline future perspectives such as synthetic endophyte consortia and genome-guided selection to improve antiviral efficacy. We sought to emphasize endophyte-mediated attenuation of viral infection and their underlying mechanism and the prospects of endophytes of sustainable plant-virus management.

Endophytes: Diversity and functional roles

Definition and classification

Endophytes are a diverse group of microorganisms that reside within plant tissues without causing visible disease symptoms. These organisms encompass a wide range of life forms, including bacteria, fungi, actinomycetes, yeasts, and, in some cases, latent viruses. First described by De Bary, they exhibit considerable taxonomic, functional, and ecological diversity, ranging from mutualistic to commensal associations depending on host genotype and environmental conditions.¹⁰ Fungal endophytes, mainly from Ascomycota and Basidiomycota, are estimated to comprise over a million species. They are commonly classified into clavicipitaceous (C-group) and non-clavicipitaceous (NC-group) endophytes.^{11,12} Distinguishing endophytes from endosphere, rhizosphere microorganisms, epiphytes, plant growth-promoting rhizobacteria (PGPR), and arbuscular mycorrhizal fungi (AMF) is important, as these terms describe different microbial lifestyles, habitats, or functional groups. The endosphere refers to the internal plant compartment inhabited by microorganisms, whereas the rhizosphere is the soil region directly influenced by plant roots and supports diverse root-associated microbial communities. In contrast, epiphytes colonize external plant surfaces without necessarily entering plant tissues. PGPR represent a functional group of beneficial rhizosphere-associated bacteria that promote plant growth through mechanisms such as nutrient mobilization, phytohormone production, siderophore synthesis, and pathogen suppression.^{13,14} AMF constitute a distinct group of beneficial soil fungi that establish symbiotic associations with plant roots and enhance nutrient acquisition and plant tolerance to biotic and abiotic stresses.¹⁵ Endophytic bacteria, including genera such as *Bacillus*, *Pseudomonas*, *Azotobacter*, *Streptomyces*, *Serratia*, and *Rhizobium*, are commonly derived from the rhizosphere and play significant roles as plant growth-promoting and biocontrol agents. Among these, *Streptomyces* spp. is particularly distinguished by their ability to synthesize a wide range of secondary metabolites exhibiting strong antimicrobial and antiviral activities.¹⁶

Colonization patterns and host specificity

Endophytes enter plants through root hairs, lateral root cracks, stomata, hydathodes, and wounds.¹² Bacterial endophytes typically colonize the roots and spread through the vascular system, while fungal endophytes enter through the epidermis or natural openings and often inhabit the apoplast. Their establishment and persistence are influenced by host genotype, developmental stage, environmental conditions, and the resident microbiome. Successful colonization requires modulation of plant immune response and competition for nutrients and space. Some endophytes are vertically transmitted through seeds, whereas others are horizontally acquired each generation.¹⁷

Ecological and evolutionary significance

Endophytes contribute significantly to plant health, ecological balance, and adaptive capacity by increasing tolerance to abiotic stresses, defending plants against pathogens and herbivores, and facilitating improved nutrient uptake. Some associations are obligate, such as grass-*Epichloe* symbioses, while others are more flexible.¹⁸ Endophytes can also enhance nitrogen fixation and phosphate uptake.¹⁶

Plants and their microbiomes are increasingly viewed as co-evolved holobionts, with endophytes expanding plant functional capabilities beyond those encoded by the plant genome.¹⁹ These functions make endophytes integral to plant defence, including defence against viral pathogens. They may also reduce insect vector attraction, indirectly influencing virus transmission dynamics.¹⁶

Plant viral diseases: challenges in sustainable management

Managing plant viral diseases is particularly difficult because of the unique nature of viruses, their intricate relationships with host plants and transmission vectors, their rapid mutation rates, and the influence of environmental factors. In contrast to other plant pathogens, viruses cannot be effectively controlled using standard chemical treatments, making it essential to rely on integrated and preventive management approaches.

Plant viral biology and epidemiology

Plant viruses are obligate intracellular parasites that depend entirely on host cellular machinery for replication. They enter plants through wounds or vectors such as insects and nematodes.²⁰ After uncoating, RNA viruses replicate in the

cytoplasm, whereas DNA viruses “such as geminiviruses and caulimoviruses” enter the nucleus and utilize host DNA polymerase for transcription and replication.²¹ Viruses spread locally through plasmodesmata using movement proteins that facilitate cell-to-cell transport and subsequently move systemically through the phloem.²² This infection cycle causes symptoms such as mosaic, chlorosis, stunting, and necrosis. Plant viruses can spread rapidly through vector populations, with aphids transmitting luteoviruses and whiteflies transmitting many geminiviruses.²³ Their broad host range further complicates disease management and eradication.

A Tri-trophic (virus-vector-host) Interaction

The majority of plant viruses rely on arthropod vectors such as insects, mites, and nematodes, as well as fungi for transmission. Aphids, whiteflies, leafhoppers, thrips, and beetles collectively transmit the most economically important plant viruses.²⁴ Depending on the virus-vector relationship, transmission may be non-persistent (briefly carried on the mouthparts), persistent circulative (virus circulates within the vector’s body), or propagative (virus replicates within the vector). Transmission efficiency is strongly influenced by vector feeding behaviour, population density, and the availability of alternative hosts. Environmental factors can enhance vector survival and reproduction, and mild winters or elevated temperatures increase viral spread.²⁵

Although insecticide-based vector control has been widely adopted, it is often ineffective for managing viral diseases due to the rapidity of virus transmission and the emergence of insecticide resistance. Moreover, vector-associated endosymbionts “such as *Wolbachia* in whiteflies” and microbial pathogens of insects can influence vector competence, implying both challenges and opportunities for disease management.²⁶ Disruption of any component of the virus-vector-plant tripartite interaction, such as reducing of vector fitness or making plants less attractive for feeding, significantly limits virus spread.

Environmental and ecological factors

Environmental conditions play a pivotal role in plant virus disease dynamics. Climate change and global warming are expected to exacerbate viral disease outbreaks.²⁷ Elevated temperatures accelerate virus replication within plants and also destabilize plant RNA-silencing defences.²⁸ Warmer climates and milder winters further expand the geographical range and overwintering survival of many insect vectors.²⁹ For example, an increase of just a few degrees can enable multiple additional virus generations or vector life cycles per season. Water stress (drought or salinity) can similarly increase plant susceptibility to viral infection by weakening overall plant health and interfering with defence signalling.^{30,31} On the other hand, high humidity or heavy rainfall may reduce the activity of some insect vectors.

Mechanisms of endophyte-mediated viral suppression

Endophytes employ several mechanisms to defend plants against viruses, which can be broadly categorized into direct and indirect antiviral actions. Often, a single endophyte may confer protection through multiple modes of action. Key mechanisms include the induction of plant defence responses, direct production of antiviral compounds (RNA interference triggers), modulation of virus vector, and microbial competition or niche exclusion.

Induction of plant defence responses

One of the primary mechanisms is the protection of plants by stimulating their own immune systems. Many endophytes trigger induced systemic resistance (ISR) or systemic acquired resistance (SAR) pathways thereby priming the plant for enhanced defensive capacity. Upon colonization, endophytes are perceived by the plant in a manner akin to a weak pathogen attack, which resulting in a heightened state of alert without disease. This phenomenon leads to faster and stronger responses upon actual pathogen invasion.³² Characteristic outcomes of ISR/SAR against viruses include accumulation of pathogenesis-related (PR) proteins, defensive enzymes such as peroxidases, β -1,3-glucanases, chitinases, and high levels of phenolic compounds in plant tissues.³³ For example, *Enterobacter asburiae* and other *Pseudomonas* spp. endophytes have been shown to confer resistance to tomato viruses by inhibiting the occurrence of disease by over 50% through ISR-associated processes.³⁴ Induced resistance is frequently associated with the mobilization of the salicylic acid (SA) or jasmonic acid/ethylene signalling pathways that are well-known to combat viruses. *Bacillus* endophytes, are well-reported ISR elicitors, while plant treatment with some *Bacillus* strains that increases SA levels and PR proteins, resulting in low viral titres. The interaction between these pathways is not strictly linear; rather, SA, JA, and ET can exhibit synergistic or antagonistic effects depending on the pathogen, microbial elicitor, and host genotype. Several *Bacillus* strains have been reported to elicit systemic resistance against fungal, bacterial, and viral pathogens, suggesting that *Bacillus*-mediated resistance may involve coordinated activation of multiple hormone-dependent defence pathways. Thus, *Bacillus* endophytes may contribute to antiviral defence by priming the plant immune system and enhancing defence-related responses, including pathogenesis-related (PR) proteins and other downstream defence mechanisms.³⁵ *Bacillus subtilis* is able to regulate the hormonal balance, and even the activity of ribonuclease in tomato and promote the development of resistance to Potato virus X and Y.³⁶ Similarly, endophytic *Cladosporium* sp. fungi induce resistance by activating SA accumulation, reactive oxygen species (ROS) production, and RNA-silencing genes, thereby reducing the production of tobacco mosaic virus (TMV).³⁷ *Bacillus cereus* AR 156 primes SA pathways in papaya against papaya ringspot virus, by subtly tuning JA levels and indicating possible hormonal crosstalk for enhanced resistance. This fine-tuning by endophytes leads to a more balanced defence response that is effective against viruses without causing excessive self-damage to the host. However, the application of engineered endophytes remains constrained by several practical and biosafety challenges, and their current use should therefore be considered an emerging rather than fully established technology. Stable and predictable colonization of engineered strains within plant tissues is difficult because host genotype, native microbial communities

and environmental conditions can strongly influence microbial persistence and activity. Recent studies emphasize that colonization stability, host compatibility and reproducibility under field conditions remain important requirements before engineered endophytes can be reliably deployed at agricultural scale. In addition, although engineered endophytes can serve as vehicles for RNA-based technologies, efficient production, transfer and delivery of functional double-stranded RNA (dsRNA) to the intended target remain technically challenging. For example, recent work demonstrated that an engineered endophytic *Fusarium babinda* could produce double standard (dsRNA) and suppress target genes in the pine wood nematode, illustrating the feasibility of the approach but also its dependence on successful dsRNA production and uptake by the target organism. Furthermore, specificity and potential off-target effects require careful assessment because engineered microbial signals or RNA molecules may interact with non-target organisms, and unintended changes in plant or soil microbiomes therefore represent important biosafety considerations. Regulatory uncertainty is another major barrier, as existing frameworks for genetically engineered microorganisms may not adequately address the environmental release of living engineered microbes, resulting in substantial differences in regulatory requirements among countries. Consequently, future development should prioritize stable colonization, controlled and target-specific delivery, genetic containment, environmental stability, non-target effects, and rigorous biosafety and regulatory evaluation through greenhouse and multi-location field studies rather than relying solely on laboratory demonstrations.^{38,39,40,41}

Direct antiviral activity

Beyond inducing host defence responses, some endophytes exhibit direct antiviral activity by producing compounds or enzymes that inactivate viruses or interfere with their life cycle.

Antiviral metabolites and enzymes

Some endophytes produce antiviral metabolites that can directly inactivate viruses or inhibit their replication. This mechanism is particularly observed among actinomycete endophytes, and these soil-derived bacteria (e.g., *Streptomyces* spp.) are prolific producers of antibiotics and enzymes. Some strains of *Streptomyces* have been used as antiviral agents against tobamoviruses, including *Streptomyces* spp., that produce an antiviral, which are capable of inhibiting the infection of tobacco plants by Tobacco mosaic virus (TMV).^{42,43} Similarly, *Streptomyces* have been proven to reduce the number of lesions caused by TMV on *Nicotiana* spp. and Potato virus Y on *Chenopodium* spp by preventing infection by viruses.⁴⁴ The marine-based actinomycete endophyte-derived metabolites suppressed the infectivity of Cucumber mosaic virus (CMV) in assay plants.⁴⁵ Also, endophytic *Bacillus* species release ribonucleases and other lytic enzymes into the plant apoplast that degrade the viral RNA directly.⁴⁶ A ribonuclease from an endophytic *Bacillus pumilus* exhibited antiviral activity against a range of plant RNA viruses in vitro.⁴⁷

Endophytic microbial consortia: a promising route towards synergistic antiviral protection

Most studies on the biological management of plant viral diseases have evaluated individual beneficial microorganisms, particularly bacterial or fungal endophytes, as inoculants. These studies demonstrate that endophytes can suppress viral infection through multiple mechanisms, including induction of systemic resistance, modulation of defence-related signalling, production of antiviral metabolites, enhancement of antioxidant defence, and interference with virus-vector interactions. For example, endophytic *Bacillus* spp. have been demonstrated to reduce groundnut bud necrosis virus (GBNV) incidence and virul titre in cowpea and tomato, highlighting the potential of individual bacterial endophytes as antiviral agents.⁴⁸ Similarly, fungal endophytes can reduce viral disease by activating plant defence responses or indirectly limiting vector-mediated transmission. Colonization of plants by *Neotyphodium uncinatum*, for instance, was associated with reduced barley yellow dwarf virus infection, whereas *Beauveria bassiana* strains protected against zucchini yellow mosaic virus.^{4,49} These findings establish the effectiveness of individual endophytes but also provide a basis for exploring whether combinations of individual endophytes but also provide a basis for exploring whether combinations of functionally complementary microorganisms can provide greater and more stable protection.

Microbial consortia represent a shift from single-strain inoculation toward the deliberate assembly of multiple microorganisms with complementary ecological and functional traits. The rationale is that different consortium members may occupy distinct niches, utilize different resources, produce different bioactive metabolites, and activate complementary plant defence pathways. Such interactions can potentially increase colonization, persistence, functional diversity, and the stability of disease suppression compared with individual inoculants.^{50,51} In plant protection, multi-strain consortia have been reported to provide stronger or more consistent disease suppression than individual microorganisms in some pathosystems. The enhanced performance may arise from complementary modes of action, stimulation of plant defence, improved microbial establishment, enhanced production of antimicrobial compounds, or facilitation of growth among consortium members.^{50,51}

However, improved performance of a consortium relative to an untreated control should not automatically be interpreted as evidence of synergism. Synergism implies that the combined effect is greater than the effect expected from the individual components acting independently. Therefore, meaningful evaluation of an endophytic consortium should include comparisons among each strain, the combined consortium, and an appropriate uninoculated control. Where possible, quantitative measurements such as virus incidence, disease severity, viral titre, plant growth, and defence-marker expression should be used to determine whether the combined treatment produces an additive, synergistic, neutral, and antagonistic interaction. This distinction is particularly important because interactions between microbial members can also be competitive, and the inclusion of additional strains does not necessarily result in improved biological control.^{50,51}

The potential relevance of consortia to plant viral disease management is particularly important because individual endophytes may act at different stages of the plant-virus interaction. A bacterial endophyte may primarily prime systemic defence or alter hormone-mediated signalling, whereas a fungal endophyte may contribute antiviral secondary metabolites, enhance host resistance, or interfere with insect vectors. For example, endophytic fungi have been associated with antiviral effects through defence activation and production of bioactive metabolites, while endophytic bacteria such as *Bacillus* spp. can induce systemic resistance and reduce virus accumulation.^{48,49,52} Combining functionally distinct endophytes could therefore theoretically provide multi-layered protection by simultaneously strengthening host defence, restricting virus multiplication, and reducing vector-mediated transmission. Nevertheless, this hypothesis requires direct experimental validation rather than inference from the performance of individual inoculants.

An important research gap is therefore the limited number of studies directly comparing individual endophytic inoculants with bacterial-bacterial, fungal-fungal, or bacterial-fungal consortia against plant viruses. Although microbial consortia have been extensively investigated for the management of fungal and bacterial diseases, their application as endophytic synthetic communities for antiviral protection remains comparatively underexplored.^{50,51} This gap is particularly relevant to the development of microbiome-based plant protection because the natural endosphere is itself a complex microbial community rather than a single-strain system. Recent perspectives on endophytic microorganisms have consequently proposed the development of designed microbial communities containing strains with complementary biocontrol, plant-growth-promoting, and resistance-inducing functions as a promising strategy for sustainable virus management.⁵³

Rhizosphere microbes as direct enhancers of induced resistance:

Although rhizosphere microbes are spatially external to the endosphere, they can act directly influence systemic plant physiology by transmitting chemical and signalling inputs through the root system. In tobacco, rhizosphere microorganisms enhanced the antiviral activity of the resistance inducer TDP against tobacco mosaic virus. The treatment restored the TMV-disrupted rhizosphere community structure, enriched beneficial genera, increased defence-enzyme activities, and enabled a six-strain consortium to enhance antiviral performance. These findings provide evidence, that rhizosphere-managed direct resistance can be both more effective and more stable when supported by microbial community reassembly.⁵⁴

Pathogens and virus-induced host reprogramming as the negative direct comparator

Beneficial microbes can counter virus-induced physiological reprogramming, which often causes chloroplast dysfunction, oxidative stress, hormonal imbalance, and growth reduction. By preserving chlorophyll, reducing oxidative damage, maintaining carbohydrate status, and stabilizing defence signalling, they exert direct disease-modulating effects even without directly killing the virus.⁵⁵

RNAi mechanism

Symbiont-mediated RNA interference (SMR) is a novel strategy for managing plant viral diseases by using engineered endophytes or plant-associated symbionts to continuously produce dsRNA targeting viral or vector genes, to activate RNAi in the host.⁵⁶ The application of crude extracts of bacterially-expressed dsRNA, when applied to orchid plants at the time of transplantation, triggered RNAi systematically in the plant and reduced Cymbidium mosaic virus (CymMV) infection.⁵⁷ It suggests that microbe-produced dsRNA can mediate antiviral protection in planta. Importantly, this was an external application of bacterially produced dsRNA (crude extract) rather than colonization by an endophytic bacterium. However, the result supported the concept that engineered endophytes produce the same dsRNA in situ for continuous antiviral defence. In parallel, experimental evidence from plant-endophyte systems showed beneficial root endophytes deliver RNAi signals into plants for induction of systemic gene silencing and RNA-directed DNA methylation, for durable antiviral resistance.⁵⁸ In aphid-borne CMV, facultative symbionts producing dsRNA against viral replicase or coat protein genes enable simultaneous suppression of virus accumulation and aphid vector efficiency, a strategy explicitly proposed for “Knockdown of aphid and plant virus genes”,⁵⁶ as seen in Fig. 2. For an aphid-transmitted virus like CMV, engineered symbiotic bacteria have been used to produce dsRNA targeting the viral replicase or coat protein genes, which simultaneously suppress virus accumulation in the plant and reduce vector competence (since the dsRNA ingested by the aphid can also silence viral or insect genes).⁵⁹ This symbiont-mediated RNAi strategy is still experimental but represents a novel direct attack on viruses that is highly specific and potentially durable as part of an integrated approach.⁶⁰ Together, these examples position symbiont-mediated RNAi as a versatile and sustainable platform for managing vector-borne plant viral diseases.

Modulation of vector

Endophytic microbes can indirectly suppress plant viruses by reducing insect vector populations or feeding by producing insecticidal and repellent secondary metabolites. For example, *Epichloe*-infected grasses accumulate alkaloids that repel aphids, reducing populations of *Rhopalosiphum padi* and the incidence of Barley yellow dwarf virus (BYDV).^{61,62} Similarly, endophytic *Trichoderma* (*Hypocrea*) *lixii* suppresses *Thrips tabaci*, the vector of Iris yellow spot virus, thereby reducing disease severity.^{63,64} Endophytic *Beauveria bassiana* also decreases aphid populations and Zucchini yellow mosaic virus (ZYMV) infection in squash through vector suppression and induction of plant defences.⁶⁵ These multitrophic interactions interrupt the viral life cycle by targeting vectors. Furthermore, endophytes contribute to virus management through enhanced host resistance, direct antiviral effects, ecological interference, and vector exclusion, strengthening plant immunity against viral pathogens.⁶⁶

Microbial competition and niche exclusion

Endophytes occupy physical and nutritional niches within the plant, which can pre-empt colonization or movement of viruses. The concept of niche exclusion still applies in some contexts of viruses though they are microscopic and inhabit host cells. A vigorously growing endophyte community might induce structural or physiological changes that make the plant less hospitable for viruses. For example, endophyte infection has been linked to enhanced deposition of callose (a polysaccharide) at plasmodesmata and along cell walls.⁶⁷ Callose deposition can act as a physical barrier to virus cell-to-cell movement. In accordance with that, *Methylobacterium* and *Bacillus* endophytes have been reported to trigger structural fortifications in plants, slowing down the systemic virus spread Walls.⁶⁸

Perspectives of endophyte-mediated virus management

The reported instances of endophytes protecting plants from viral diseases are summarised based on the type of endophytes as Bacteria, actinomycetes, fungi, and arbuscular mycorrhizal fungi.

Antiviral roles of endophytic bacteria in plants

Beneficial bacteria are among the most studied endophytes for managing viruses. Most growth-promoting rhizobacteria (PGPR) are also endophytic, colonizing intestinal tissues following initial root contact. Endophytic bacteria (*Bacillus*, *Pseudomonas*, *Serratia*, *Streptomyces*, etc.) have been demonstrated to be highly successful in alleviating viral diseases in a variety of crops³, as mentioned in Table 4. They typically induce host defences (ISR) and generate antiviral products.

Early pioneering work demonstrated that certain PGPR can guard the plants against CMV and Tobacco mottle virus.^{68,69} In the last decade, there has been a lot of research expanding upon this finding. A typical example was Cotton leaf curl virus (CLCuV) inhibited by the application of *Pseudomonas aeruginosa*, *Burkholderia* sp., and *Bacillus* sp. in cotton.⁷⁰ The maximum inhibition was achieved with the consortium, a combination of three bacterial strains, with the lowest disease rates of 0.4%, compared to 74% with untreated controls.⁷⁰ This highlights a potential synergistic impact of mixed endophyte inocula. *Bacillus* species were of particular interest because of its spore-forming capacity and extensive activity.⁷¹ *Bacillus* endophytes can colonize roots and shoots without causing disease and have a cocktail of lipopeptides, polyketides, and enzymes. For example, the strain of *Bacillus amyloliquefaciens* MBI600 and *B. subtilis* strain Ch13 have been shown to cause SA-dependent resistance in tomato by drastically decreasing the incidence of Tomato spotted wilt virus (TSWV) and Potato virus Y, which is explained by the fact that the bacterium produces surfactin lipopeptides and stimulates the SA pathway of the tomatoes.⁷² Similarly, strains of *Bacillus subtilis* have been reported to have antiviral properties against TMV by inducing pathogenesis-related proteins and secretion of ribonucleases that degrade viral RNA.^{73,47}

Three endophytic *Bacillus* species, viz., *B. licheniformis*, *B. tequilensis*, and *B. velezensis*, were highly effective against Groundnut bud necrosis virus (GBNV). These strains reduced local lesions on cowpea by over 90% and lowered disease incidence in infected tomato plants to 16-24%, compared with untreated controls (88%).⁴⁸ Treated tomatoes showed only mild or no symptoms, while untreated plants developed severe systemic necrosis and often died. It is reported that some *Azotobacter* suppress Potato virus X and PVY in potato, and *Stenotrophomonas* sp. suppress TMV in tobacco.⁶⁷ Similarly, cyanogenic PGPR, *Pseudomonas fluorescens* CHA0 and its derivatives have been demonstrated to protect tobacco against Tobacco necrosis virus by the production of SA and other signals that pre-empt defence.⁷⁴

In a field study in India, a formulation of *Pseudomonas fluorescens* plus chitosan significantly reduced tomato leaf curl virus incidence in tomato.⁷⁵ There is another case of combined application of biocontrol using *Bacillus pumilus* INR7 with a chemical elicitor (BTH), which protected chili pepper against CMV.⁷⁶ At the molecular level, research efforts are illuminating the plant genes regulated by bacterial endophytes in response to viral challenge. The application of PGPRs to ridge gourd plants has altered the expression of various defence-responsive genes during CMV infection and upregulated the genes for PR proteins, antioxidative enzymes, and RNA-silencing components, with reduced CMV load.⁷⁷ The *Bacillus cereus* AR156 endophyte primed the SA pathway in papaya to control Papaya ringspot virus.⁷⁸ Interestingly, the jasmonate levels were also regulated, which implies hormonal crosstalk and resistance against this potyvirus.

Actinomycete-derived antiviral defence in plants

Actinomycetes, in the genus *Streptomyces*, are filamentous Gram-positive bacteria known for producing a wide array of secondary metabolites (including over two-thirds of known antibiotics).⁸³ Actinomycetes as endophytes colonize the internal parts of plants and provide barriers against pathogens through in situ biosynthesis of bioactive compounds.⁸⁴ The antiviral effect against plant viruses of endophytic actinomycetes has been reported in several studies. *Streptomyces* endophytes from medicinal plants were found to suppress TMV in tobacco hosts.⁸⁵ It is worth noting that *Streptomyces ahygroscopicus* and *Streptomyces noursei* var. *xichangensis* were highly active against TMV when used as a treatment on tobacco leaves.^{86,87} It is likely that these actinomycetes stimulate the plant defense pathways and have the potential to induce anti-TMV compounds. Indeed, ϵ -poly-L-lysine (ϵ -PL), an antiviral poly-amino acid first discovered in *S. ahygroscopicus*, inactivates TMV.⁴² The purified ϵ -PL, upon spraying on leaves, significantly reduced TMV lesions on the leaves.⁴³

Latake and Borkar (45) identified 28 marine actinomycetes isolates with inhibitory effects against CMV. The metabolites of actinomycetes were tested as seed treatments and foliar sprays to prevent CMV infection in squash under greenhouse conditions.⁸⁸ Notably, *Streptomyces olivaceus* triggers the phenylpropanoid pathway in plants, which results in the accumulation of phenolics that reinforce the cell walls and prevent the spread of CMV and TMV.⁸⁹

Similarly, *Streptomyces* spp. expresses a suite of enzymes (chitinases, glucanases) and antiviral proteins. These include extracellular ribonucleases similar to bacterial barnase or benzonase that break down viral genomes. Manjunatha et al. (4) observed that the RNase activity increased in plants under the colonization of *Streptomyces* when the plant faced a challenge in the form of a virus. The defence-related molecular responses triggered by actinomycetes against plant viral pathogens are detailed in Table 2.

One of the most interesting methods is the application of actinomycete-derived compounds as “green antivirals”. Ningnanmycin (a microbial metabolite produced by *Streptomyces noursei*) and cytosinepeptidomycin are also developed as commercial plant antiviral agents in China.⁹⁰ Ningnanmycin is used to manage TMV in tobacco and other plants, and has a dual mode of action as it directly binds to viral RNA to inhibit viral replication and induces plant SAR (systemic acquired resistance). Although these are used as formulations instead of being directly delivered by a live endophyte, they highlight the chemical weaponry that endophytic actinomycetes possess. As an example, *Streptomyces* isolates synthesize new antiviral compounds that are effective against tobacco mosaic tobamovirus and Potato Y potyvirus.⁹¹ Formulations of *Streptomyces* have been tested on pepper and tomato fields against potyviruses, which showed reduced disease incidence.⁹²

Endophytic fungi in plant virus management

Fungal endophytes extend to a wide group of ascomycetes and basidiomycetes that are placed inside plant tissues and do not cause any symptoms. Most of them are known to confer resistance to abiotic stress, fungal pathogens and herbivores. Recent research has indicated that fungal endophytes may also play a role in viral diseases, not only through their ability to improve the plant defences, but also through their effects on the vectors.

The capability to produce bioactive secondary metabolites that may prevent pests and pathogens is considered to be one of the major characteristics of most endophytic fungi. Indirectly, such a potent mechanism is insect vector deterrence in the context of viruses. As explained in the above section, *Trichoderma* spp. have been used to eliminate thrips vectors of orthotospoviruses. Inoculated onion plants with an endophytic strain of *Hypocrea lixii* F3ST1.63. According to Lehtonen et al. (61), meadow ryegrass infected with *Neotyphodium uncinatum*, an endophyte in most cool-season grasses, had much fewer aphids and lower rates of BYDV infection than endophyte-free grass. The endophyte synthesizes loline alkaloids that are lethal to the BYDV (Barley yellow dwarf virus)-carrying aphids and provide some degree of protection against viral infection. Fungal endophytes may also induce systemic resistance in a manner similar to that of bacteria. Some foliar endophytes elicit SA- or JA-dependent responses during colonization. An example is *Chaetomium globosum*, which is a saprophytic fungus that has been reported to induce PR gene expression and enhance phenolics when it becomes an endophyte in plants. Endophytic *Cladosporium* sp. reduced the accumulation of the Tobacco mosaic virus by activating the defence and RNA-silencing genes through ultra- high activity of endophytic elicitor.³⁷

The direct antiviral effects of fungal endophytes are not as well documented as those of actinomycetes. Medicinal plant endophytic fungi extracts have also shown activity in plant viral inhibition in laboratory tests. One such instance is an endophytic *Aspergillus* sp. on *Heliotropium*, which produced a compound that prevented TMV.⁹⁶

Phoma and *Colletotrichum* endophytes in beet were linked to reduced loads of Beet yellows virus.⁹⁷ Other than *Beauveria bassiana*, *Metarhizium anisopliae* is also capable of endophytic colonization of plants. The results have shown that *Metarhizium* endophytes in soybean decreased the activity of bean aphids and cases of Soybean mosaic virus.⁹⁶ Such fungi can also generate insecticidal compounds (such as destruxins from *Metarhizium*) that are incorporated into the plant tissues, which act as a permanent defence. Rochal et al. (98) used a novel method that involved the use of consortia of endophytic fungi. They pooled various isolates of the endophytic *Trichoderma* into a consortium that was used to control Pepper leaf curl virus, a begomovirus, on pepper plants. The consortium-treated peppers exhibited weak symptom development and a reduction in accumulation of viral DNA as compared to control plants. It is likely that these mixed endophytes were causing a severe immune reaction in the plant and may even be a case of synergistic interaction in the plant microbiome to outshine their rivals.

Roles of arbuscular mycorrhizal fungi in plant viral disease management.

Arbuscular mycorrhizal fungi (AMF) represent a specialized group of plant symbionts that establish mutualistic associations with the roots of most terrestrial plants. Unlike free-living endophytes, AMF belonging to the phylum Glomeromycota are obligate biotrophs, relying entirely on their host for survival. They facilitate the uptake of essential soil nutrients such as phosphate and nitrogen, while in return receiving photosynthetically derived carbon compounds from the plants. AMF improve the nutritional conditions and stress resistance of plants, and can also regulate plant immune responses, a phenomenon also referred to as mycorrhiza-induced resistance (MIR).⁶⁶

Effect of AMF on viral diseases

The mycorrhizal inoculation of plants usually enhances tolerance to a viral attack, and mycorrhizal plants are less affected by the virus in terms of loss in yield or the degree of symptoms.⁶⁶ Reduction in disease symptoms should not be considered synonymous with viral suppression, as endophytes may alleviate symptoms by enhancing host defence or tolerance without necessarily reducing virus accumulation. Therefore, antiviral effects should be supported by direct measurements of viral titer or viral RNA using methods such as ELISA and qPCR. Recent studies on endophytic *Bacillus* spp. demonstrated both reduced symptom severity and decreased GBNV titre, providing stronger evidence of actual viral suppression.^{48,102} The colonization of tomato by AMF *Rhizophagus intraradices* reduced disease symptoms of Tomato yellow leaf curl Sardinia virus (TYLCSV, a begomovirus).¹⁰³ Apparently, AMF prepares the

plant's defence (e.g., ISR) and may also trigger some heat-shock proteins or antioxidants to help make the plant withstand the viral infection.¹⁰⁴

Moreover, AMF can modify plant volatile profiles and physiology to influence vectors; certain mycorrhizal plants produce volatiles that are not attractive to aphids, which reduces the number of vectors initially carrying the virus.¹⁰⁵

Molecular and physiological insights into endophytes-virus-plant interactions

To fully harness endophytes for viral protection, it is crucial to understand the molecular and physiological changes that occur in the plant during endophyte colonization and virus challenges. Recent studies employing transcriptomics, metabolomics, and gene expression analyses have shed light on how endophytes reprogram plant responses and what key pathways are involved.

Transcriptomic and metabolomic changes during endophyte-mediated defence

Transcriptomic studies show that endophytes prime a wide range of defence-related genes during viral infection, including PR proteins, antioxidant enzymes, and RNA-silencing components, thereby enhancing both basal immunity and RNAi-mediated antiviral defence.¹¹⁰ The ridge gourd plants infected with CMV and treated with a consortium of PGPR showed elevated expression of PR protein genes, increased antioxidant levels, and higher expression of genes related to siRNA generation, correlating with lower virus levels.⁷⁷ This indicates an orchestrated activation of both basal immunity (PR proteins, etc.) and RNAi-based antiviral defence.

Metabolomic analyses reveal that endophyte-colonized plants accumulate higher levels of defence metabolites, particularly phenolics and flavonoids. In PVY-infected potato, treatment with *B. licheniformis* POT 1 enhanced phenylpropanoid metabolism and increased chlorogenic acid and flavonoids associated with resistance.⁸¹ Endophytes also modulate hormonal responses, often inducing a moderate rise in SA and related metabolites. *Bacillus* AR156 primed papaya plants for faster SA response and improved antioxidant accumulation following PRSV infection.⁷⁸ Flavonoid biosynthesis genes are likewise upregulated, contributing to antiviral defence.¹¹¹

Host gene expression and defence pathways

Several genes have been identified as important markers or mediators of endophyte-induced antiviral resistance. PR genes such as PR-1, PR-2 (β -1,3- glucanase), PR-5 (thaumatin-like protein) are often reported to be upregulated in endophyte-treated, virus- infected plants (e.g., *Trichoderma viride* Tvd44 increased PR-1 in PVY challenged potatoes).¹⁰¹ Enzymatic defences like polyphenol oxidase (PPO), peroxidase (POD), superoxide dismutase (SOD), and catalase are boosted by many endophytes.¹¹² These enzymes help manage oxidative stress and reinforce cell walls, indirectly hampering virus movement.

Genes involved in the salicylic acid pathways (such as ICS-isochorismate synthase for SA biosynthesis, or NPR1 a master regulator of SA-mediated defense) can be influenced by endophytes. *Streptomyces* sp. treatment increased plant salicylic acid content and upregulated PR-1 and PR-2 in TYLCV-infected tomatoes.¹¹³ Concurrently, components of the jasmonate pathways (like LOX-lipoxygenase, or PDF 1.2-a JA-responsive defensive gene) might be modulated, sometimes downregulated to favour SA (if virus defense requires SA), or co- activated if needed for a balanced response (some viruses cause necrosis where JA might help wall off infection).

Crucially, genes of the RNA interference (RNAi) pathways in plants, which are a key antiviral mechanism, have been noted to change. An endophytic fungus induced expression of DCL (Dicer-like) and RDR (RNA-dependent RNA polymerase) genes in tobacco, enhancing the production of siRNAs against TMV.³⁷ Similarly, the presence of PGPR upregulated Argonaute, Dicer, and RDR genes in CMV-infected plants, implying that the endophyte primed that plant's gene silencing machinery.¹¹⁴ Another category is structural genes; for example, genes for callose synthase or those in the phenylpropanoid pathways (like PAL- phenylalanine ammonia lyase, and CCR-cinnamoyl-CoA reductase for lignin) can be elevated, contributing to physical barriers against viruses.

Crosstalk between plant immunity and endophyte signaling

Endophytes interact with the plant immune system through complex signalling networks involving hormone crosstalk and defense pathways. Microbe-associated molecular patterns (MAMPs), such as bacterial flagellin and fungal chitin, are capable of triggering basal defense responses in plants. However, in contrast to pathogenic organisms, endophytes elicit a finely tuned response that primes the plant immune system without causing cellular damage. This indicates that endophytes may regulate host immunity through the secretion of specific effector molecules. A central aspect of this regulation involves the interaction between salicylic acid and jasmonic acid/ ethylene (JA/ ET) signalling pathways. Because SA-dependent signalling plays a critical role in resistance to biotrophic pathogens, including many plant viruses, certain endophytes enhance antiviral defense by stimulating SA-mediated immune responses. For instance, *Bacillus* AR156 in papaya elevated SA defences while keeping JA in check enough not to interfere with SA's action.¹¹⁵ Similarly, *Trichoderma hamatum* Th23 in tomato induced SA (PR-1, PR-7 genes) against TMV and presumably did not strongly activate JA.¹⁰⁰

CONCLUSION

Plant viruses are expected to remain a major constraint to global agriculture owing to their rapid mutation rates, broad host ranges, complex interactions with hosts and vectors, and the lack of effective direct chemical control options. In this context, endophytes have emerged as a promising yet relatively underutilized resource for the sustainable management of viral diseases in plants. Endophytic bacteria, fungi, and actinomycetes have been shown to mitigate disease incidence and severity across various crop-virus systems through diverse mechanisms. These mechanisms

include activation of host defense responses, production of antiviral compounds, and disruption of virus transmission by insect vectors. While significant challenges and knowledge gaps remain, continued advances in formulation technology and field validation are likely to accelerate the practical deployment of endophyte-based solutions. Harnessing these beneficial microorganisms offers a promising pathway toward resilient, environmentally responsible, and long-term management of plant viral diseases in modern agriculture.

Future prospects

Endophyte-mediated management of plant viral diseases often shows variable field performance because environmental conditions, host genotype, soil properties, and competition with native microbiota can affect endophyte colonization, persistence, and activity. Host- endophyte specificity may further limit the transferability of effective strains across crop varieties and production environments. In addition, challenges related to strain consistency, mass production, formulation stability, shelf life, biosafety assessment, regulatory approval, and large-scale field validation remain important barriers to practical application. Limited knowledge of the molecular mechanisms underlying endophyte-mediated antiviral activity, including signalling crosstalk and possible non-target effects, also needs to be addressed before widespread deployment.

Recent advances in genomics, multi-omics, synthetic biology, and microbiome engineering provide opportunities to identify and optimize beneficial endophytes and microbial consortia with more predictable functions. However, engineered endophytes designed for RNA-based or other targeted antiviral delivery should currently be regarded as an emerging research direction rather than an established field technology. Their practical development will require stable plant colonization, reliable delivery and expression of the desired antiviral molecules, genetic stability, efficacy against diverse viral strains, and evaluation under greenhouse and multi-location field conditions. Equally important are studies on environmental persistence, horizontal gene transfer, effects on non-target microorganisms, and regulatory compliance. Therefore, a realistic future strategy is to combine strain screening, genome-and microbiome-based selection, controlled formulation, and stepwise field validation before commercial deployment. Such approaches could contribute to sustainable viral disease management by complementing, rather than immediately replacing, existing integrated disease-management practices

However, the environmental release of endophytes also requires careful consideration of their ecological persistence and interactions with native microbial communities. Introduced strains may alter the composition or activity of resident endophytes and rhizosphere microorganisms, potentially affecting nutrient cycling, plant-microbe interactions, and natural disease-suppressive functions. Non-target colonization of neighbouring plants and interactions with beneficial microorganisms should therefore be evaluated before field application. These concerns become more particularly important for engineered endophytes, where genetic stability, horizontal gene transfer, unintended metabolic changes, and the environmental fate of introduced genetic components require assessment. Similarly, RNA-based antiviral strategies should be evaluated for sequence specificity and possible effects on non-target organisms. Therefore, long-term field studies incorporating monitoring of endophyte persistence, microbiome changes, genetic stability, and non-target effects are essential for establishing the ecological safety of endophyte-based viral disease management.

Table 1. Bacterial bioagents inducing systemic resistance and defence- related molecular responses against plant viral pathogens.

Bacterial bioagent	Virus (s)	Host plant (s)	Mechanism of diseases reduction	References
<i>Pseudomonas fluorescens</i> , P. aeruginosa	Tobacco necrosis virus (TNV)	Tobacco (N. tabacum)	Activation of ISR and enhanced plant defence responses against viruses	79, 80
<i>Bacillus amyloliquefaciens</i> MBI600	Potato virus Y (PVY); Tomato spotted wilt virus (TSWV)	Tomato	SA-dependent ISR (reduced symptom severity)	72
<i>Bacillus licheniformis</i> POT1	Alfalfa mosaic virus (AMV)	Potato	Induced systemic resistance via flavonoid pathway (increased F3H, anthocyanins)	81
<i>Bacillus subtilis</i> (strain 26D/Ttl2)	Potato virus Y (PVY)	Potato	ISR; reduced virus accumulation	36
<i>Rhizobium leguminosarum</i> pv. <i>Viciae</i>	Bean yellow mosaic virus (BYMV)	Faba bean (Vicia faba)	ISR (increased antioxidant enzymes, chlorogenic acid pathway)	82

Table 2. Actinomycete-mediated induction of systemic resistance and defence- related molecular responses against plant viral pathogens.

Actinomycete species/source	Target plant virus	Host plant (s)	Mechanism of diseases reduction	References
<i>Streptomyces pactum</i> Act12	Tomato yellow leaf	Tomato	ISR (increased salicylic acid, jasmonic acid, PR proteins; ~38% reduction of	93

	curl virus (TYLCV)		TYLCV	
Streptomyces cellulosa (Actino 48)	Tobacco mosaic virus	Tomato	ISR (Increased peroxidase, chitinase, PR proteins; reduced viral accumulation)	94
Streptomyces sampsonii, Streptomyces rochei & Streptomyces griseus	Zucchini yellow mosaic virus	Squash	ISR- antiviral metabolites (Behenic alcohol/ docosanol downregulated viral replication)	95
Streptomyces sparsogenes	Zucchini yellow mosaic virus	Cucumber	ISR	94
Streptomyces variabilis stain ph6 & Streptomyces sp. Strain MARH	Cucumber mosaic virus	Squash	ISR/SAR (increased phenolic compounds, antioxidant enzymes, PRgene expression)	88

Table 3. Fungal endophytes are reported to attenuate plant viral infections through host- mediated activation of physiological, biochemical, and molecular defence responses, predominantly via induced systemic resistance.

Fungal microorganism/ product	Target virus	Host plant (s)	Major induced defence mechanism	References
Trichoderma harzianum	Tobacco mosaic virus	Tobacco	Induced systemic resistance (ISR), enhanced antioxidant enzymes	99
Endophytic fungus (ZhiNengCong, ZNC)	Potato X virus	Nicotiana benthamiana	Salicylic acid (SA) accumulation, RO; production, activation of RNA silencing (PTGS)	37
Endophytic fungus (ZhiNengCong, ZNC)	Potato X virus	Nicotiana benthamiana	Salicylic acid (SA) accumulation, RO; production, activation of RNA silencing (PTGS)	37
Trichoderma hamatum (Th23)	Tobacco mosaic virus	Tomato	ISR via PR-1/PR-7 induction (Salicylic acid defence)	100
Trichoderma viride (isolate Tvd44)	Potato virus Y	Potato	Induced systemic resistance; upregulation of PR-1, PAL and flavonoid genes	101
Fungal microorganism/ product	Target virus	Host plant (s)	Major induced defence mechanism	References
Trichoderma harzianum	Tobacco mosaic virus	Tobacco	Induced systemic resistance (ISR), enhanced antioxidant enzymes	99
Endophytic fungus (ZhiNengCong, ZNC)	Potato X virus	Nicotiana benthamiana	Salicylic acid (SA) accumulation, RO; production, activation of RNA silencing (PTGS)	37
Endophytic fungus (ZhiNengCong, ZNC)	Potato X virus	Nicotiana benthamiana	Salicylic acid (SA) accumulation, RO; production, activation of RNA silencing (PTGS)	37
Trichoderma hamatum (Th23)	Tobacco mosaic virus	Tomato	ISR via PR-1/PR-7 induction (Salicylic acid defence)	100
Trichoderma viride (isolate Tvd44)	Potato virus Y	Potato	Induced systemic resistance; upregulation of PR-1, PAL and flavonoid genes	101

Table 4. AMF species and consortia are reported to influence plant viral diseases through host defense responses and modulation of systemic resistance.

AMF Species (or consortia)	Target virus	Host plant (s)	Major induced defense mechanism	Reference
Mycorrhizal fungi (Glomus spp.)	Tomato spotted wilt virus	Tomato	Priming of host defense and improved nutritional status	106
Glomus mosseae (single species)	Tomato spotted wilt virus	Tomato	No suppression; AMF limited defense transcriptome	107
Funneliformis mosseae + Rhizoglomus clarum + Rhizophagus aggregatus	Tomato mosaic virus	Tomato	Enhanced phenylpropanoid/ flavonoid defences (increased PAL1, HQT, etc.)	108
AMF (mixed inoculum)	Zucchini yellow mosaic virus	Cucumber	Systemic acquired resistance (increased PR Proteins, antioxidants)	109

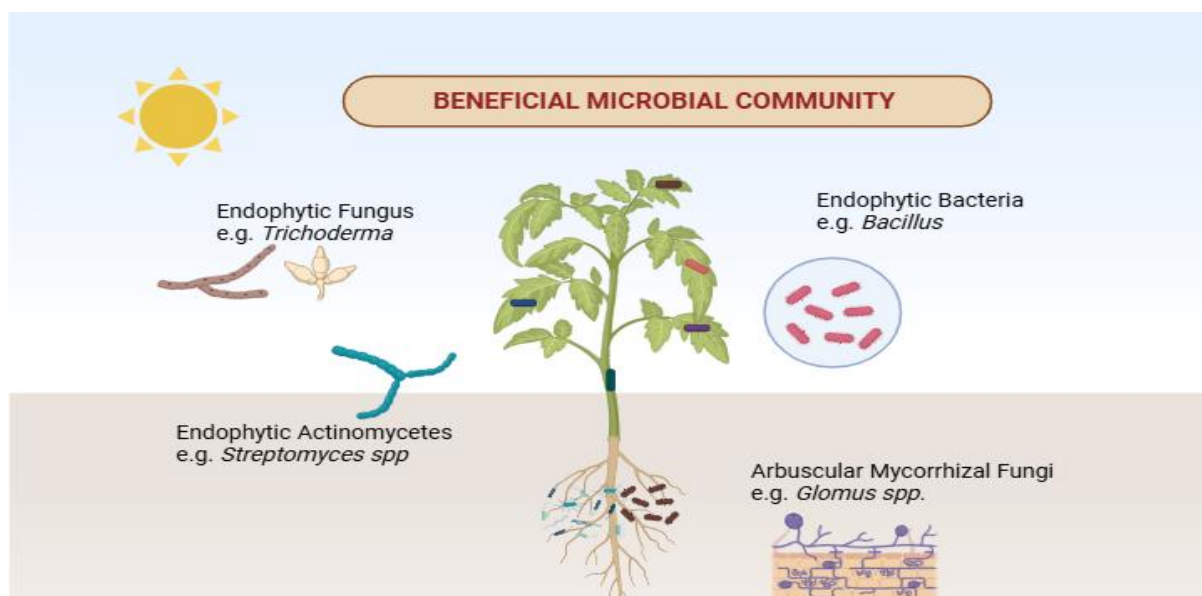


Fig. 1. Schematic representation of the plant holobiont illustrating the synergistic interactions of beneficial endophytic and mycorrhizal microorganisms in promoting plant health and resilience.

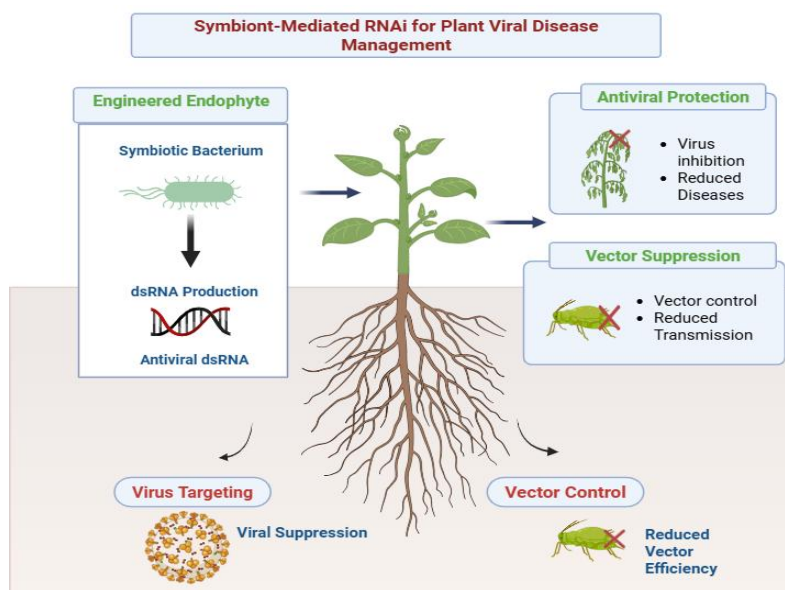


Fig. 2. Conceptual framework illustrating symbiont-mediated RNA interference (RNAi) for plant viral disease management, in which an engineered endophytic microorganism produces antiviral double- stranded RNA to suppress viral replication and reduce vector- mediated transmission, for systemic plant protection.

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Conflict Of Interest

The authors declare that there is no conflict of interest.

Authors' Contribution

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