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## Sustainable management of wilt and root rot of cumin under field conditions

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#### Abstract

Cumin (*Cuminum cyminum* L.) is an economically important seed spice, widely cultivated in India, particularly in Gujarat and Rajasthan. It plays a vital role in India's spice export market. However, its productivity is threatened by diseases such as wilt, blight, powdery mildew and more recently root rot. Root rot has been associated with multiple *Fusarium* species in Rajasthan and other pathogens in China, including *Rhizoctonia* spp. To address these issues, root rot-infected cumin plant samples were collected from research centers and farmers' fields across North Gujarat, and associated pathogens such as *Fusarium oxysporum* f.sp. *cumini* and *Macrophomina phaseolina* were isolated. A field experiment was conducted at the Seed Spices Research Station, SDAU, Jagudan, using a randomized block design across multiple Rabi seasons. The results showed that the most effective control of wilt and root rot was achieved with the application of 1 t/ha enriched FYM containing *Trichoderma viride* or *T. harzianum* 1.15 WP ( $2 \times 10^8$  cfu/g) and *Pseudomonas fluorescens* 1.15 WP @ 2.5 kg/ha each, applied at sowing. FYM enrichment with bio-agents at 15 days before sowing.

**Keywords:** Cumin, wilt, root rot, bio-control

#### Introduction

Cumin (*Cuminum cyminum* L.) is a vital seed spice crop extensively cultivated in the arid and semi-arid zones of India. Gujarat and Rajasthan are the principal states contributing to its large-scale cultivation and productivity (Meena et al., 2022). India holds a predominant position in the global cumin market, playing a crucial role in spice exports due to favorable agro-climatic conditions and traditional agronomic practices. Despite its economic significance, cumin cultivation faces substantial constraints due to various biotic stresses. Wilt, incited by *Fusarium oxysporum* f. sp. *cumini*, is the most devastating soil-borne disease, often resulting in considerable yield losses. Other prevalent diseases include blight (*Alternaria burnsii*) and powdery mildew (*Erysiphe polygoni*). In recent times, root rot has emerged as an additional threat in cumin-growing

regions, particularly in Gujarat and Rajasthan. Previous reports from Rajasthan have implicated a complex of Fusarium species including *F. oxysporum*, *F. solani* and *F. equiseti* as causal organisms. Similar incidences in China have identified *F. oxysporum*, *F. solani*, *Rhizoctonia* spp. as contributors to root rot.

Although synthetic fungicides provide some level of control, their continuous use raises concerns regarding resistance build-up, environmental hazards and unacceptable residue levels in export-oriented produce. As a sustainable alternative, biological control agents have gained attention for their eco-friendly and multi-mechanistic approach. Species of *Trichoderma* and *Pseudomonas fluorescens* have demonstrated antagonistic potential against soil-borne pathogens through myco-parasitism, competition and the induction of host defense mechanisms.

Considering the increasing prevalence of wilt and root rot in North Gujarat, the present investigation was undertaken to assess the efficacy of bio-agent enriched organic amendments in the integrated management of these diseases under field conditions.

## Material and methods

A field experiment was conducted in a randomized block design with three replications during Rabi 2017-18, 2018-19, 2019-20 and 2020-21 at Seed Spices Research Station, S. D. Agricultural University, Jagudan. Cumin cv. Gujarat Cumin 4 (GC4) was sown in the month of November at a distance of 30 cm row spacing by using 12 kg seed rate. A total of three biocontrol agents enriched with FYM alone and mixed with each other, soil drenching with carbendazim as well as copper oxychloride was compared with untreated control. Observations on wilt and root-rot were recorded from three rows of 1m length from each plot and percentage was calculated along with seed yield (kg/ha).

## Results and discussion

### Wilt incidence (%):

It is revealed from the data that there was significant difference in wilt incidence during all the year and pooled results also (Table 2). All the treatments were found significantly superior in controlling wilt as compared to untreated control. The minimum wilt incidence was observed with T<sub>5</sub> i.e soil application of *T. viride* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha and *Pseudomonas*

*fluorescens* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application and was at par with treatments T<sub>4</sub> i.e soil application of *T. harzianum* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha and *Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application, T<sub>3</sub> i.e soil application of *Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application and T<sub>2</sub> i.e soil application of *Trichoderma viride* ( $2 \times 10^6$  cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application in all the years and pooled results except 2019-20. Whereas, during 2019-2020 it was remained at par with T<sub>4</sub> and T<sub>3</sub>.

### Root rot incidence (%):

It is revealed from the data that there was significant difference in root rot incidence during all the years and pooled results also (Table 3). All the treatments were found significantly superior in controlling root rot as compared to untreated control. The minimum root rot incidence was recorded with T<sub>5</sub> i.e soil application of *T. viride* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha and *Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application and was at par with treatments T<sub>4</sub> i.e soil application of *T. harzianum* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha and *Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application, T<sub>3</sub> i.e soil application of *Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application and T<sub>2</sub> i.e soil application of *Trichoderma viride* ( $2 \times 10^6$  cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application during all the year and pooled results except 2017-18. Whereas, during 2017-2018 it was remaining at par with T<sub>4</sub> and T<sub>3</sub>.

### Seed Yield:

Effect of different treatments on cumin seed yield was found significant during all the years and pooled results also (Table 4). All the treatments were found effective and producing significantly higher seed yield over untreated control. Significantly higher seed yield was recorded in treatment T<sub>5</sub> i.e soil application of *T. viride* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha and *Pseudomonas*

*fluorescens* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application and was at par with treatments viz., T<sub>4</sub> i.e soil application of *T. harzianum* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha and *Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application, T<sub>3</sub> i.e soil application of

*Pseudomonas fluorescens* ( $2 \times 10^6$  cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application and T<sub>2</sub> i.e soil application of *Trichoderma viride* ( $2 \times 10^6$  cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application during all the years. Whereas, in pooled results it was remained at par with T<sub>4</sub>.

**Table 1.** Treatment details for sustainable management of cumin wilt

|                |  |
|----------------|--|
| T <sub>1</sub> | Soil application of <i>Trichoderma harzianum</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  |
| T <sub>2</sub> | Soil application of <i>Trichoderma viride</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application   |
| T <sub>3</sub> | Soil application of <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  |
| T <sub>4</sub> | Soil application of <i>T. harzianum</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application |
| T <sub>5</sub> | Soil application of <i>T. viride</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application    |
| T <sub>6</sub> | Soil drenching with carbendazim 0.05% at 20 DAG @ 500 g/500 L/ha.  |
| T <sub>7</sub> | Soil drenching with copper oxychloride 0.2% at 20 DAG @ 2000g/500 L/ha.  |
| T <sub>8</sub> | Untreated Control  |



**Fig 1.** Cumin root rot infected plant sample

Table 2. Effect of different treatments on wilt incidence

| Sr. No         | Treatments   | Wilt incidence (%)              |                                |                                |                                |                                |
|----------------|--|---------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
|                |  | 2017-18                         | 2018-19                        | 2019-20                        | 2020-21                        | Pooled                         |
| T <sub>1</sub> | Soil application of <i>Trichoderma harzianum</i> (2 x 10 <sup>6</sup> cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application   | 19.65* <sup>bc</sup><br>(11.33) | 19.23 <sup>bc</sup><br>(10.87) | 18.11 <sup>cd</sup><br>(9.67)  | 18.88 <sup>c</sup><br>(10.47)  | 18.97 <sup>bc</sup><br>(10.58) |
| T <sub>2</sub> | Soil application of <i>Trichoderma viride</i> (2 x 10 <sup>6</sup> cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  | 18.05 <sup>bc</sup><br>(9.67)   | 18.13 <sup>c</sup><br>(9.70)   | 17.44 <sup>cde</sup><br>(9.00) | 17.12 <sup>d</sup><br>(8.70)   | 17.68 <sup>cd</sup><br>(9.27)  |
| T <sub>3</sub> | Soil application of <i>Pseudomonas fluorescens</i> (2 x 10 <sup>6</sup> cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application   | 17.72 <sup>bc</sup><br>(9.33)   | 18.17 <sup>c</sup><br>(9.73)   | 17.12 <sup>cde</sup><br>(8.67) | 16.83 <sup>d</sup><br>(8.40)   | 17.46 <sup>cd</sup><br>(9.03)  |
| T <sub>4</sub> | Soil application of <i>T. harzianum</i> (2 x 10 <sup>6</sup> cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> (2 x 10 <sup>6</sup> cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application | 18.38 <sup>bc</sup><br>(10.00)  | 18.19 <sup>c</sup><br>(9.77)   | 16.77 <sup>de</sup><br>(8.33)  | 16.43 <sup>d</sup><br>(8.00)   | 17.44 <sup>cd</sup><br>(9.03)  |
| T <sub>5</sub> | Soil application of <i>T. viride</i> (2 x 10 <sup>6</sup> cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> (2 x 10 <sup>6</sup> cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application    | 15.93 <sup>c</sup><br>(7.67)    | 17.34 <sup>c</sup><br>(8.90)   | 16.07 <sup>e</sup><br>(7.67)   | 16.03 <sup>d</sup><br>(7.63)   | 16.34 <sup>d</sup><br>(7.97)   |
| T <sub>6</sub> | Soil drenching with carbendazim 0.05% at 20 DAG @ 1 g/1 L  | 17.75 <sup>bc</sup><br>(9.33)   | 18.79 <sup>bc</sup><br>(10.40) | 18.42 <sup>bc</sup><br>(10.00) | 19.77 <sup>bc</sup><br>(11.80) | 18.68 <sup>bc</sup><br>(10.38) |
| T <sub>7</sub> | Soil drenching with copper oxychloride 0.2% at 20 DAG @ 4g/1 L   | 20.26 <sup>b</sup><br>(12.00)   | 20.46 <sup>b</sup><br>(12.23)  | 19.66 <sup>b</sup><br>(11.33)  | 20.74 <sup>b</sup><br>(12.57)  | 20.28 <sup>b</sup><br>(12.03)  |
| T <sub>8</sub> | Untreated Control  | 31.07 <sup>a</sup><br>(26.67)   | 28.39 <sup>a</sup><br>(22.63)  | 24.34 <sup>a</sup><br>(17.00)  | 25.96 <sup>a</sup><br>(19.17)  | 27.44 <sup>a</sup><br>(21.37)  |
|                | S. Em  | 1.13                            | 0.66                           | 0.45                           | 0.51                           | 0.55                           |
|                | C.D at 5%  | 3.42                            | 1.99                           | 1.35                           | 1.55                           | 1.61                           |
|                | C.V%   | 9.84                            | 5.73                           | 4.17                           | 4.68                           | 6.19                           |
|                | <b>Y X T</b>   | -                               | -                              | -                              | -                              | S                              |

\*Arcsine values, Figures in the parenthesis are retransformed values, Treatments means with the letter (s) in common are not significant by DNMRT at 5% level of significance

Table 3. Effect of different treatments on root rot incidence

| Sr. No         | Treatments   | Root rot incidence (%)          |                                |                                |                               |                                |
|----------------|--|---------------------------------|--------------------------------|--------------------------------|-------------------------------|--------------------------------|
|                |  | 2017-18                         | 2018-19                        | 2019-20                        | 2020-21                       | Pooled                         |
| T <sub>1</sub> | Soil application of <i>Trichoderma harzianum</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  | 19.89* <sup>bc</sup><br>(11.67) | 18.22 <sup>cd</sup><br>(9.83)  | 16.41 <sup>bcd</sup><br>(8.00) | 17.55 <sup>bc</sup><br>(9.10) | 18.02 <sup>bc</sup><br>(9.65)  |
| T <sub>2</sub> | Soil application of <i>Trichoderma viride</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application   | 18.40 <sup>bcd</sup><br>(10.00) | 17.13 <sup>cde</sup><br>(8.70) | 15.70 <sup>bcd</sup><br>(7.33) | 16.42 <sup>cd</sup><br>(8.00) | 16.91 <sup>cd</sup><br>(8.51)  |
| T <sub>3</sub> | Soil application of <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  | 16.74 <sup>cde</sup><br>(8.33)  | 16.53 <sup>de</sup><br>(8.10)  | 16.05 <sup>bcd</sup><br>(7.67) | 15.77 <sup>de</sup><br>(7.40) | 16.27 <sup>cd</sup><br>(7.88)  |
| T <sub>4</sub> | Soil application of <i>T. harzianum</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application | 15.26 <sup>de</sup><br>(7.00)   | 15.95 <sup>e</sup><br>(7.57)   | 14.90 <sup>cd</sup><br>(6.67)  | 14.95 <sup>e</sup><br>(6.67)  | 15.26 <sup>d</sup><br>(6.98)   |
| T <sub>5</sub> | Soil application of <i>T. viride</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application    | 14.15 <sup>e</sup><br>(6.00)    | 15.14 <sup>e</sup><br>(6.83)   | 14.15 <sup>d</sup><br>(6.00)   | 14.52 <sup>e</sup><br>(6.30)  | 14.49 <sup>d</sup><br>(6.28)   |
| T <sub>6</sub> | Soil drenching with carbendazim 0.05% at 20 DAG @ 1 g/1 L  | 19.29 <sup>bc</sup><br>(11.00)  | 18.99 <sup>bc</sup><br>(10.60) | 17.08 <sup>bc</sup><br>(8.67)  | 18.37 <sup>b</sup><br>(9.93)  | 18.43 <sup>bc</sup><br>(10.05) |
| T <sub>7</sub> | Soil drenching with copper oxychloride 0.2% at 20 DAG @ 4g/1 L   | 21.68 <sup>b</sup><br>(13.67)   | 20.43 <sup>b</sup><br>(12.20)  | 17.44 <sup>b</sup><br>(9.00)   | 18.87 <sup>b</sup><br>(10.47) | 19.60 <sup>b</sup><br>(11.33)  |
| T <sub>8</sub> | Untreated Control  | 32.14 <sup>a</sup><br>(28.33)   | 28.01 <sup>a</sup><br>(22.07)  | 20.26 <sup>a</sup><br>(12.00)  | 22.50 <sup>a</sup><br>(14.67) | 25.73 <sup>a</sup><br>(19.27)  |
|                | S.Em   | 1.02                            | 0.66                           | 0.73                           | 0.44                          | 0.87                           |
|                | C.D at 5%  | 3.11                            | 2.00                           | 2.21                           | 1.33                          | 2.55                           |
|                | C.V%   | 9.00                            | 6.08                           | 7.66                           | 4.37                          | 6.80                           |
|                | Y X T  | -                               | -                              | -                              | -                             | S                              |

\*Arcsine values, Figures in the parenthesis are retransformed values, Treatments means with the letter (s) in common are not significant by DNMRT at 5% level of significance

Table 4. Effect of different treatments on seed yield

| Sr. No         | Treatments   | Seed yield (Kg/ha) |                   |                    |                    |                   |
|----------------|--|--------------------|-------------------|--------------------|--------------------|-------------------|
|                |  | 2017-18            | 2018-19           | 2019-20            | 2020-21            | Pooled            |
| T <sub>1</sub> | Soil application of <i>Trichoderma harzianum</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  | 402 <sup>b</sup>   | 425 <sup>ab</sup> | 485 <sup>bcd</sup> | 443 <sup>bcd</sup> | 439 <sup>cd</sup> |
| T <sub>2</sub> | Soil application of <i>Trichoderma viride</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application   | 446 <sup>ab</sup>  | 499 <sup>ab</sup> | 532 <sup>abc</sup> | 483 <sup>abc</sup> | 490 <sup>bc</sup> |
| T <sub>3</sub> | Soil application of <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application  | 463 <sup>ab</sup>  | 486 <sup>ab</sup> | 562 <sup>ab</sup>  | 504 <sup>ab</sup>  | 504 <sup>b</sup>  |
| T <sub>4</sub> | Soil application of <i>T. harzianum</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application | 468 <sup>ab</sup>  | 504 <sup>ab</sup> | 565 <sup>ab</sup>  | 514 <sup>ab</sup>  | 513 <sup>ab</sup> |
| T <sub>5</sub> | Soil application of <i>T. viride</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha and <i>Pseudomonas fluorescens</i> ( $2 \times 10^6$ cfu/g) @ 2.5 kg/ha at the time of sowing enriched in 1000 kg FYM prior to 15 days of application    | 502 <sup>a</sup>   | 583 <sup>a</sup>  | 604 <sup>a</sup>   | 555 <sup>a</sup>   | 561 <sup>a</sup>  |
| T <sub>6</sub> | Soil drenching with carbendazim 0.05% at 20 DAG @ 1 g/1 L  | 416 <sup>ab</sup>  | 428 <sup>ab</sup> | 456 <sup>cd</sup>  | 404 <sup>cd</sup>  | 426 <sup>d</sup>  |
| T <sub>7</sub> | Soil drenching with copper oxychloride 0.2% at 20 DAG @ 4g/1 L   | 372 <sup>b</sup>   | 370 <sup>b</sup>  | 427 <sup>d</sup>   | 378 <sup>d</sup>   | 387 <sup>d</sup>  |
| T <sub>8</sub> | Untreated Control  | 252 <sup>c</sup>   | 175 <sup>c</sup>  | 244 <sup>e</sup>   | 256 <sup>e</sup>   | 232 <sup>e</sup>  |
|                | S.Em   | 28.89              | 62.59             | 27.96              | 27.59              | 18.61             |
|                | C.D at 5%  | 87.59              | 189.81            | 84.81              | 83.70              | 52.74             |
|                | C.V%   | 12.03              | 25.02             | 10.00              | 10.82              | 14.52             |
|                | <b>Y X T</b>   |                    |                   |                    |                    | NS                |

Treatments means with the letter (s) in common are not significant by DNMR at 5% level of significance

The present findings are in close alignment with those reported by Chawla *et al.* (2012), who investigated the efficacy of four biological control agents—*Trichoderma harzianum*, *T. viride*, *Pseudomonas fluorescens* and *Bacillus subtilis*—against cumin wilt caused by *Fusarium oxysporum* f. sp. *cumini* under field conditions. All the evaluated bio-agents demonstrated a significant reduction in the mycelial development of *F. oxysporum* f. sp. *cumini*. Among them, *P. fluorescens* exhibited the highest suppression of fungal growth, followed closely by *T. harzianum* and *T. viride* in both laboratory (*in vitro*) and field (*in vivo*) experiments.

As reported by Deepak *et al.* (2008), the biological control agents demonstrating the highest suppression of the pathogen under field conditions were applied through soil amendment, seed treatment, or foliar application. Among the treatments, soil application of *Trichoderma harzianum* resulted in the lowest incidence of wilt disease, with a percent disease index (PDI) of 27.40%. The application of *T. harzianum* at the rate of 40 kg/ha under field conditions appears to be an effective and eco-friendly strategy for the sustainable management of cumin wilt.

Chhata *et al.* (2017) carried out a field study to evaluate the effectiveness of various organic modules in managing cumin (*Cuminum cyminum* L.) wilt disease. Among the tested treatments, the module consisting of seed treatment with *Trichoderma harzianum* at 8 g/kg of seed, along with three foliar applications of Azadirachtin at 2 ml/litre each—applied during 45–60, 60–75, and 90–100 days after sowing (DAS)—demonstrated significantly better disease suppression compared to the untreated control. This integrated approach also resulted in the highest cumin seed yield of 5.76 quintals per hectare.

Gangopadhyay and Gopal (2011) demonstrated the effectiveness of *Trichoderma harzianum* and *T. viride* applied as both seed treatment and soil incorporation, with or without the addition of farmyard manure, in managing cumin wilt caused by *Fusarium oxysporum* f. sp. *cumini* under *in vivo* conditions in pathogen-infested soil. The highest suppression of disease incidence was observed when *T. harzianum* was applied as a seed treatment at 4 g per kg of seed combined with a soil application at 5 g per kg of soil, supplemented with farmyard manure at a rate of 10 kg per unit soil.

Kumar *et al.* (2016) investigated the potential of different fungal and bacterial bioagents, isolated from the cumin rhizosphere, for managing cumin wilt caused by *Fusarium oxysporum* f. sp. *cumini*. Among the fungal antagonists, *Trichoderma viride*, *T. pseudokoningii*, *T. harzianum* and *C. sitophila*, along with the bacterial agents *Pseudomonas fluorescens* and *Bacillus subtilis*, demonstrated significant suppression of the pathogen under field conditions.

Sharma *et al.* (2014) conducted an experiment for management of cumin wilt by applying of *Trichoderma viride* and *Pseudomonas fluorescens* as seed and soil treatment and showed that seed treatment with *T. viride* (10g/kg seed) and soil application (2.5 kg/ha) recorded minimum per cent disease incidence.

Kamal *et al.* (2022) the present study investigates the biocontrol potential of some endophytes against *F. solani* and their effect on the induction of defense-related enzymes. In *in-vivo*, the application of *T. harzianum*, *T. longibrachiatum*, and *C. globosum* caused a reduction in disease severity (67.7%, 58.1%, and 59.3%, respectively) on cumin plants, with a lower disease severity (20%, 26%, and 25%, respectively) recorded in treated plants compared to the infected control (62%).

These observations align closely with the findings reported by Bardia and Rai (2007), who investigated the efficacy of fungal biocontrol agents and chemical fungicides in managing cumin wilt, caused by *Fusarium oxysporum* f. sp. *cumini*, under field conditions at Jobner, Rajasthan. Various combinations of antagonistic fungi and fungicides were assessed, among which the most effective treatment was seed treatment using carbendazim at 2 g per kg of seed, combined with *Trichoderma harzianum* isolate I6 at a concentration of 10 spores per ml. This integrated approach significantly reduced wilt incidence to 11.7% and recorded the highest seed yield of 6.17 quintals per hectare.

## Conclusion

The results across multiple years and pooled analysis clearly demonstrated that all bioagent-enriched treatments significantly reduced the incidence of wilt and root rot in cumin while enhancing seed yield compared to the untreated control. Among the treatments, the application of *Trichoderma viride* (2 ×

10 cfu/g) @ 2.5 kg/ha combined with *Pseudomonas fluorescens* ( $2 \times 10$  cfu/g) @ 2.5 kg/ha enriched in 1000 kg FYM applied 15 days prior to sowing (T5) consistently recorded the lowest disease incidence and the highest seed yield. This treatment remained statistically at par with T4 (*T. harzianum* + *P. fluorescens*), T3 (*P. fluorescens* alone), and T2 (*T. viride* alone) in most years and pooled results, confirming their effectiveness. These findings highlight the potential of integrated biological management using enriched FYM for sustainable and eco-friendly control of wilt and root rot in cumin.

### Conflict of Interest

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

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