

Efficacy of bio-control agents against *Fusarium oxysporum* f. sp. *cumini* causing wilt in cumin (*Cuminum cyminum* L.)

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Introduction

Cumin (*Cuminum cyminum* L.) is a high-value seed spice cultivated predominantly in arid and semi-arid regions, with India contributing nearly 70 per cent of global production and trade (Jadon *et al.*, 2025). Cumin is a commercially important spice crop of the *Apiaceae* family, widely valued for its culinary, aromatic, and medicinal properties. Cultivated predominantly during

Abstract

A two-year field investigation (2022–24) was conducted to evaluate the efficacy of different bio-control agents in managing cumin wilt caused by *Fusarium oxysporum* f. sp. *cumini*. Six treatments, including soil applications of farmyard manure (FYM) enriched with *Trichoderma harzianum*, *T. viride*, other microbial antagonists, and a control, were assessed for wilt incidence at 30, 45, and 60 days after sowing (DAS). Among the treatments, FYM enriched with *T. harzianum* (T2) consistently recorded the lowest disease incidence at all stages in both years, with the greatest reduction (up to 70.69%) compared with the untreated control (T6). Similarly, *T. viride* (T1) was also effective, with a substantial reduction in disease incidence. Pooled data showed that T2 and T1 achieved the lowest mean wilt incidence (11.46% and 14.23%, respectively). Area Under Disease Progress Curve (AUDPC) values further confirmed the superior performance of *T. harzianum* and *T. viride* in both seasons. Seed yield significantly improved under these treatments, with pooled yields of 6.54 q/ha (T2) and 6.24 q/ha (T1), compared to 2.39 q/ha in the control. No significant differences were observed among treatments for volatile oil content and 1000-seed weight. The results highlight the potential of *T. harzianum* and *T. viride* as effective, eco-friendly biocontrol agents for sustainable management of cumin wilt and enhanced crop productivity.

Keywords: *Trichoderma harzianum*, *Trichoderma viride*, *Fusarium wilt*, *cumin*, *bio-control*

the Rabi season, it thrives in dry, cool climates, making the arid and semi-arid regions of Gujarat and Rajasthan ideal for production (Didwania, 2019). Gujarat recorded the highest production of 518 MT from 5.30 lakh hectares during 2023-24, while Rajasthan leads in cultivated area (Anonymous, 2024). Cumin productivity is frequently constrained by biotic stresses, particularly diseases and insect pests. Among them, *Fusarium* wilt caused by

Fusarium oxysporum f. sp. *cumini* is the most devastating, with the potential to cause yield losses of up to 80 per cent (Dar *et al.*, 2019). The disease is favoured by specific soil and environmental conditions and is widespread in major cumin-growing regions. Over time, new pathogenic races have emerged, compromising the durability of wilt-resistant cultivars and reducing their effectiveness. Chemical fungicides, though widely used, pose environmental and economic challenges, including soil and water contamination, resistance development and higher input costs. Hence, there is growing interest in sustainable, eco-friendly management strategies. Recent studies have highlighted the potential of microbial bioagents such as *Trichoderma*, *Bacillus* and *Pseudomonas* for the sustainable management of soil-borne plant pathogens. These microorganisms suppress *Fusarium* spp. through competition for nutrients and space, mycoparasitism, antibiosis, siderophore production and secretion of cell wall degrading enzymes. *Trichoderma* spp. can directly parasitize fungal pathogens and produce hydrolytic enzymes and antifungal metabolites, while *Bacillus* spp. produce antimicrobial lipopeptides and other secondary metabolites that inhibit pathogen growth. *Pseudomonas* spp. contribute through siderophore production, antibiosis and induction of plant defence responses (Singh *et al.*, 2025). Bioagents may also promote plant growth and enhance induced systemic resistance, improving plant defence against infection. Given these considerations, this study evaluated the impact of different bio-control agents on cumin wilt incidence, aiming to identify sustainable alternatives to chemical control measures.

Materials and methods

A two-year field study was conducted during the Rabi seasons of 2022-23 and 2023-24 to evaluate the impact of various biological control agents on cumin wilt incidence, caused by *Fusarium oxysporum* f. sp. *cumini*. The experiment was conducted with the cultivar Gujarat Cumin 4 (GC 4) under open-field conditions. The

experiment comprised six treatments: T₁-soil application of farmyard manure (FYM) enriched with *Trichoderma viride* 1.50 WP at 1 kg per 100 kg FYM; T₂-FYM enriched with *T. harzianum* 1.50 WP at 1 kg per 100 kg FYM; T₃-FYM enriched with *T. atroviride* at 1 kg per 100 kg FYM; T₄-FYM enriched with *Pseudomonas fluorescens* 1.75 WP at 1 kg per 100 kg FYM; T₅-FYM enriched with *Bacillus subtilis* 2.0 AS at 1 L per 100 kg FYM; and T₆-untreated control.

The trial was arranged in a Randomized Block Design (RBD) with six treatments and four replications. Each gross plot measured 3.0 m × 4.0 m, with a net plot size of 2.4 m × 3.0 m, and an inter-row spacing of 30 cm was maintained throughout. This experimental layout enabled uniform application of treatments and effective assessment of disease incidence under field conditions. The study aimed to assess the efficacy of these organic inputs in reducing wilt incidence while promoting sustainable disease management in cumin cultivation.

Observations recorded:

- Per cent disease incidence assessed at 30, 45, and 60 days after sowing from three randomly selected spots (1 m row length each) per plot
- Area Under Disease Progress Curve (AUDPC) for wilt incidence
- Seed yield (q/ha)
- Volatile oil content (%)
- 1000-seed weight (g)

For volatile oil (%) analysis of cumin seeds, steam distillation method was used as described by Guenther (1972) and followed by Singh *et al.* (2006).

The Area Under Disease Progress Curve (AUDPC) was calculated to evaluate the effect of various treatments against cumin wilt disease incidence as per the below-mentioned method suggested by Shaner and Finney (1977):

$$\text{AUDPC} = \sum_{i=1}^{n-1} \frac{(T_{i+1} - T_i)}{2} (Y_i + Y_{i+1})$$

Where:

Y_i = Disease incidence (%) at the i^{th} observation

Y_{i+1} = Disease incidence (%) at the $(i+1)^{\text{th}}$ observation

T_i = Time (days after sowing) at the i^{th} observation

T_{i+1} = Time at the $(i+1)^{\text{th}}$ observation

n = Number of observations

Results and discussion

Per cent disease incidence

Year 2022-23

During the first year of experimentation (2022–23), the effect of six different bio-control treatments on cumin wilt incidence was recorded at 30, 45, and 60 days after sowing (DAS), along with pooled observations. The results revealed significant differences among treatments.

At 30 DAS

Minimum wilt incidence (4.17%) was observed in treatment T₂ (soil application of farm yard manure enriched with *Trichoderma harzianum* 1.50 WP @ 1 kg/100 kg FYM). This was statistically at par with T₁ (FYM enriched with *T. viride*, 5.08%) and significantly lower than the untreated control (T₆), which recorded 24.94% disease incidence.

At 45 DAS

Treatment 2 continued to exhibit the least disease incidence (11.24%), remaining statistically at par with T₁ (14.52%), whereas the control recorded a significantly higher disease incidence of 32.00 per cent.

At 60 DAS

Treatment T₂ recorded the lowest wilt incidence of 16.56 per cent, which was again statistically at par with T₁ (20.75%) and significantly superior to the control (46.84%).

Reduction over control

The highest reduction over control in per cent disease incidence at 60 DAS was observed in T₂ (64.65%) followed by T₁ (55.70%). Overall, soil application of FYM enriched with *T. harzianum* (T₂) and *T. viride* (T₁) proved to be the most effective in reducing cumin wilt incidence as compared to other treatments and the control.

Year 2023-24

During the second year of experimentation (2023–24), the effect of six different bio-control treatments on cumin wilt incidence was recorded at 30, 45, and 60 days after sowing (DAS), along with pooled observations. The results showed significant differences among treatments in controlling cumin wilt disease.

At 30 DAS

Minimum wilt incidence was observed in treatment T₂ (soil application of farmyard manure enriched with *Trichoderma harzianum* 1.50 WP @ 1 kg/100 kg FYM), recording 5.08 per cent disease incidence. This was statistically at par with T₁ (soil application of FYM

enriched with *T. viride*, 6.08%) and significantly lower than the untreated control (T₆), which recorded a high disease incidence of 33.30 per cent.

At 45 DAS

Treatment T₂ again showed the lowest wilt incidence (15.48%), remaining statistically at par with T₁ (17.68%), while the untreated control recorded the highest incidence (45.83%).

At 60 DAS

Treatment 2 continued to perform best with a disease incidence of 15.58 per cent, statistically at par with T₁ (20.68%) and significantly superior to the control (53.16%).

Reduction over control

The highest reduction over control in per cent disease incidence at 60 DAS was observed in T₂ (70.69%) followed by T₁ (61.10%). Overall, soil application of FYM enriched with *Trichoderma harzianum* (T₂) and *T. viride* (T₁) consistently proved to be the most effective treatments in reducing cumin wilt incidence as compared to other treatments and the untreated control during the second year.

Pooled over year data

Pooled results over two years (2022–23 and 2023–24) showed a consistent trend of reduced cumin wilt incidence with the application of bio-control agents. Among all treatments, soil application of farm yard manure enriched with *Trichoderma harzianum* (T₂) was found to be the most effective, recording the lowest mean disease incidence (11.46%), followed by *T. viride* (T₁) with 14.23%. In contrast, the untreated control (T₆) recorded the highest disease incidence (39.41%).

The consistent superior performance of *T. harzianum* and *T. viride* can be attributed to their strong antagonistic properties against soil-borne pathogens like *Fusarium oxysporum* f. sp. *cumini*, the causal agent of cumin wilt. These bio-control agents not only suppress the pathogen population in the rhizosphere through competition and mycoparasitism but also enhance plant health by promoting root growth and inducing systemic resistance.

Thus, it can be concluded that soil application of farm yard manure enriched with *Trichoderma harzianum* or *T. viride* before sowing is an effective, eco-friendly and sustainable approach for managing cumin wilt disease and can be recommended for integrated disease management practices in cumin cultivation.

AUDPC study of different bio-control agents on cumin wilt disease (2022-23)

The effect of different bio-control agents on cumin wilt disease incidence was evaluated through AUDPC analysis during the first year (2022-23). The lowest average AUDPC value (328.14) was recorded in the treatment involving FYM + *Trichoderma harzianum* soil application, indicating its superior efficacy in reducing disease progression. This was followed by the treatment with FYM + *Trichoderma viride* soil application, which recorded an AUDPC value of 414.09. In contrast, the untreated control showed the highest AUDPC value (1023.45), highlighting the significant impact of bio-control agents in mitigating cumin wilt disease.

AUDPC study of different bio-control agents on cumin wilt disease (2023-24)

The Area Under Disease Progress Curve (AUDPC) analysis for the effect of different bio-control agents on cumin wilt disease incidence during the second year (2023-24) revealed significant differences among treatments. The lowest average AUDPC value of 390.66 was recorded in the FYM + *Trichoderma harzianum* treatment, indicating the highest efficacy in disease suppression. This was followed by FYM + *Trichoderma viride*, which exhibited an AUDPC value of 468.79. In contrast, the untreated control plot showed the highest AUDPC value of 1335.90, reflecting the severe disease progression in the absence of bio-control intervention.

Effect of different treatments on volatile oil of cumin seeds

The volatile oil percentage observed under field conditions in both years (2022-23 and 2023-24) showed no significant difference among the bio-control treatments. The volatile oil percentage for both the years ranged from 4.41 to 4.54 per cent across all treatments, including the control. Healthy seeds from all treatments were selected for the volatile oil analysis to ensure consistency and accuracy in the results. This outcome suggests that the genetic factors of the GC 4 variety,

which may play a dominant role in volatile oil production, likely influenced oil content.

Effect of different treatments on 1000 seed weight of cumin seeds

The results for the 1000 seed weight observed under field conditions in both years (2022-23 and 2023-24) showed no significant difference among the various bio-control treatments. The 1000-seed weight ranged from 4.24 g to 4.37 g across all treatments, including the control. Healthy seeds from all treatments were selected for the study of 1000-seed weight, and thus it might have shown a non-significant result.

Effect of different treatments on cumin yield

The impact of different bio-control agents on the seed yield of cumin was thoroughly evaluated over two consecutive years (2022-23 and 2023-24), and the results consistently demonstrated the superiority of certain treatments.

Year 2022-23

Among the six treatments tested, the treatment T₂: soil application of farmyard manure enriched with *Trichoderma harzianum* (1.50 WP @ 1 kg/100 kg FYM) recorded the highest seed yield of 6.46 q/ha, which was statistically at par with T₁ (FYM enriched with *T. viride*) producing 6.12 q/ha. This clearly indicated the effectiveness of both these beneficial fungi in managing cumin wilt disease and supporting plant growth and productivity. In contrast, the control (T₆), where no bio-control agents were applied, resulted in a significantly lower seed yield of 2.53 q/ha, reflecting the adverse impact of unchecked disease incidence on crop productivity.

Year 2023-24

The same trend was observed, reinforcing the consistency and reliability of these treatments. T₂ again recorded the highest seed yield of 6.62 q/ha, on par with T₁ at 6.35 q/ha, while the control recorded a further reduction to 2.25 q/ha. This indicates that the integrated use of enriched organic amendments not only controls soil-borne pathogens but also maintains soil health and promotes sustained crop productivity across different seasons.

Pooled over the year

A similar pattern emerged. The cumulative analysis showed that T2 consistently provided the highest seed

yield (6.54 q/ha), followed by T1 (6.24 q/ha), both significantly higher than the untreated control, which recorded a pooled average yield of only 2.39 q/ha.

Table 1. Effect of the different bio-control agents on cumin wilt disease incidence and yield

Treat. No.	Per cent disease incidence (2022-23)				Per cent disease incidence (2023-24)				Pooled over year	Seed yield (q/ha)		
	30 DAS	45 DAS	60 DAS	ROC (%)	30 DAS	45 DAS	60 DAS	ROC (%)		2022-23	2023-24	Pooled
1	13.02 ^c (5.08)	22.39 ^c (14.52)	27.09 ^{cd} (20.75)	55.70	14.27 ^d (6.08)	24.85 ^c (17.68)	27.04 ^c (20.68)	61.10	21.44 ^d (14.23)	6.12 ^a	6.35 ^a	6.24 ^a
2	11.78 ^c (4.17)	19.58 ^c (11.24)	24.00 ^d (16.56)	64.65	13.03 ^d (5.08)	23.16 ^c (15.48)	23.24 ^c (15.58)	70.69	19.13 ^d (11.46)	6.46 ^a	6.62 ^a	6.54 ^a
3	24.00 ^b (16.56)	29.95 ^{ab} (24.94)	36.47 ^b (35.35)	24.53	27.09 ^b (20.75)	34.56 ^b (32.20)	39.55 ^b (40.58)	23.66	31.94 ^b (28.47)	4.69 ^b	4.39 ^c	4.54 ^c
4	20.56 ^b (12.35)	25.48 ^{bc} (18.52)	31.26 ^{bc} (26.95)	42.46	23.24 ^c (15.58)	32.60 ^b (29.05)	36.47 ^b (35.35)	33.50	28.27 ^c (23.09)	5.39 ^b	5.14 ^b	5.26 ^b
5	21.54 ^b (13.50)	25.48 ^{bc} (18.52)	32.53 ^{bc} (28.94)	38.22	25.53 ^{bc} (18.59)	33.29 ^b (30.15)	38.94 ^b (39.53)	25.64	29.55 ^{bc} (25.00)	4.97 ^b	4.79 ^{bc}	4.88 ^{bc}
6	29.95 ^a (24.94)	34.44 ^a (32.00)	43.17 ^a (46.84)	-	35.23 ^a (33.30)	42.59 ^a (45.83)	46.79 ^a (53.16)	-	38.70 ^a (39.41)	2.53 ^c	2.25 ^d	2.39 ^d
SEm.	1.21	1.94	1.87	-	1.05	1.47	1.76	-	1.07	0.23	0.22	0.16
T	-	-	-	-	-	-	-	-	0.78	-	-	-
P	-	-	-	-	-	-	-	-	0.37	-	-	0.09
Y	-	-	-	-	-	-	-	-	1.10	-	-	-
T x P	-	-	-	-	-	-	-	-	0.90	-	-	0.22
T X Y	-	-	-	-	-	-	-	-	0.64	-	-	-
P X Y	-	-	-	-	-	-	-	-	1.56	-	-	-
T X P	-	-	-	-	-	-	-	-	-	-	-	-
X Y	-	-	-	-	-	-	-	-	-	-	-	-
CD at 5%	3.66	5.84	5.63	-	3.17	4.43	5.31	-	3.88	0.69	0.67	0.44
T	-	-	-	-	-	-	-	-	NS	-	-	-
T X Y	-	-	-	-	-	-	-	-	-	-	-	-
C.V. (%)	12.05	14.77	11.52	-	9.13	9.23	9.97	-	11.06	9.06	8.96	9.01

Note:

1. Figures outside the parentheses are arc sine transformed values and those inside the parentheses are retransformed values.

2. Treatment means followed by the same letter(s) are not significantly different by Duncan's New Multiple Range Test (DNMRT) at 5% level of significance

T₁: Soil application of FYM enriched with *Trichoderma viride* 1.50 WP @ 1 kg per 100 kg FYM;

T₂: FYM enriched with *T. harzianum* 1.50 WP @ 1 kg per 100 kg FYM;

T₃: FYM enriched with *T. atroviride* @ 1 kg per 100 kg FYM;

T₄: FYM enriched with *Pseudomonas fluorescens* 1.75 WP @ 1 kg per 100 kg FYM;

T₅: FYM enriched with *Bacillus subtilis* 2.0 AS @ 1 L per 100 kg FYM;

T₆: Untreated control.

Table 2. Effect of different bio-control agents on 1000 seed weight (g) and volatile oil (%) in relation to wilt disease

Treat. No.	1000 seed weight (g)		Volatile oil (%)	
	2022-23	2023-24	2022-23	2023-24
1	4.37	4.36	4.45	4.49
2	4.24	4.35	4.53	4.50
3	4.45	4.27	4.47	4.55
4	4.29	4.37	4.53	4.41
5	4.32	4.26	4.45	4.47
6	4.33	4.25	4.51	4.54
SEm.	0.06	0.08	0.07	0.06
T				
Y	-	-	-	-
Y x T	-	-	-	-
CD at 5%	NS	NS	NS	NS
C.V. (%)	2.62	3.94	3.07	2.79

Note:

Treatment means followed by the same letter(s) are not significantly different by Duncan's New Multiple Range Test (DNMRT) at 5% level of significance

T₁: Soil application of FYM enriched with *Trichoderma viride* 1.50 WP @ 1 kg per 100 kg FYM;

T₂: FYM enriched with *T. harzianum* 1.50 WP @ 1 kg per 100 kg FYM;

T₃: FYM enriched with *T. atroviride* @ 1 kg per 100 kg FYM;

T₄: FYM enriched with *Pseudomonas fluorescens* 1.75 WP @ 1 kg per 100 kg FYM;

T₅: FYM enriched with *Bacillus subtilis* 2.0 AS @ 1 L per 100 kg FYM;

T₆: Untreated control.

**Fig. 1:** AUDPC study of different bio-control agents on cumin wilt disease (2022-23)



Fig. 2: AUDPC study of different bio-control agents on cumin wilt disease (2023-24)

The consistent increase in seed yield with T₂ and T₁ treatments can be attributed to the dual benefits of disease suppression and plant growth promotion. The bio-control agents *Trichoderma harzianum* and *Trichoderma viride* effectively suppressed cumin wilt disease by antagonizing the pathogen and enhancing soil health. These fungi also promoted root development and nutrient uptake, which are critical for higher productivity. In contrast, the control, with no bio-control agents, had higher disease incidence and poorer plant health, resulting in reduced yields. Thus, bio-control agents not only provide effective disease management but also support sustainable, higher-yielding cumin cultivation.

In line with the findings of Singh et al. (2007), who recorded minimum wilt disease incidence of 9.20 per cent with *T. harzianum* treatments, our results also support *T. harzianum*'s superiority in managing cumin wilt. The present study observed that *T. harzianum* (T₂) resulted in the lowest disease incidence, with values of 4.17 per cent and 5.08 per cent in the first and second years, respectively, which were significantly better than the control treatment, which showed much higher disease incidence (24.94% in 2022-23 and 33.30% in 2023-24).

Similarly, *T. viride* (T₁) also showed effective results, with disease incidence at par with *T. harzianum* (T₂), supporting findings from various researchers. Gangopadhyay and Gopal (2010) reported that *T. viride* applied with farmyard manure resulted in the greatest reduction in disease incidence under greenhouse conditions. In the present study, the soil application of farmyard manure enriched with *T. viride* (T₁) also showed effective disease control, with disease incidences of 5.08

per cent (2022-23) and 6.08 per cent (2023-24), both significantly lower than the control treatments.

The observed reduction in disease incidence can be attributed to the biocontrol potential of *T. viride* and *T. harzianum*, both of which exhibit strong antagonistic properties against *Fusarium oxysporum*. These *Trichoderma* species act by competing for space and nutrients, producing antifungal metabolites, and inducing systemic resistance in plants, all of which contribute to pathogen suppression.

Regarding seed yield, both *T. viride* and *T. harzianum* treatments also produced significantly higher yields than the control. In the first year, *T. harzianum* (T₂) gave the highest seed yield of 6.46 q/ha, which was at par with *T. viride* (T₁) at 6.12 q/ha, while the control produced only 2.53 q/ha. Similar trends were observed in the second year, where *T. harzianum* (T₂) gave a yield of 6.62 q/ha and *T. viride* (T₁) produced 6.35 q/ha., both significantly outperforming the control (2.25 q/ha). These results corroborate the findings of Deepak et al. (2008), who observed a significant increase in plant growth and biomass with *T. harzianum* treatments.

The increase in seed yield can be attributed to the enhanced plant health and reduced disease incidence, leading to better overall plant development and productivity. Additionally, the improved nutrient uptake and disease suppression likely contributed to higher yields in both *T. viride* and *T. harzianum* treatments, as observed by Kumar et al. (2016), who reported reduced disease incidence and enhanced plant growth with *T. viride* in cumin.

Overall, both *T. viride* and *T. harzianum* proved to be highly effective in managing cumin wilt disease and improving seed yield. *T. harzianum*, however, consistently demonstrated superior performance in reducing disease incidence and enhancing seed yield, making it a promising biocontrol agent for the management of cumin wilt disease.

Conclusions

The present investigation establishes that biological management through FYM enriched with effective microbial antagonists offers a practical and sustainable approach for reducing *Fusarium* wilt of cumin. Among the evaluated treatments, *Trichoderma harzianum* and *T. viride* demonstrated consistent disease-suppressive potential along with improved crop productivity. Their performance indicates that enrichment of FYM with suitable *Trichoderma* spp. can strengthen the biological suppression of *F. oxysporum* f. sp. *cumini* under field conditions. The findings support integrating these bioagents into eco-friendly disease management practices for cumin. Further studies on their long-term efficacy and integration with other compatible management components would help strengthen their adoption under diverse production conditions.

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Declaration of interest statement

The authors declare that there is no conflict of interest associated with this publication.

Author contributions

B.K. Prajapati: Conceptualization, methodology, investigation, data curation, formal analysis, writing an original draft. N. R. Patel: Conceptualization, methodology, supervision, data curation, writing -review and editing. Both authors have read and approved the final version of the manuscript.

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