PLANT SCIENCE TODAY
Vol 13(sp1): 1-8
https://doi.org/10.14719/pst.12167

eISSN 2348-1900

REVIEW ARTICLE

Harnessing endophytic microorganisms for sustainable plant virus management: Mechanisms, applications and prospects

Siva Ramakrishnan Sivadoss[1], Kannan Rengasamy[1*], Gopalakrishnan Chellapan[2], Preetha Gnanadhas[3], Swarnakumari Narayanan[4] & Jayakanthan Mannu[5]

[1]Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Department of Rice, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Directorate of Seed Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Plant Protection, Horticultural College and Research Institute for Women, Tiruchirappalli 620 009, Tamil Nadu, India
[5]Department of Molecular Biology and Bioinformatics, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - kannan.r@tnau.ac.in

Received: 08 October 2025; Accepted: 28 December 2025; Available online: Version 1.0: 27 January 2026

Cite this article: Siva RS, Kannan R, Gopalakrishnan C, Preetha G, Swarnakumari N, Jayakanthan M. Harnessing endophytic microorganisms for sustainable plant virus management: Mechanisms, applications and prospects. Plant Science Today. 2026; 13(sp1): 1-8. https://doi.org/10.14719/pst.12167

Abstract

Plant viruses represent a persistent and severe threat to global crop productivity with conventional management strategies often proving inadequate. This review highlights the emerging potential of endophytic microorganisms as a sustainable approach to plant virus management. We synthesize current advances on the diverse mechanisms through which bacterial and fungal endophytes exert antiviral effects, including the induction of systemic resistance, production of antiviral metabolites and direct competition with pathogens. Translational applications from screening and formulation to field deployment are examined to underscore their potential as novel biocontrol agents. Despite encouraging progress, challenges such as variability in efficacy, ecological adaptability and commercialization barriers remain. We critically evaluate these limitations and discuss future perspectives, emphasizing the integration of advanced omics technologies and synthetic biology to design next-generation microbial inoculants.

Keywords: antiviral mechanisms; biocontrol; endophyte; induced systemic resistance; plant virus

Introduction

Plant viruses account for nearly 30 % of all crop diseases, representing a major constraint to global agricultural productivity. Notably, over 80 % of plant viruses possess ribonucleic acid (RNA) genomes, underscoring their remarkable genetic diversity and evolutionary adaptability. Recently, viruses such as tomato yellow leaf curl virus (TYLCY) are among the most destructive plant pathogens, causing severe yield and quality losses in tomato worldwide. More than 25 virus families infect a broad range of host plants worldwide, leading to substantial yield losses and significant economic damage across agroecosystems (1). Orthotopspovirus can cause devastating yield losses of up to 40 %, particularly tomato, pepper and groundnut in tropical and subtropical regions of Asia, Africa and the America. It can be able to produce wide range of symptoms, including necrosis, leaf distortion, rolling, mottling and twisting, often accompanied by reduced fruit, vegetable and grain size (2, 3). They are classified into several families, including Tombusviridae, Geminiviridae and Potyviridae, many of which cause devastating diseases in staple crops. Notably, begomoviruses (family Geminiviridae) transmitted by whiteflies (*Bemisia tabaci*) infect a wide range of dicotyledonous plants and have been associated with yield losses of up to 100 % in susceptible crops across tropical and subtropical regions (4, 5). Beyond Begomoviruses, Orthotospoviruses (family *Tospoviridae*), including tomato spotted wilt orthotospovirus and groundnut bud necrosis orthotospovirus, are major pathogens of solanaceous and legume crops. Transmitted by thrips, these viruses cause yield losses of up to ~40 % or higher in crops such as tomato, pepper and groundnut. In addition to well-characterized plant viruses, several newly emerging and re-emerging plant viruses of global significance have been documented in recent years (Table 1).

Their widespread occurrence in tropical and subtropical regions of Asia, Africa and the America make them key constraints to sustainable food production (12). These losses are frequently exacerbated by large-scale epidemics driven by highly efficient transmission through insect vectors, nematodes and soil-borne fungi, making vectors critical targets for integrated disease management strategies. However, conventional management of plant virus remains a formidable challenge; vector control, as reliance on insecticides for vector suppression often leads to resistance development and environmental contamination, limiting long-term effectiveness. In addition, the inherent potential for viral recombination further complicates durable disease management. Approaches such as breeding or employing advanced genetic engineering approaches, including RNA interference (RNAi) and CRISPR/Cas9, offer significant promise, these strategies are often resource-intensive, time-consuming and constrained by regulatory hurdles and public acceptance issues (13, 14). Consequently, there is

Table 1. Major plant virus, vector and economic impact

Virus name	Genome type	Major host crops	Insect vector	Estimated yield loss (%)	References
TYLCV	ssDNA (*Begomovirus*, *Geminiviridae*)	Tomato, pepper, beans	Whitefly (*B. tabaci*)	90–100 %	(6)
PLRV	(+)ssRNA (*Polerovirus*, *Solemoviridae*)	Potato, solanaceous crops	Aphids (*Myzus persicae*)	>50 %	(7)
Bean golden yellow mosaic virus (BGYMV)	ssDNA (*Begomovirus*, *Geminiviridae*)	Common bean	Whitefly (*B. tabaci*)	Up to ~100 %	(8)
Soybean mosaic virus (SMV)	(+)ssRNA (*Potyvirus*, *Potyviridae*)	Soybean	Aphids (various species)	8–35 %	(9)
Cassava mosaic virus (CMD)	ssDNA (*Begomovirus*, *Geminiviridae*)	Cassava	Whitefly (*B. tabaci*)	15–30 %	(10)
PVYx	(+)ssRNA (*Potyvirus*, *Potyviridae*)	Potato, tomato, pepper	Aphids (e.g., *Myzus persicae*)	20–40 %	(11)

an urgent need to develop effective, sustainable and eco-friendly strategies for the management of plant viral diseases.

In this context, beneficial endophytic microorganism residing within plant tissue without causing harm to have emerged as novel and promising biocontrol agents. Certain endophytic bacteria and fungi suppress plant virus spread by reducing vector colonization and feeding efficiency and by modulating plant volatile emissions, while simultaneously enhancing plant vigor through improved nutrient acquisition, phytohormone regulation and antioxidant defense, thereby alleviating virus-induced yield losses (15–17). Entomopathogenic endophytes are distinguish their mode of action from classical induced systemic resistance (ISR) and the suppression of insect vector population. Recent advances in genomics, transcriptomics, metabolomics and microbiome analyses have elucidated the complex molecular networks governing endophyte–plant–virus interactions and accelerated the discovery of novel antiviral microbes and metabolites. This review synthesizes current insights into the mechanisms, applications and translational challenges of endophyte-based virus management, highlighting their potential as core components of sustainable and environmentally responsible plant protection strategies.

Endophyte diversity and colonization

Endophytic microorganisms, including bacteria, fungi and actinomycetes, inhabit internal plant tissues without causing disease, colonizing roots, stems, leaves, seeds and reproductive organs (18). Common bacterial genera include *Bacillus*, *Pseudomonas* and *Burkholderia*, while fungal endophytes often comprise *Trichoderma*, *Beauveria* and *Metarhizhium*. Endophyte establishment depends on host genotype, developmental stage, environmental factors and they can be transmitted vertically by seed and horizontally from soil and the rhizosphere (19). This intimate association underpins their role in enhancing plant health and antiviral defense, making them valuable for sustainable crop protection (Fig. 1).

Bacterial endophytes

Bacterial endophytes represent one of the most extensively studied and promising groups for sustainable plant virus management. Numerous studies have demonstrated their ability to suppress viral replication, enhance host immunity and improve plant growth across diverse crop–virus systems. For instance, *Enterobacter asburiae* has been shown to ISR against TYLCV in tomato, significantly reducing disease severity through host defense

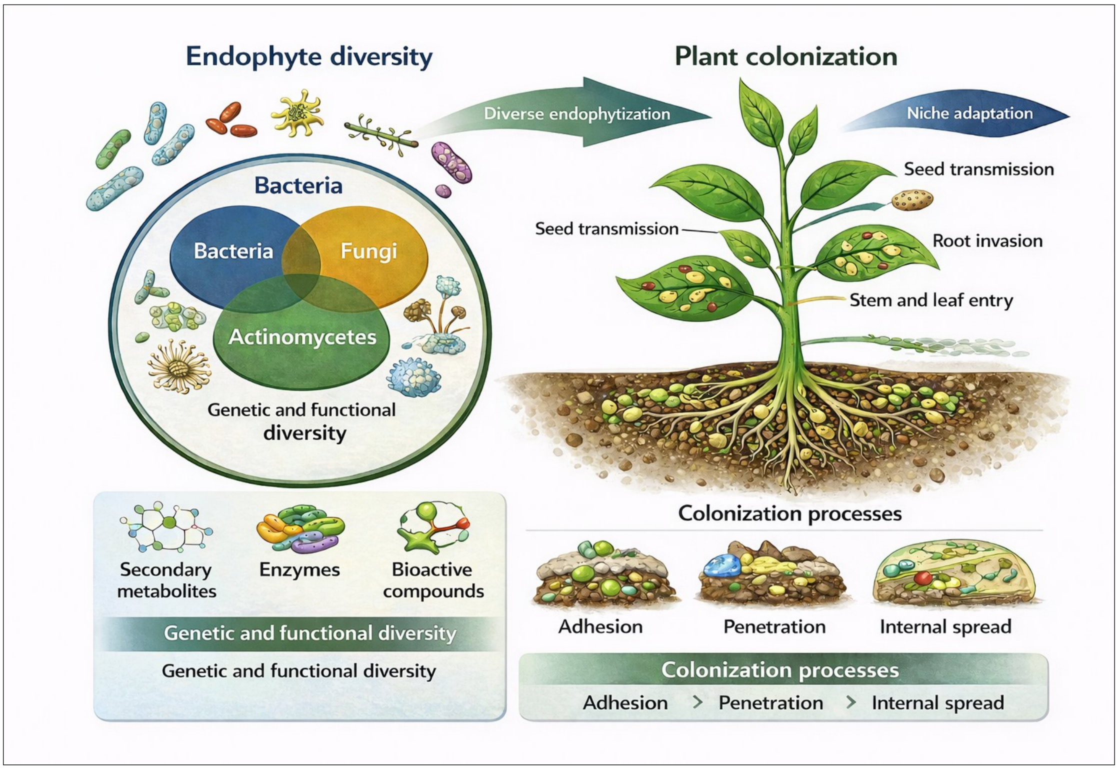

Fig. 1. Schematic illustration of diversity and colonization pattern.

activation (20). Consortium-based approaches have proven particularly effective. Endophytic strains of *Pseudomonas aeruginosa, Burkholderia* sp. and *Bacillus* sp., evaluated individually and in combination against cotton leaf curl virus (CLCuV), showed that mixed bacterial inoculation conferred superior protection. Disease incidence was reduced to 0.4 %, with a marked decrease in viral load compared to 74 % infection in untreated controls, a relationship further validated by principal component analysis (21). Application of *Bacillus siamensis* B30 through soil or foliar spray enhanced faba bean growth and conferred resistance against bean yellow mosaic virus (BYMV). Several *Bacillus* species have consistently demonstrated strong antiviral potential. *Bacillus amyloliquefaciens* effectively suppressed tomato spotted wilt virus (TSWV) by activating host defense responses, reducing virus accumulation, alleviating symptom severity and promoting plant growth (22). Similarly, *B. subtilis* strains 26D and Ttl2 enhanced resistance to potato virus X (PVX) and potato virus Y (PVY) in tomato by modulating redox homeostasis and maintaining cellular redox balance (23). Additional studies reported reduced virus titers of PVY using *B. amyloliquefaciens* MBI600 and suppression of tomato mosaic virus (ToMV) by *Streptomyces ovatisporus* LC597360 (24, 25). Treatment with plant growth-promoting bacteria (PGPB) frequently resulted in complete symptom suppression of tobacco mosaic virus (TMV)-infected tomato plants (26). Beyond direct antiviral activity, bacterial endophytes also enhance plant performance under viral stress. *Pseudomonas pseudoalcaligenes* in combination with arbuscular mycorrhizal fungi (AMF) induced resistance against marigold mosaic virus (MMV) while maintaining growth and increasing essential oil production (27). Likewise, tomato plants treated with plant growth-promoting rhizobacteria (PGPR) exhibited reduced accumulation of tomato mosaic virus (ToMV) (28). Application of *Bacillus* spp. further reduced disease incidence, severity and viral titer of groundnut bud necrosis virus (GBNV) in tomato by upregulating defense-related genes (29). Consortium-based microbial formulations have shown broad-spectrum efficacy. Combined inoculation of *B. amyloliquefaciens* IN937a, *B. pumilus* SE34 and *B. pumilus* T4 effectively reduced infections caused by papaya ringspot virus (PRSV) in papaya and tomato chlorotic spot virus (TCSV) in tomato (24, 29). Similarly, *B. polymyxa* and *Pseudomonas fluorescens* combined with chitin significantly suppressed squash mosaic virus (SqMV) in cucumber (30). Mechanistic studies reveal that bacterial endophytes activate multiple layers of plant immunity. Microbe-associated molecular patterns (MAMPs) such as flagellin (Flg) and elongation factor Tu (EF-Tu) from *Bacillus* spp. trigger MAMP-triggered immunity (MTI) via pattern recognition receptors (PRRs), leading to enhanced expression of defense genes including MAPKK1, WRKY33, NPR1, PR1 and reduced GBNV titers in tomato (31). In addition, secondary metabolites produced by *Bacillus* spp. play a crucial role in immune activation. Endophytes also indirectly limit virus spread by targeting vectors. *Bacillus subtilis* BS3A25 significantly reduced populations of the melon aphid (*Aphis gossypii*), a major vector of cucumber mosaic virus (CMV) (32). Likewise, *B. amyloliquefaciens* suppressed *Phoma betae* infections, thereby indirectly reducing beet necrotic yellow vein virus (BNYVV) incidence in sugar beet (33). Advanced molecular studies have provided deeper insights into bacterial endophyte-mediated antiviral resistance. Species like *B. amyloliquefaciens*, *B. subtilis* and *B. velezensis* are prolific producers of lipopeptides (e.g., surfactin, iturin, fengycin) and antibiotics that can directly inhibit viral replication, suppress vector population and enhanced tomato resistance to ToMV by inducing hydrogen peroxide accumulation and activating salicylic acid (SA)-responsive genes such as PR-2 and PAL (34). *Bacillus velezensis* HN-2 effectively colonized host tissues and induced systemic resistance against pepper veinal mottle virus (PVMV), while *B. amyloliquefaciens* FZB42 produced cyclodipeptides that activated SA signaling and enhanced resistance to TMV in *Nicotiana benthamiana* (35). Transcriptomic analyses further confirmed the coordinated activation of SA, jasmonic acid (JA) and ethylene (ET) dependent pathways, with upregulation of genes such as WRKY, NPR1, PAL, PPO, PDF1.2 and LOX1 in tomato and chili treated with *Bacillus* spp. (36). Additionally, volatile organic compounds (VOCs) produced by *B. subtilis* strains were shown to interfere with TMV replication in *N. benthamiana* (37). Members of the genus *P. fluorescens* and *P. putida*, are also well-recognized inducers of ISR, priming plant immune responses for rapid and robust defense upon viral challenge. Emerging evidence further highlights the antiviral potential of *Streptomyces* spp. *Streptomyces* strain SN40 effectively suppressed TMV in *Nicotiana glutinosa* and PVY in *N. benthamiana*, with metabolomic profiling revealing anisomycin and trans-3-indoleacrylic acid as key antiviral compounds (38). Additional studies showed that *Streptomyces* strains possess vector-suppressive properties (39), while *Streptomyces fradiae* QD3 significantly reduced PVY severity and accumulation in potato, concurrently promoting plant growth and physiological performance (40). In addition, selected representative examples are summarized in Table 2.

Overall, these studies collectively demonstrate that bacterial endophytes, particularly *Bacillus*, *Pseudomonas* and *Streptomyces* spp. confer antiviral protection through a multifaceted strategy involving ISR, hormonal signaling (SA, JA, ET), production of bioactive metabolites, transcriptomic reprogramming of host defenses and suppression of insect vectors. While *Bacillus* spp. dominates current research due to their metabolic versatility and field applicability, the consistent efficacy observed across diverse crops and virus systems highlights bacterial endophytes as robust, broadly deployable components of sustainable plant virus management, though their performance under heterogeneous field conditions remains a key research gap.

Fungal endophytes

Fungal endophytes are asymptomatic inhabitants of internal plant tissues and have been reported from virtually all plant organs, including roots, stems, leaves and reproductive structures (42). Among them *Trichoderma harzianum* and *T. asperellum* are well-recognized for their ability to establish stable endophytic colonization in both root and shoot tissues and to act as potent elicitors of plant systemic resistance. Recent studies have demonstrated that root colonization by *T. asperellum* T34 in tomato confers effective systemic protection against TYLCV. This protection is mediated through immune priming involving the enhanced expression of pathogenesis-related (PR) genes and activation of JA and ET signaling pathways, leading to reduced viral accumulation and symptom severity (43). In addition, *Trichoderma* induced innate immunity and enhanced stress tolerance have been linked to the stimulation of the phenylpropanoid biosynthetic pathway, which plays a central role in strengthening host defense barriers. Emerging evidence further suggests that *Trichoderma* mediated antiviral activity may involve SA-dependent signaling. The ability of *Trichoderma* bioagents to produce and release SA under *in vitro*

Table 2. Bacterial endophytes with antiviral activity

Endophyte species/strain	Host plant	Target virus	Mode of action	Experimental system	References
B. subtilis 26D & Ttl2	Tomato	PVX; PVY	Elevated plant RNase activity; ISR via hormone balance	Greenhouse	(23)
B. subtilis (foliar/soil)	Potato	PVY	Enhanced antiviral resistance; reduction in virus titer & severity	Greenhouse	(23)
B. amyloliquefaciens (multiple isolates)	*N. benthamiana*	TSWV	Defense activation; increased antioxidant enzymes	Glasshouse	(22)
B. licheniformis, *B. tequilensis*, *B. velezensis*	Cowpea & Tomato	GBNV	Reduced virus incidence & titer; symptom suppression	Lab and greenhouse	(29)
Paraburkholderia fungorum R8; *Paenibacillus pasadenensis* R16; *Pantoea agglomerans*	*N. benthamiana*	CymRSV; CMV	ISR induction; defense gene upregulation	Controlled conditions	(41)

conditions has been implicated in the suppression of pepper leaf curl virus (PeLCV), highlighting a multilayered defense mechanism that integrates both hormonal signaling and secondary metabolite production (44). Beyond direct antiviral effects, fungal endophytes can also indirectly limit virus spread by targeting insect vectors. *Hypocrea lixii* F3ST1 and *T. asperellum* M2RT4 successfully colonized tomato plants and ISR against *Trialeurodes vaporariorum*, a major vector of tomato infectious chlorosis virus (TICV) and tomato chlorosis virus (ToCV), thereby reducing vector pressure and potential virus transmission (45). This highlights the dual role of fungal endophytes in suppressing both viruses and their vectors. In addition, other fungal endophytes have shown promising antiviral activity. Culture filtrates from endophytic *Epicoccum layuense* and *E. nigrum* significantly restricted TMV infection, limiting initial virus establishment and reducing viral accumulation in treated plants compared with controls. Metabolomic profiling identified multiple differential metabolites, including compounds previously known to have anti-TMV activity, implicating fungal secondary metabolites in this antiviral effect (46). In addition, selected representative examples are summarized in Table 3.

Taken together, fungal endophytes such as *Beauveria*, *Trichoderma*, *Piriformospora* and *Hypocrea* spp. emerge as strong modulators of antiviral resistance by integrating direct virus suppression with vector control and host immune priming. Their ability to simultaneously enhance plant growth, activate JA/ET-mediated defenses and interfere with viral accumulation underscores their dual functional role in crop protection. However, variability in colonization efficiency and environment-dependent performance necessitates further mechanistic and field-scale validation before large-scale deployment.

Mechanisms of endophyte-mediated antiviral activity

Endophytic microorganisms suppress plant viruses through a multilayered network of direct and indirect mechanisms that collectively enhance host immunity, restrict viral replication and limit disease spread (Fig. 2). A comprehensive understanding of these mechanisms is crucial for the strategic development of endophyte-based biocontrol formulation.

Direct antiviral effects

Certain endophytes directly interfere with viral replication and movement by the production of bioactive metabolites, enzymes and volatile organic compounds (47). Bacterial endophytes such as *Bacillus* and *Streptomyces* spp. secrete lipopeptides (e.g., surfactins, fengycins), cyclodipeptides and antibiotics with antiviral activity. For instance, lecithin-induced production of fengycin lipopeptides by *B. amyloliquefaciens* PPL significantly enhanced resistance to CMV in pepper, while exogenous fengycin treatment elicited comparable defense responses, highlighting a direct role for lipopeptide-mediated antiviral defense (48). These molecules also function as immune elicitors, activating JA and SA dependent signaling cascades that reinforce antiviral resistance (49). Similarly, fungal endophytes such as *Epicoccum* and *Trichoderma* spp. produce phenolics, polyketides and other secondary metabolites that attenuate viral virulence. Recent studies demonstrate that culture filtrates from *Trichoderma* spp. reduced PVY symptom severity in potato, with in silico and molecular analyses indicating strong interactions between fungal metabolites and viral proteins, alongside modulation of host defense gene expression (50).

Induction of systemic resistance

Endophytic microorganisms can prime robust systemic resistance against plant viruses by activating host immune signaling networks. Endophytes such as *B. velezensis* PEA1 have been shown to ISR against CMV, significantly reducing viral accumulation and symptom development. Likewise, endophytic *Paraburkholderia, Paenibacillus, Pantoea* and *Pseudomonas* strains enhanced ISR and mitigated infections by Cymbidium ringspot virus (CymRSV) and CMV in *N. benthamiana* (41). In many cases, endophyte colonization also activates systemic acquired resistance (SAR), characterized by SA accumulation and upregulation of PR genes mediated through NPR1 and WRKY transcription factors (51).

Table 3. Fungal endophytes suppressing plant virus

Fungal endophyte	Host plant	Virus suppressed	Key metabolites / mechanism	Vector involvement (Yes/No)	References
H. lixii F3ST1	Tomato	TICV; ToCV	Systemic resistance induction; reduced virus replication & vector feeding	Yes (*T. vaporariorum*)	(45)
T. asperellum M2RT4	Tomato	TICV; ToCV	Endophytic colonization triggers immune defense; lower virus incidence	Yes (Vector feeding reduced)	(45)
Trichoderma harzianum	Maize (*Zea mays*)	*Sugarcane mosaic virus* (SCMV)	Colonization reduces viral titer and disease severity	No	(46)
Metarhizium anisopliae	Maize	SCMV	Endophytic colonization associated with virus suppression	No	(46)

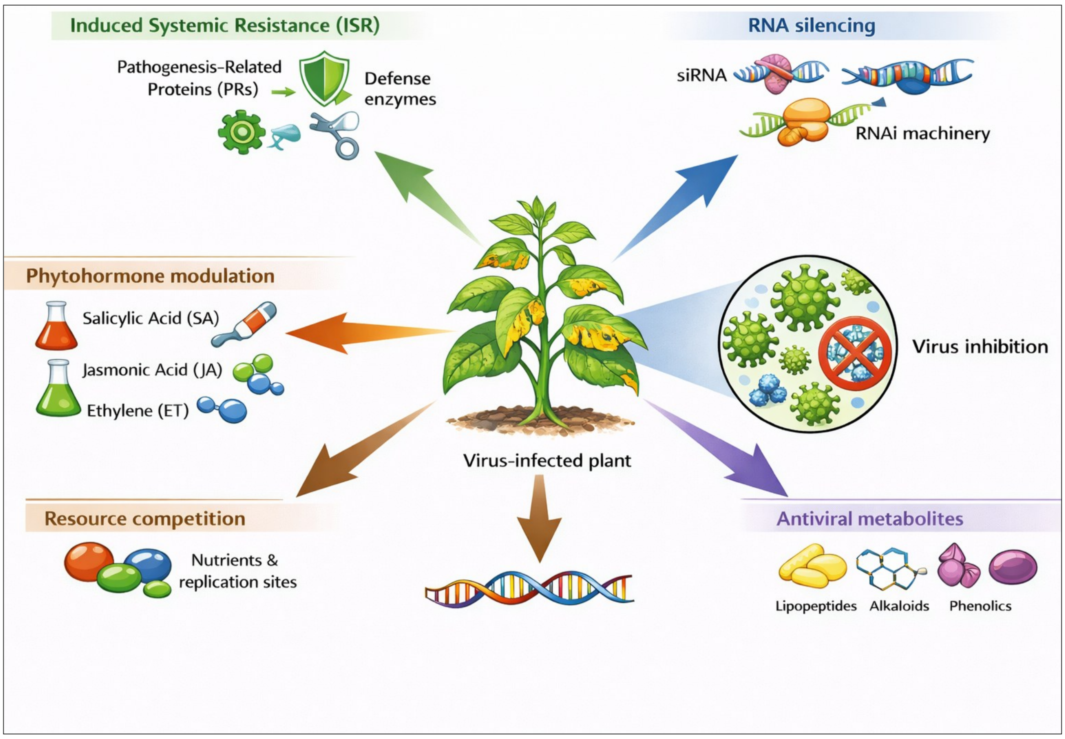

Fig. 2. Mechanisms of endophytes against plant virus.

Transcriptomic profiling of endophyte-treated plants challenged with GBNV revealed strong induction of SA-responsive defense genes, correlating with reduced viral titers and enhanced systemic immunity (52, 53).

Modulation of RNA silencing pathways

Emerging evidence indicates that endophytes can engage host RNA-silencing machinery, a central antiviral defense in plants. Endophytic *Fusarium solani* strain K was shown to deliver small RNAs into *N. benthamiana*, triggering RDR6-dependent systemic RNA silencing and host DNA methylation (54). Although direct demonstrations against specific plant viruses remain limited, this mechanism has strong implications for antiviral defense, as RNAi pathways are essential for resistance to RNA viruses such as CMV and ToMV (55). These findings suggest that endophytes may potentiate antiviral RNA-silencing responses through cross-kingdom RNA signaling.

Enzymatic degradation and vector-mediated effects

Endophyte-derived enzymes provide an additional layer of antiviral protection. Endophytic *B. subtilis* strains 26D and Ttl2 secrete ribonucleases and elevate host RNase activity, leading to marked reductions in viral RNA accumulation of PVX and PVY in tomato. This response is accompanied by upregulation of nuclease-associated PR genes (PR4 and PR10), supporting enzymatic degradation of viral genomes as a defense mechanism (23). Beyond direct antiviral effects, endophytes can indirectly suppress virus spread by targeting vectors. Endophytic entomopathogenic fungi such as *Beauveria bassiana*, which produce chitinases and proteases, alter plant volatile profiles and reduce aphid performance, thereby impairing transmission efficiency of viruses such as Potato leafroll virus (PLRV) (56).

Omics insights into endophyte plant virus interactions

Recent multi-omics studies have substantially advanced our understanding of endophyte–plant–virus interactions by revealing the molecular frameworks underlying endophyte-mediated antiviral defense. Integrated metagenomics and metatranscriptomics have identified specific endophytic taxa, colonization traits and biosynthetic gene clusters associated with antiviral metabolite production and host adaptation (57). Transcriptome and hormone-targeted metabolomics studies in virus-infected citrus revealed dynamic changes in phytohormone signaling (JA, SA, abscisic acid (ABA)) and associated gene networks during infection, demonstrating the utility of omics for identifying defense-linked pathways (58). Metabolomic analyses further reveal the accumulation of secondary metabolites, lipopeptides, phenolics and phytohormone modulators produced during endophyte colonization that are strongly associated with suppression of viral replication and symptom severity (59). Small RNA and transcriptome studies have additionally highlighted the potential role of endophytes in priming RNA-silencing pathways and redox-associated defense networks during viral infection (57). Importantly, microbiome-scale omics analyses demonstrate that endophyte-driven shifts in community composition influence disease outcomes, providing a basis for rational microbiome engineering.

Biotechnological applications in enhancing endophyte-mediated virus management

Biotechnological innovations are rapidly extending the antiviral capabilities of endophytes beyond their natural phenotypes, enabling precise and programmable virus control. Genome editing tools such as CRISPR/Cas9 have recently been applied to endophytic fungi and bacteria to manipulate genes involved in secondary metabolite biosynthesis, stress tolerance and host colonization, thereby enhancing traits linked to antiviral efficacy (60). Editing of regulatory and biosynthetic genes in *Trichoderma* spp. has been shown to optimize metabolite production and plant interaction traits relevant to disease suppression (61). In parallel, RNAi technologies are increasingly being integrated with microbial delivery systems, positioning endophytes as in planta factories for antiviral RNA molecules. Recent studies demonstrated that engineered double-stranded RNAs (edsRNAs) targeting viral replicase and movement protein genes provided strong protection against CMV and ToMV, highlighting the feasibility of RNAi-based antiviral strategies (62). Synthetic microbial communities (SynComs), which include antiviral endophytes alongside growth-promoting microbes, offer an integrated strategy.

Challenges and limitations

Despite strong experimental evidence, the field-level deployment of endophytic microorganisms for plant virus management remains inconsistent. A major constraint is the poor translation of greenhouse efficacy to open-field conditions, where soil properties, climate and native microbiomes strongly influence endophyte establishment and function (63). Recent field microbiome studies show that competitive exclusion by indigenous microbes often limits persistence of introduced endophyte (64). Antiviral efficacy is further constrained by the high specificity of host–endophyte–virus interactions, with performance varying across plant genotypes and viral strains. Context dependency adds complexity, as endophytes may shift along the mutualism–neutralism continuum depending on host physiology and environmental stress. Even effective strains face scale-up challenges, requiring optimized fermentation and formulation strategies to preserve viability and bioactivity (65). These technical demands increase production costs and hinder commercialization. Regulatory uncertainty further slows adoption, as microbial inoculants frequently fall between pesticide and biofertilizer frameworks. Overcoming these barriers will require standardized field validation, formulation innovation and harmonized regulatory pathways.

Future directions

The challenges limiting endophyte-based virus management are counterbalanced by emerging technological and ecological opportunities. Future advances will require a shift from discovery-driven studies to hypothesis-driven engineering of plant microbiomes for predictable antiviral outcomes. Integration of multi-omics approaches can unravel the molecular dialogue among plants, endophytes and viruses, identifying biosynthetic gene clusters and immune elicitors underlying antiviral activity. This knowledge enables synthetic biology based engineering of endophytes with enhanced functions (66). Promising directions include the heterologous expression of antiviral pathways and the development of endophytes capable of in planta delivery of RNAi molecules targeting viral genes (67). Research is also moving beyond single-strain inoculants toward synthetic microbial consortia that provide functional complementarity and field-level stability. At a broader scale, managing the plant microbiome as an integrated unit offers new opportunities to suppress viral diseases while enhancing tolerance to abiotic stresses (68). Collectively, these findings underscore the potential of endophyte-based management considered as environmentally sustainable tools that enhance crop resilience to viral diseases while reducing reliance on chemical pesticides in resilient agricultural systems.

Conclusion

Plant viral diseases remain a major challenge to global food security and endophytic microorganisms offer a promising, eco-friendly alternative to conventional management methods. Acting through multiple mechanisms, such as antiviral metabolite production, immune priming and improved plant vigour, endophytes provide a resilient tool for integrated pest management while reducing dependence on chemical pesticides. Their ability to complement genetic resistance and other biocontrol strategies highlights their central role in sustainable agriculture. However, translating laboratory success into reliable field performance requires overcoming challenges in environmental stability, large-scale production and regulatory approval. Future research should prioritize advanced formulation, deep insights into host–microbiome–pathogen interactions and the design of robust synthetic microbial communities to fully harness the potential of endophytes in plant virus management.

Acknowledgements

The authors are thankful to the Department of Plant Pathology and the Dean, School of Post Graduate Studies, Tamil Nadu Agricultural University, Coimbatore for technical support.

Authors' contributions

SRS conceptualized the review and drafted the manuscript. KR critically reviewed and revised the manuscript. GC, PG, SN and JM provided overall supervision, scholarly guidance and critical inputs throughout the preparation of the review. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. He S, Krainer KMC. Pandemics of people and plants: Which is the greater threat to food security? Mol Plant. 2020;13(7):933–34. https://doi.org/10.1016/j.molp.2020.06.007
2. Jiao Z, Tian Y, Cao Y, Wang J, Zhan B, Zhao Z. A novel pathogenicity determinant hijacks maize catalase 1 to enhance viral multiplication and infection. New Phytol. 2021;230(3):1126–41. https://doi.org/10.1111/nph.17206
3. Jiang T, Du K, Xie J, Sun G, Wang P, Chen X, et al. Activated malate circulation contributes to the manifestation of light-dependent mosaic symptoms. Cell Rep. 2023;42(4):112345. https://doi.org/10.1016/j.celrep.2023.112333
4. Ferreira AL, Ghanim M, Xu Y, Pinheiro PV. Interactions between common bean viruses and their whitefly vector. Viruses. 2024;16(10):1567. https://doi.org/10.3390/v16101567
5. Naveed H, Islam W, Jafir M, Andoh V, Chen L, Chen K. A review of interactions between plants and whitefly-transmitted begomoviruses. Plants. 2023;12(21):3677. https://doi.org/10.3390/plants12213677
6. Iftikhar Y, Mubeen M, Sajid A, Zeshan MA, Shakeel Q, Abbas A, et al. Effects of tomato leaf curl virus on growth and yield parameters of tomato crop. Arab J Plant Prot. 2021;39(1):1–7. https://doi.org/10.22268/AJPP-039.1.079083
7. Alharbi SA, Ali MH, Elsaid EM, Eid MR, Hassanin WS. Addressing various strategies for combating the leaf-roll virus in potato plants. Int J Math Sci. 2025;2025(1):7186685. https://doi.org/10.1155/ijmm/7186685
8. Osogo AK, Muyekho F, Okoth P, Were H, Ayaaga G. Occurrence, distribution, incidence and severity of common bean viral diseases in resource-limited smallholder farms of western Kenya. Crop Prot. 2025;194:107231. https://doi.org/10.1016/j.cropro.2025.107231

9. Maugeri M, Rodríguez M, Bejerman N, Laguna IG, Rodríguez Pardina P. Biological, molecular and physiological characterization of four soybean mosaic virus isolates present in Argentine soybean crops. Viruses. 2025;17(7):995. https://doi.org/10.3390/v17070995

10. Pattanavongsawat C, Malichan S, Vannatim N, Chaowongdee S, Hemniam N, Paemanee A, et al. Enhancing plant resistance to Sri Lankan cassava mosaic virus using salicylic acid. Metabolites. 2025;15(4):261. https://doi.org/10.3390/metabo15040261

11. Dupuis B, Nkuriyingoma P, Ballmer T. Economic impact of potato virus Y (PVY) in Europe. Potato Res. 2024;67(1):55–72. https://doi.org/10.1007/s11540-023-09623-x

12. Hossain MM, Sultana F, Mostafa M, Ferdus H, Rahman M, Rana JA, et al. Plant disease dynamics in a changing climate: Impacts, molecular mechanisms and climate-informed strategies for sustainable management. Discov Agric. 2024;2(1):132. https://doi.org/10.1007/s44279-024-00144-w

13. Makarova SS, Makarov VV, Taliansky ME, Kalinina NO. Resistance to viruses of potato: Current status and prospects. Vavilov J Genet Breed. 2017;21:62–73. https://doi.org/10.18699/VJ17.223

14. Andika IB, Wei S, Cao C, Salaipeth L, Kondo H, Sun L. Phytopathogenic fungus hosts a plant virus: A naturally occurring cross-kingdom viral infection. Proc Natl Acad Sci USA. 2017;114:12267–72. https://doi.org/10.1073/pnas.1714916114

15. Khalid B, Javed MU, Ashraf MA, Saeed HZ, Shaheen M, Riaz T, et al. Microbial bio stimulants as sustainable strategies for enhancing plant resistance to viral diseases: Mechanisms and applications. Hosts Viruses. 2025:12(93-110).

16. Lee GH, Ryu CM. Spraying of leaf-colonizing *Bacillus amyloliquefaciens* protects pepper from cucumber mosaic virus. Plant Dis. 2016;100:2099–105. https://doi.org/10.1094/PDIS-02-16-0129-RE

17. Pathak VM, Verma VK, Rawat BS, Kaur B, Babu N, Sharma A, et al. Current status of pesticide effects on environment, human health and its eco-friendly management as bioremediation: A comprehensive review. Front Microbiol. 2022;13:962619. https://doi.org/10.3389/fmicb.2022.962619

18. Ongaga EG, Muli JK, Kamau PK, Budambula NL. Endophytic microflora of *Crotalaria*: Their diversity and role in plant growth promotion. Curr Microbiol. 2025;82(5):1–8. https://doi.org/10.1007/s00284-025-04181-6

19. Khan D, Shaw R, Kabiraj A, Paul A, Bandopadhyay R. Microbial inheritance through seed: A clouded area needs to be enlightened. Arch Microbiol. 2025;207(1):23. https://doi.org/10.1007/s00203-024-04225-8

20. Litwin A, Nowak M, Różalska S. Entomopathogenic fungi: Unconventional applications. Rev Environ Sci Biotechnol. 2020;19:23–42. https://doi.org/10.1007/s11157-020-09525-1

21. Yadav AN, Kumar V, Dhaliwal HS, Prasad R, Saxena AK. Microbiome in crops: Diversity, distribution and potential role in crop improvement. In: Prasad R, Gill SS, Tuteja N, editors. Crop improvement through microbial biotechnology. India: Elsevier; 2018. p. 305–32. https://doi.org/10.1016/B978-0-444-63987-5.00015-5

22. Khan R, He P, Chen X, Ahmed A, Wu Y, Tang G, et al. *Bacillus* endophytes for sustainable management of tomato spotted wilt virus and yield production. Pest Manag Sci. 2025;81(4):2073–85. https://doi.org/10.1002/ps.8606

23. Veselova SV, Sorokan AV, Alekseev VY, Maksimov IV. Effect of endophytic bacteria *Bacillus subtilis* on the components of pro-/antioxidant system of tomato (*Solanum lycopersicum* L.) plants infected with potato viruses X and Y. Appl Biochem Microbiol. 2025;61:1141–50. https://doi.org/10.1134/S0003683825601519

24. Beris D, Theologidis I, Skandalis N, Vassilakos N. *Bacillus amyloliquefaciens* strain MBI600 induces salicylic acid-dependent resistance in tomato plants against tomato spotted wilt virus and potato virus Y. Sci Rep. 2018;8(1):10320. https://doi.org/10.1038/s41598-018-28677-3

25. Taha M, Ghaly M, Atwa H, Askoura M. Evaluation of the effectiveness of soil *Streptomyces* isolates for induction of plant resistance against tomato mosaic virus. Curr Microbiol. 2021;78(8):3032–43. https://doi.org/10.1007/s00284-021-02567-w

26. El-Gendi H, Al-Askar AA, Király L, Samy MA, Moawad H, Abdelkhalek A. Foliar applications of *Bacillus subtilis* HA1 culture filtrate enhance tomato growth and induce systemic resistance against tobacco mosaic virus infection. Horticulturae. 2022;8(4):301. https://doi.org/10.3390/horticulturae8040301

27. Jha Y, Kumari A, Ghanaim AM, Saglam NG, Mohamed HI. Bacterial endophytes and arbuscular mycorrhizal fungi mitigate marigold mosaic virus in *Tagetes erecta* via antioxidant enzyme induction and gene regulation. Eur J Plant Pathol. 2025;173:943–58. https://doi.org/10.1007/s10658-025-03104-2

28. Sofla ASSA, Taheri H, Parizipour MHG, Soleymani F. Molecular and phenotypic responses of rhizobacteria-treated tomato plants to tomato mosaic virus under greenhouse conditions. Iran J Biotechnol. 2023;21(1):e3220. https://doi.org/10.30498/ijb.2022.319382.3220

29. Gayathri M, Sharanya R, Renukadevi P, Nakkeeran S, Saranya N, Varanavasiappan S, et al. Deciphering the antiviral nature of endophytic *Bacillus* spp. against groundnut bud necrosis virus in cowpea and tomato. Front Microbiol. 2024;15:1410677. https://doi.org/10.3389/fmicb.2024.1410677

30. Abdalla OA, Bibi S, Zhang S. Application of plant growth-promoting rhizobacteria to control papaya ringspot virus and tomato chlorotic spot virus. Arch Phytopathol Plant Prot. 2017;50:584–97. https://doi.org/10.1080/03235408.2017.1352248

31. Firmansyah D. Use of chitosan and plant growth-promoting rhizobacteria to control squash mosaic virus on cucumber plants. Am J Plant Physiol. 2017;12:148–55. https://doi.org/10.3923/ajppaj.2017.148.155

32. Vanthana M, Nakkeeran S, Malathi VG, Renukadevi P, Vinodkumar S. Induction of in planta resistance by flagellin and elongation factor-Tu of *Bacillus amyloliquefaciens* (VB7) against groundnut bud necrosis virus in tomato. Microb Pathog. 2019;137:103757. https://doi.org/10.1016/j.micpath.2019.103757

33. Basit A, Shah ST, Ullah I, Mohamed HI. Microbial bioactive compounds produced by endophytes and their uses in plant health. In: Plant growth-promoting microbes for sustainable biotic and abiotic stress management. Springer; 2021. p. 285–318. https://doi.org/10.1007/978-3-030-67920-6_13

34. Li H, Ding X, Wang C, Ke H, Wu Z, Wang Y, et al. Control of tomato yellow leaf curl virus disease by *Enterobacter asburiae* BQ9 through priming plant resistance. Turk J Biol. 2016;40:150–59. https://doi.org/ 10.3906/biy-1502-12

35. Vinodkumar S, Nakkeeran S. *Bacillus amyloliquefaciens* (VB7) with diverse antimicrobial peptide genes: A potential antagonist for fairy ring spot in carnations. Curr Sci. 2018;115:1519–24. https://doi.org/10.18520/cs/v115/i8/1519-1524

36. Amin HA, El Kammar HF, Saied SM, Soliman AM. Effect of *Bacillus subtilis* on potato virus Y disease resistance and growth promotion in potato plants. Eur J Plant Pathol. 2023;167:743–58. https://doi.org/10.1007/s10658-023-02658-9

37. Ramzan M, Bushra T, Idrees AN. Identification and application of biocontrol agents against cotton leaf curl virus disease in *Gossypium hirsutum* under greenhouse conditions. Biotechnol Equip. 2016;30:469–78. https://doi.org/10.1080/13102818.2015.1135087

38. Abdelkhalek A, Al-Askar AA, Hamzah KA, Elbeaino T, Moawad H, El-Gendi H, et al. *Bacillus siamensis* strain B30 enhances systemic resistance against bean yellow mosaic virus in faba bean plants. Eur J Plant Pathol. 2024;169:1–15. https://doi.org/10.1007/s10658-024-02943-9

39. Alam K, Mazumder A, Sikdar S, Zhao YM, Hao J, Song C, et

al. *Streptomyces*: The biofactory of secondary metabolites. Front Microbiol. 2022;13:968053. https://doi.org/10.3389/fmicb.2022.968053

40. Xuan Z, Wang Y, Shen Y, Pan X, Wang J, Liu W, et al. *Bacillus velezensis* HN-2: A potent antiviral agent against pepper veinal mottle virus. Front Plant Sci. 2024;15:1403202. https://doi.org/10.3389/fpls.2024.1403202
41. Shahzad GI, Passera A, Maldera G, Casati P, Marcello I, Bianco PA. Biocontrol potential of endophytic plant-growth-promoting bacteria against phytopathogenic viruses: Molecular interaction with the host plant and comparison with chitosan. Int J Mol Sci. 2022;23(13):6990. https://doi.org/10.3390/ijms23136990
42. Sarsaiya S, Shi J, Chen J. A comprehensive review on fungal endophytes and their dynamics in Orchidaceae plants. Bioengineered. 2019;10(1):316–34. https://doi.org/10.1080/21655979.2019.1644854
43. Al-Abedy AN, Al-Shujairi KA, Al-Salami I, Ashfaq M, AL-Musawi BH. Genetic variation among tomato yellow leaf curl virus isolates and their control using biological control fungi and nanoparticles. Int J Agricult Stat Sci. 2021;17(1):229–36.
44. Ochal KKL, Pierre E, Diane YY, Sahu KP, Vanessa ND, Herman KWT. Biological elicitor potential of endospheric *Trichoderma* against pepper (*Capsicum annuum* L.) leaf curl virus. Arch Phytopathol Plant Prot. 2021;54(19–20):1926–52. https://doi.org/10.1080/03235408.2021.1957412
45. Paweer MMZ, Namikoye ES, Nchore SB, Akutse KS. Can fungal endophytes suppress *Trialeurodes vaporariorum* and virus transmission under field conditions? Front Cell Infect Microbiol. 2025;15:1470821. https://doi.org/10.3389/fcimb.2025.1470821
46. An Q, Nzabanita C, Zhang L, Wang Y, Wang S, Guo L, Zhao Y. Culture filtrates from *Epicoccum* spp. confer resistance against tobacco mosaic virus in *Nicotiana benthamiana*. Physiol Mol Plant Pathol. 2025;138:102732. https://doi.org/10.1016/j.pmpp.2025.102732
47. Jiang T, Hao T, Chen W, Li C, Pang S, Fu C, et al. Reprogrammed plant metabolism during viral infections: Mechanisms, pathways and implications. Mol Plant Pathol. 2025;26(2):e70066. https://doi.org/10.1111/mpp.70066
48. Kang BR, Park JS, Jung WJ. Antiviral activity of lecithin-induced fengycin lipopeptides against cucumber mosaic virus. Microb Pathog. 2021;155:104910. https://doi.org/10.1016/j.micpath.2021.104910
49. Qiao J, Borriss R, Sun K, Zhang R, Chen X, Liu Y, et al. Regulatory mechanisms of surfactin production by *Bacillus*: Research advances. Microb Cell Fact. 2024;23:100. https://doi.org/10.1186/s12934-024-02372-7
50. Rizk MN, Ketta HA, Shabana YM. *Trichoderma* culture filtrates as biocontrol agents for potato virus Y management. Potato Res. 2025;68:4467–92. https://doi.org/10.1007/s11540-025-09926-1
51. Karthikeyan G, Barkavi G, Harish S, Varanavasiappan S. Expression of defense genes in cucumber mosaic virus–PGPR interactions in ridge gourd (*Luffa acutangula*). Physiol Mol Plant Pathol. 2024;129:102176.
52. Gore S, Singh S, Swarnkar P, Rathore KS. Endophyte-mediated plant defence responses against pathogenic bacteria and fungi. Discov Plants. 2025;2:331. https://doi.org/10.1007/s44372-025-00429-4
53. Sharanya R, Gayathri M, Renukadevi P, Saranya N, Suganthy M, Varanavasiappan S, et al. Induction of innate immunity in tomato reveals antiviral nature of bacterial endophytes against groundnut bud necrosis virus. J Virol. 2025;99(2):e01803-24. https://doi.org/10.1128/jvi.01803-24
54. Dalakouras A, Katsaouni A, Avramidou M, Dadami M, Tsiouri E, Vasileiadis O, et al. A beneficial fungal root endophyte triggers systemic RNA silencing and DNA methylation. RNA Biol. 2023;20(1):20–30. https://doi.org/10.1080/15476286.2022.2159158
55. Liu S, Chen M, Li R, Li WX, Gal-On A, Jia Z, et al. Identification of regulators of antiviral RNA interference in *Arabidopsis thaliana*. Nat Commun. 2022;13:2994. https://doi.org/10.1038/s41467-022-30771-0
56. Veselova SV, Sorokan AV, Burkhanova GF, Rumyantsev SD, Cherepanova EA, Alekseev VY, et al. *Bacillus subtilis* induces defense responses against potato viruses X and Y in tomato plants. Biomolecules. 2022;12(2):288. https://doi.org/10.3390/biom12020288
57. Jangra S, Devendran R, Ghosh A. Plant–virus–vector interactions explored through omics. BMC Genomics. 2024;25:866. https://doi.org/10.1186/s12864-024-10758-5
58. Hu X, Liang L, Chen X, Deng L, Zou L, Dong M, et al. Transcriptomic and phytohormone metabolomic changes in *Citrus limon* infected by citrus yellow vein clearing virus. Horticulturae. 2024;10(3):231. https://doi.org/10.3390/horticulturae10030231
59. Mishra S, Priyanka, Sharma S. Metabolomic insights into endophyte -derived bioactive compounds. Front Microbiol. 2022;13:835931. https://doi.org/10.3389/fmicb.2022.835931
60. Kim TH, Lee SW. Therapeutic applications of genome editing technologies in viral diseases. Int J Mol Sci. 2022;23(10):5399. https://doi.org/10.3390/ijms23105399
61. Scott K, Konkel Z, Gluck-Thaler E, David GEV, Simmt CF, Grootmyers D, et al. Endophyte genomes support greater metabolic gene cluster diversity in *Trichoderma*. PLoS One. 2023;18(12):e0289280. https://doi.org/10.1371/journal.pone.0289280
62. Knoblich M, Gursinsky T, Gago-Zachert S, Weinholdt C, Grau J, Behrens SE. dsRNAs designed from characterized siRNAs are highly effective against cucumber mosaic virus. Nucleic Acids Res. 2025;53(5):gkaf136. https://doi.org/10.1093/nar/gkaf136
63. Mohanan A, Nigam R, Yeliya P, Daniel GR, Devi NO, Sahu R, et al. The role of plant microbiomes in suppressing soilborne pathogens: A review. J Adv Microbiol. 2025;25(5):160–78. https://doi.org/10.9734/jamb/2025/v25i5942
64. Bard NW, Cronk QC, Davies TJ. Fungal endophytes can modulate plant invasion. Biol Rev. 2024;99(5):1652–71. https://doi.org/10.1111/brv.13085
65. Ganeshan S, Kim SH, Vujanovic V. Scaling-up production of plant endophytes in bioreactors. Bioresour Bioprocess. 2021;8(1):63. https://doi.org/10.1186/s40643-021-00417-y
66. Shishodia SK, Thakur R, Shankar J, Singh R, De LosRios-Escalante P. Unlocking endophytic mysteries using multi-omics. In: Multi-omics approach to investigate endophyte diversity. Springer Nature; 2025. p. 125–44. https://doi.org/10.1007/978-981-96-4100-0_6
67. Venu E, Ramya A, Babu PL, Srinivas B, Kumar S, Reddy NK, et al. Exogenous dsRNA-mediated RNAi for viral disease resistance in plants. Viruses. 2024;17(1):49. https://doi.org/10.3390/v17010049
68. Sharma A, Bora P. Engineering synthetic microbial communities to restructure the phytobiome. World J Microbiol Biotechnol. 2025;41(7):228. https://doi.org/10.1007/s11274-025-04460-1

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.