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PHYLLOSPHERIC ENDOPHYTIC BACTERIA FOR CHILLI LEAF CURL DISEASE MANAGEMENT AND PLANT GROWTH PROMOTION IN CHILLI (*Capsicum annuum*)

P.R. Anuranj¹, N.S. Radhika^{1*}, S. Anu Rajan², T. Anuradha³, N.V. Radhakrishnan¹ and B.A. Krishna¹

¹Department of Plant Pathology, College of Agriculture, Vellayani, Kerala Agricultural University, Thiruvananthapuram – 695 522, Kerala, India.

²Department of Microbiology, College of Agriculture, Vellayani Kerala Agricultural University, Thiruvananthapuram – 695 522, Kerala, India.

³Department of Molecular Biology and Biotechnology, College of Agriculture, Vellayani, Kerala Agricultural University, Thiruvananthapuram – 695 522, Kerala, India.

*Corresponding author E-mail : radhika.ns@kau.in

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ABSTRACT

Exploration of the phyllosphere microbiome of chilli leaf curl disease tolerant chilli plants for prospective endophytic bacteria for virus disease management and growth promotion was attempted in this study. Ten endophytic bacteria were isolated from the leaves of tolerant *Capsicum* spp (*C. annuum*, *C. frutescens*, *C. chinense*), which is in the flowering stage and not showing any symptoms from the fields of College of Agriculture, Vellayani. Maintenance of virus culture of chilli leaf curl disease complex by graft inoculation on the susceptible variety Vellayani Athulya was undertaken and presence of virus infection was confirmed by PCR amplification using chilli leafcurl virus coat protein specific primer (120bp). The in planta experiment laid out under insect proof net house condition in CRD design with twenty days old plants of chilli variety Vellayani Athulya revealed that foliar application of isolated bacterial growth (2% @10⁸cfu ml⁻¹) 5 days before the introduction of virus reduced disease severity relative to the untreated, virus-inoculated control, and isolates VITJ,VIKD,VIIC recorded the lowest post-inoculation disease index (33.33, 37.78 and 37.78 per cent, respectively, against 60.00 per cent in the control) and were selected for further evaluation. Seed biopriming with 2% solution of these three isolates for 4 hours significantly enhanced shoot length, root length, total seedling length and seedling vigour index over the absolute control, with isolate VIIC recording the highest germination percentage (88.33%) and seedling vigour index (971.6), providing a 67.7 percent enhancement over the control plants (579.2). Colony morphology, biochemical characterization and 16S rRNA gene sequencing identified best three isolates as *Priestia aryabhattai* (VITJ), *Bacillus albus* (VIKD) and *Bacillus velezensis* (VIIC). These findings indicate that endophytic bacterial isolates, particularly VITJ, VIKD and VIIC can be formulated and utilized effectively for the management of chilli leaf curl virus disease.

Key words : Chilli leaf curl disease, Endophytic bacteria, Capsicum, Induced systemic resistance, Biopriming, Plant growth promotion.

Introduction

Chilli (*Capsicum* spp.) is one of the most important commercial vegetable cum spice crop grown worldwide. Its immature green fruits are widely consumed as a vegetable, while the mature, dried fruits are used as a spice on account of their pronounced pungency and distinctive flavour profile (Hasan *et al.*, 2014). In India, chilli is cultivated over an area of about 377,000 ha with

an annual production of 3.78 million tonnes (National Horticulture Board, 2018), making it a crop of substantial economic significance to Indian agriculture. In Kerala, chilli occupied an area of 2,860 ha with a production of 58,617 tonnes during 2023–24 (DASD, 2023-24), reflecting its importance as a homestead and commercial vegetable cultivation across the state.

Chilli crop is severely constrained by a wide range

of pathogens, among which viruses are particularly damaging. As many as 65 viruses have been reported to infect chilli, including several begomoviruses that cause chilli leaf curl virus disease (ChiLCVD) across chilli-growing regions of the world (Nigam *et al.*, 2015). ChiLCVD is regarded as the most destructive viral disease of chilli in terms of both incidence and yield loss, with reports of complete loss of marketable fruit under severe infection (Senanayake *et al.*, 2007; Kumar *et al.*, 2011a, b; Senanayake *et al.*, 2012). The disease is caused by a complex consisting of a monopartite chilli leaf curl virus together with a DNA- α satellite component (Zehra *et al.*, 2017).

Current management strategies for begomovirus-associated leaf curl diseases rely largely on the use of tolerant or resistant varieties and on insecticidal control of the whitefly vector, since no source of whitefly resistance has yet been identified in *Capsicum* spp. (Nalla *et al.*, 2023). However, no chemical viricide is currently available for the direct management of plant viral diseases, unlike the fungicides and antibiotics available for fungal and bacterial pathogens. This gap underscores the need for alternative, sustainable disease management strategies.

Beneficial bacterial endophytes offer a promising, eco-friendly alternative for managing viral diseases in crop plants. Endophytic bacteria can trigger induced systemic resistance (ISR), protecting the host against a broad spectrum of pathogens, including soil-borne fungi, biotrophic pathogens, viruses, nematodes and insect herbivores (Oukala *et al.*, 2021). In addition to their protective role, endophytic bacterial consortia have shown to enhance seed germination and overall seed quality without any deleterious effects on the host (Matthews *et al.*, 2024), indicating a dual potential for both disease management and plant growth promotion.

Against this background, the present study was undertaken to explore bacterial endophytes from the leaves of tolerant *Capsicum* spp. with the objective of utilizing it for a sustainable, eco-friendly strategy that combines plant growth promotion with the management of chilli leaf curl disease complex.

Materials and Methods

The study was undertaken at the Department of Plant Pathology, College of Agriculture, Vellayani, Thiruvananthapuram, Kerala, using the chilli variety Vellayani Athulya as the standard test/susceptible variety.

Maintenance of virus culture and molecular detection

Infected scions showing typical symptoms of chilli



Plate 1 : Score chart (0-5) for chilli leaf curl disease complex [0 : No symptoms, 1 : Slight leaf curling, 2 : Moderate leaf curling, 3 : Severe leaf crinkling, 4 : Severe leaf reduction, 5 : Extreme stunting & distortion].

leaf curl disease were collected from college farm and fields in Thiruvananthapuram district. Twenty-day-old chilli seedlings (Vellayani Athulya) were artificially inoculated with Chilli leaf curl virus (ChiLCV) *via* graft transmission. Infected scions were excised from symptomatic plants of the chilli variety 'Vellayani Athulya' exhibiting a uniform disease rating score of 4 on a standard 0–5 disease severity scale (Plate 1). Grafting was performed by cleft/wedge method onto the healthy rootstocks. A specific primer pair targeting the coat protein (AV1) gene was additionally designed based on the reference sequence of chilli leaf curl virus isolate VLNY1 (GenBank accession MN231253.1), to confirm the identity of the virus used for graft inoculation and the presence of the virus in the scion source was confirmed by PCR using the designed chilli leafcurl virus coat protein specific primer (120bp).

Isolation of endophytic bacteria

Endophytic bacteria were isolated from leaves of tolerant *Capsicum* spp. Growing at the fields of College of Agriculture, Vellayani, following a modified isolation procedure described by Sarmah *et al.* (2023). Top 3 or 4 chilli leaves of tolerant plants were brought to the laboratory and washed under running water to remove surface impurities, followed by surface sterilization using ethanol (70%) for 3 minutes. Leaf bits were subsequently cut and immersed in sodium hypochlorite (NaOCl @4%) for 1 minute and were rinsed thrice in sterile distilled water to remove residual disinfectants. To confirm the efficacy of the surface sterilization procedure, a 100 μ L of the final rinse water was spread-plated onto nutrient agar (NA) plates and incubated at $28 \pm 2^\circ\text{C}$ for 24–48 hours; absence of any microbial colony growth confirmed surface sterilization, whereas batches displaying growth were discarded. Surface sterilised leaf bits were then placed on nutrient agar (NA) medium, regular subculturing was undertaken at weekly intervals.

Screening of bacterial isolates against chilli leaf curl disease

Pot culture studies were conducted to evaluate the efficacy of the isolated bacterial endophytes in managing

chilli leaf curl disease, using a Completely Randomized Design (CRD) with the isolates obtained as treatments, along with a virus-inoculated control, on the chilli variety Vellayani Athulya. Virus transmission was carried out *via* scion grafting to twenty days old healthy plants and a foliar application of bacterial suspensions ($2\% @ 10^8$ cfu ml^{-1}) was carried out five days before grafting (pre-treatment) and five days after grafting (post-treatment). Disease severity was scored on a 0–5 scale following Banerjee and Kalloo (1987), and disease index (DI) was computed from these severity scores.

Disease severity was converted to Percent Disease Index according to the method described by McKinney (1923)

$$DI = \left[\frac{\sum(\{\text{Numerical rating}\})}{\{\text{Total number of plants scored}\} \times \{\text{Maximum disease grade}\}} \right] \times 100$$

where the maximum disease grade was 5, corresponding to the 0–5 scale of Banerjee and Kalloo (1987).

Evaluation for growth promotion (Seed biopriming)

The three best-performing isolates were selected and used for biopriming of chilli seeds (variety Vellayani Athulya) at 10^8 cfu ml^{-1} , following the standard protocol of Yildirim *et al.* (2021). The experiment was laid out in a CRD with four treatments an absolute (healthy, non-bioprimed) control and biopriming with isolates VITJ, VIKD and VIIC each replicated tentimes. Biopriming was carried out by dipping the seeds in solution of bacterial endophytes (2%) for four hours followed by shade drying. The paper towel method of Abdul-Baki and Anderson (1973) was followed to calculate the seedling vigor index based on the germination percentage and seedling (shoot and root) length measured 15 days after sowing.

Characterization of endophytic bacteria

Colony and culture characteristics (shape, size, colour, texture and elevation) of the three best-performing isolates were recorded. Molecular identification of the isolates was undertaken through 16S rRNA gene sequencing.

Statistical analysis

Data generated on disease incidence, disease severity, germination percentage, seedling growth parameters and seedling vigour index were statistically analysed for a Completely Randomized Design and tested for significance at the 5 per cent level using the GRAPES software (Gopinath *et al.*, 2021).

Results

Maintenance of virus culture and molecular detection

Twenty days old chilli plants were infected with chilli leaf curl virus through graft transmission technique using scions of Vellayani Athulya having a uniform disease score (4).

PCR amplification of DNA extracted from the graft-inoculated scion source, using chilli leafcurl virus coat protein specific primer yielded the expected diagnostic amplicon of approximately 120 bp (Fig. 1), confirming the presence of chilli leafcurl virus and validating the virus culture used as the source of inoculum for the subsequent screening trial.

Isolation of endophytic bacteria

A total of ten bacterial endophytes were isolated and maintained as pure culture from the leaves of six tolerant *Capsicum* genotypes from chilli fields at Instructional Farm, College of Agriculture, Vellayani (Table 1). Colonies isolated from surface-sterilised leaf tissue of Local (VIKA), Vellayani Athulya (VIAT1–VIAT3), Jwalamukhi (VIJM1–VIJM3), Thejus (VITJ), KD-2 (VIKD) and IC-208580 (VIIC) (Plate 2). In every case, the absence of bacterial growth on the corresponding wash-water sterility-check plate confirmed the effectiveness of the surface-sterilisation procedure, indicating that the isolates recovered were of true endophytic origin rather than leaf surface colonisers.

Screening of bacterial isolates against chilli leaf curl disease

Under pot culture conditions, disease incidence did not differ significantly among the virus-inoculated treatments, ranging from 77.8% to 100.0%, whereas the uninoculated absolute control remained completely free of infection (0.00%) (Tables 2 and 3).

Table 1 : Details of endophytic bacterial isolates and the source of isolation.

Isolate code	Source chilli genotype / variety
VIKA	Local (<i>C. frutescens</i>)
VIAT1	Vellayani Athulya (<i>C. annum</i>)
VIAT2	Vellayani Athulya (<i>C. annum</i>)
VIAT3	Vellayani Athulya (<i>C. annum</i>)
VIJM1	Jwalamukhi (<i>C. annum</i>)
VIJM2	Jwalamukhi (<i>C. annum</i>)
VIJM3	Jwalamukhi (<i>C. annum</i>)
VITJ	Vellayani Thejus (<i>C. annum</i>)
VIKD	KD-2 (<i>C. annum</i>)
VIIC	IC-208580 (<i>C. frutescens</i>)

Table 2 : Disease incidence and disease index (DI) of chilli leaf curl disease in chilli plants after pre-treatment application (30 DAT) of endophytic bacterial isolates, under pot culture conditions.

Treatments	Disease incidence (%) 30 DAT	Disease Index (DI)
Foliar application of VIKA isolate	100.000 ± 0.000 ^b	77.778 ± 16.777 ^{bc}
Foliar application of VIAT1 isolate	100.000 ± 0.000 ^b	86.667 ± 6.667 ^c
Foliar application of VIAT2 isolate	100.000 ± 0.000 ^b	75.556 ± 21.430 ^{bc}
Foliar application of VIAT3 isolate	100.000 ± 0.000 ^b	80.000 ± 11.547 ^{bc}
Foliar application of VIJM1 isolate	100.000 ± 0.000 ^b	88.889 ± 7.698 ^c
Foliar application of VIJM2 isolate	100.000 ± 0.000 ^b	86.667 ± 11.547 ^c
Foliar application of VIJM3 isolate	100.000 ± 0.000 ^b	55.556 ± 7.698 ^{ab}
Foliar application of VITJ isolate	88.889 ± 19.245 ^a	48.889 ± 3.849 ^a
Foliar application of VIKD isolate	88.889 ± 19.245 ^a	48.889 ± 20.367 ^a
Foliar application of VIIC isolate	88.889 ± 19.245 ^a	42.222 ± 23.413 ^a
Virus-inoculated control (no endophyte)	100.000 ± 0.000 ^b	75.556 ± 20.367 ^{bc}
Absolute control (virus-free, endophyte-free)	0.000 ± 0.000	0.000 ± 0.000
SE(m) ±	5.556	8.438
SE(d) ±	7.857	11.933
CD (0.05)	16.216	24.628

Values are means of the replications ± SD. Within a column, means followed by the same letter(s) are not significantly different by Duncan's Multiple Range Test (P = 0.05).

**Fig. 1 :** PCR amplification confirming the presence of chilli leafcurl virus in graft-inoculated chilli plants exhibiting the specific ~120 bp amplicon [L- 100bp DNA marker; 1,2,3- infected leaf samples].

Disease severity, expressed as disease index (DI), varied significantly among treatments across both application schedules. When applied five days prior to grafting (pre-treatment), DI ranged from 42.22% (VIIC) to 88.89% (VIJM1) among the ten isolates, compared to 75.56% in the inoculated untreated control (Table 2). Following application five days after grafting (post-

treatment), overall disease severity was further suppressed, with DI ranging from 33.33% (VITJ) to 82.22% (VIJM1) relative to 60.00% in the control (Table 3).

Among the tested endophytes, isolates VITJ, VIKD, and VIIC consistently recorded the lowest DI values under both application schedules and were statistically on par with each other. Post-treatment application of these strains significantly reduced disease severity compared to the untreated control, achieving reductions of 44.4% (VITJ), 37.0% (VIKD) and 37.0% (VIIC), respectively (Table 3).

Evaluation for growth promotion (seed biopriming)

Biopriming of chilli seeds with the three selected isolates (VITJ, VIKD and VIIC) significantly influenced all growth parameters recorded 15 days after sowing, relative to the absolute (non-bioprimed) control (Table 4). Seedling growth under the roll paper towel method 15 days after sowing is presented in Plate 3.

Biopriming resulted in a significant increase in mean shoot length over the control (4.00 cm), recording increases of 16.50% (4.66 cm), 15.50% (4.62 cm) and 16.00% (4.64 cm) with VITJ, VIKD and VIIC, respectively. Root length exhibited enhancement over the control (4.58 cm), with VIKD showing the highest increase of 47.60% (6.76 cm), followed by VIIC at 38.86% (6.36 cm) and VITJ at 19.87% (5.49 cm). Consequently, total seedling length improved significantly from 8.58 cm in the control, recording increases of 32.63% (11.38 cm), 28.21% (11.00 cm) and 18.30% (10.15 cm) in seedlings

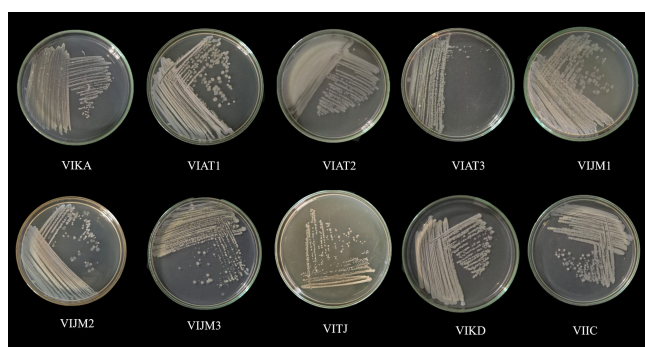
**Plate 2 :** Colony morphology of endophytic bacterial isolates on nutrient agar.

Table 3 : Disease incidence and disease index (DI) of chilli leaf curl disease in chilli plants after post-treatment application (30 DAT) of endophytic bacterial isolates, under pot culture conditions.

Treatments	Disease incidence (%) 30 DAT	Disease Index (DI)
Foliar application of VIKa isolate	100.000 ± 0.000 ^b	62.222 ± 7.698 ^{cd}
Foliar application of VIAT1 isolate	100.000 ± 0.000 ^b	75.556 ± 15.396 ^d
Foliar application of VIAT2 isolate	100.000 ± 0.000 ^b	71.111 ± 7.698 ^d
Foliar application of VIAT3 isolate	100.000 ± 0.000 ^b	62.222 ± 15.396 ^{cd}
Foliar application of VIJM1 isolate	100.000 ± 0.000 ^b	82.222 ± 7.698 ^d
Foliar application of VIJM2 isolate	100.000 ± 0.000 ^b	77.778 ± 16.777 ^d
Foliar application of VIJM3 isolate	100.000 ± 0.000 ^b	46.667 ± 17.638 ^{abc}
Foliar application of VITJ isolate	88.889 ± 19.245 ^a	33.333 ± 11.547 ^a
Foliar application of VIKD isolate	88.889 ± 19.245 ^a	37.778 ± 10.184 ^{ab}
Foliar application of VIIC isolate	77.778 ± 38.490 ^a	37.778 ± 25.240 ^{ab}
Virus-inoculated control (no endophyte)	100.000 ± 0.000 ^b	60.000 ± 6.667 ^{bcd}
Absolute control (virus-free, endophyte-free)	0.000 ± 0.000	0.000 ± 0.000
SE(m) ±	7.857	7.751
SE(d) ±	11.111	10.962
CD (0.05)	22.932	22.624

Values are means of the replications ± SD. Within a column, means followed by the same letter(s) are not significantly different by Duncan's Multiple Range Test (P = 0.05).

Table 4 : Shoot length, root length and total seedling length of bioprimered chilli seedlings with selected endophytic bacterial isolates.

Treatments	Shoot length (cm)	Root length (cm)	Total seedling length (cm)
VITJ	4.66 ± 0.61	5.49 ± 1.05	10.15 ± 0.96
VIKD	4.62 ± 0.43	6.76 ± 0.91	11.38 ± 0.79
VIIC	4.64 ± 0.37	6.36 ± 1.03	11.00 ± 1.14
Control	4.00 ± 0.43	4.58 ± 0.67	8.58 ± 0.88
F value (df 3,36)	4.64	10.86	17.16
P value	0.008	<0.001	<0.001
SE(m)±	0.149	0.294	0.300
CD(5%)	0.427	0.844	0.861

primed with VIKD, VIIC and VITJ, respectively.

Germination percentage was improved by bioprimering, increasing from 67.50% in the control to 83.33%, 78.30% and 88.33% with VITJ, VIKD and VIIC, respectively. Consequently, the seedling vigour index (SVI), which integrates germination percentage and seedling length,

was highest following bioprimering with VIIC (971.6) a 67.7% enhancement over the control (579.2) followed by VIKD (891.1; +53.9%) and VITJ (845.8; +46.0%) (Table 5).

Characterization of endophytic bacteria

Colony characterisation, biochemical profiling and 16S rRNA gene sequencing of the three selected isolates identified VITJ, VIKD and VIIC as *Priestia aryabhattai* (accession PZ276148), *Bacillus albus* (accession PZ276152) and *Bacillus velezensis* (accession PZ276163), respectively (Table 6). VITJ formed circular, medium, yellowish colonies with a smooth, texture and a flat to slightly raised elevation. VIKD produced irregular/amoeboid, large, off-white colonies that were rough in texture, with flat colonies bearing lobate margins. VIIC developed irregular, medium, whitish cream colonies with a mucoid texture and a raised elevation.

Table 5 : Germination percentage and seedling vigour index of chilli seedlings following bioprimering with selected endophytic bacterial isolates.

Treatments	Mean total seedling length (cm)	Germination percentage (%)	Seedling vigour index (SVI-I)
VITJ	10.15	83.33	845.8
VIKD	11.38	78.30	891.1
VIIC	11.00	88.33	971.6
Absolute control	8.58	67.50	579.2

**Plate 3 :** Seedling growth (roll paper towel method) of chilli 15 days after bioprimering with selected endophytic bacterial isolates.

Table 6 : Colony morphology and molecular identity of the three selected endophytic bacterial isolates.

Isolate	Identified organism	Gram reaction	Shape	Size	Colour	Texture	Elevation
VITJ	<i>Priestia aryabhatai</i>	Gram +ve	Circular	Medium	Yellowish	Smooth	Flat to slightly raised
VIKD	<i>Bacillus albus</i>	Gram +ve	Irregular/ amoeboid	Large	Off-white	Rough	Flat, lobate margins
VIIC	<i>Bacillus velezensis</i>	Gram +ve	Irregular	Medium	Whitish-cream	Mucoid	Raised

Discussion

Chilli leaf curl disease complex, caused by whitefly-transmitted begomoviruses, remains one of the most destructive constraints to chilli (*Capsicum* spp.) cultivation, capable of causing near-total loss of marketable yield under severe infection, with no source of whitefly resistance or direct chemical control currently available. Endophytic bacteria, capable of triggering induced systemic resistance and promoting plant growth, therefore represent a promising, eco-friendly alternative for managing the disease. A study was conducted at the Department of Plant Pathology, College of Agriculture, Vellayani, Kerala Agricultural University, to isolate phyllospheric endophytic bacteria from tolerant *Capsicum* genotypes and evaluate their efficacy against chilli leaf curl disease complex, as well as their potential for plant growth promotion, in the chilli variety Vellayani Athulya. The identity of the virus used for inoculation was confirmed by amplification with a coat protein-specific primer pair designed from the reference sequence of Chilli leaf curl virus isolate VLNY1 (GenBank accession MN231253.1), supporting its classification within this begomovirus. This disease is a major constraint to chilli production, caused by a monopartite begomovirus associated with a DNA- α satellite (Zehra *et al.*, 2017) and capable of causing complete loss of marketable yield under severe infection (Senanayake *et al.*, 2007; Kumar *et al.*, 2011a, b; Senanayake *et al.*, 2012).

All ten endophytic bacterial isolates from leaves of tolerant/resistant *Capsicum* genotypes reduced disease severity relative to the untreated, virus-inoculated control, supporting the broader body of evidence that endophytic bacteria can suppress viral disease expression through induced systemic resistance and related mechanisms (Oukala *et al.*, 2021). The consistently lower post-treatment disease index (DI) recorded for isolates VITJ, VIKD and VIIC mirrors patterns reported for other bacterial endophytes against economically important plant viruses, such as the reduction in tobacco streak virus incidence in cotton following application of *Bacillus amyloliquefaciens* (Vinodkumar *et al.*, 2018) and the suppression of tospovirus severity in cowpea by *Bacillus*

pumilus VLY17 (Ramseena, 2023). Similarly, the beneficial fungal root endophyte *Piriformospora indica* has been reported to mitigate chilli leaf curl virus severity through enhanced antioxidant activity (Nair *et al.*, 2024), lending further support to endophyte-mediated management as a viable strategy against this disease across different classes of microbial endophytes. The isolation of the most effective isolates specifically from tolerant/resistant *Capsicum* genotypes also aligns with the rationale that such hosts may harbour a distinct and more protective endophytic microbiome, as similarly explored in other pathosystems (Marzan *et al.*, 2018; Sharanya *et al.*, 2024).

Notably, disease incidence itself did not differ significantly among the virus-inoculated treatments, whereas disease severity (DI) was significantly reduced by the more effective isolates. This distinction suggests that the protective effect of endophytic bacterial treatment in this study operated primarily by limiting symptom expression and disease progression rather than by preventing initial infection outright a pattern consistent with an induced resistance based mode of action rather than direct exclusion of the virus or its whitefly vector (Oukala *et al.*, 2021) and one that merits confirmation through gene-expression studies of defense related pathways in future work.

The three isolates selected for further studies identified through colony morphology, biochemical profiling and 16S rRNA gene sequencing as *Priestia aryabhatai* (VITJ), *Bacillus albus* (VIKD) and *Bacillus velezensis* (VIIC) all belong to genera with well-documented plant growth promoting and biocontrol activity. This is consistent with earlier reports identifying efficient plant growth promoting endophytes as *Ochrobactrum* and *Enterobacter* species in pea root nodules (Tariq *et al.*, 2014) and *Bacillus* species with antiviral and growth-promoting activity in cotton and cowpea (Vinodkumar *et al.*, 2018; Ramseena, 2023), reinforcing the recurrent association between members of the genus *Bacillus* (and the closely related, recently reclassified genus *Priestia*) and beneficial endophytic activity in diverse cropping systems.

The significant improvement in shoot length, root length, total seedling length and seedling vigour index following biopriming with VITJ, VIKD and VIIC supports earlier reports of endophyte-mediated improvements in seed germination and seedling quality (Matthews *et al.*, 2024; Yildirim *et al.*, 2021). Notably, VIKD produced the highest root length and total seedling length, whereas VIIC recorded the highest germination percentage and, consequently, the highest seedling vigour index, an improvement of 67.7 per cent over the absolute control. This differential response suggests that the three isolates, although all effective, may act through partially distinct or complementary growth-promotion mechanisms, an aspect that merits further physiological and molecular investigation.

The dual efficacy of VITJ, VIKD and VIIC in reducing chilli leaf curl disease severity in enhancing seedling growth and vigour supports their potential as components of an integrated, eco-friendly management strategy for chilli leaf curl disease complex, combining biocontrol with plant growth promotion in a manner consistent with the broader endophyte literature (Kobayashi and Palumbo, 2000; Kandel *et al.*, 2017; Oukala *et al.*, 2021).

Conclusion

The present study demonstrates that endophytic bacteria isolated from the leaves of tolerant chilli genotypes possess dual potential for the management of chilli leaf curl disease and plant growth promotion. Among the ten isolates screened under pot culture conditions, VITJ (*Priestia aryabhattai*), VIKD (*Bacillus albus*) and VIIC (*Bacillus velezensis*) emerged as the most promising in lowering the disease index with significant improvements in seed germination, seedling growth and vigour index. Compatibility studies of the promising isolates evolving a bioformulation, evolving a suitable field testing can lead to the development of an integrated, sustainable management strategy for chilli leaf curl disease complex.

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Funding Competing interests

The authors declare no competing interests.

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