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# Impact of Biological and Chemical Seed Treatments on Wilt of Castor (*Ricinus communis* L.) Caused by *Fusarium oxysporum* f. sp. *ricini*

**A. Chandini[1], R. D. Prasad[2*], K. Sakthivel[2], P. Duraimurugan[2], K. S. V. P. Chandrika[3], Ch. Sarada[4] and M. Suresh[2]**

[1]Dept. of Plant Pathology, Agricultural College, Bapatla, Acharya N.G. Ranga Agricultural University, Andhra Pradesh (522 101), India

[2]Dept. of Crop Protection, [3]Dept. of Agricultural Chemicals, [4]Dept. of Agricultural Statistics, ICAR-IIOR, Hyderabad (500 030), India

**Corresponding Author**

R. D. Prasad
*e-mail*: ravulapallidurgaprasad@gmail.com

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**Abstract**

The experiment was conducted during January, 2024-March, 2025 at ICAR-IIOR, plant pathology unit to study the impact of various biological and chemical treatments on controlling the most important wilt disease caused by *Fusarium oxysporum* f. sp. *ricini* in castor crop**.** The biocontrol agent *Trichoderma harzianum,* Th4d strain and castor wilt virulent pathogen, *Fusarium oxysporum* f. sp. *ricini* were sourced from the ICAR-IIOR Pathology Unit. The impact of chemical and biological seed treatments i.e., Vitavax (carboxin 37.5%+thiram 37.5% WS at 3.0 g kg$^{-1}$), *T. harzianum* Triguard Th-WP (Th4d 1.5% WP at 10.0 g kg$^{-1}$) and Evergol xtend (penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS at 1.0 ml kg$^{-1}$) against castor wilt through poisoned food technique under *in vitro* and pot culture study under *in vivo* conditions. Among the different treatments tested, Th4d was effective in reducing disease incidence by 26.1% and 28.1% respectively under *in vitro* and *in vivo* conditions. The results suggest that seed treatment with chemical fungicides and the biological control agent can be effective in management of the wilt pathogens. The concerns over environmental impacts of chemicals, their toxicity and possibility of development pathogen resistance have led to a shift towards more sustainable solutions. In this context, the biological seed treatment with *Trichoderma* Th4d strain has emerged as a promising method for managing the wilt pathogen in castor.

***Keywords:*** Th4d WP, wilt, fungicides, disease management, paper towel, pot culture

## 1. INTRODUCTION

Castor (*Ricinus communis* L.) is an important non-edible oilseed crops grown in India's arid and semi-arid regions, primarily in Gujarat, Rajasthan, Andhra Pradesh, Telangana, Tamil Nadu, Karnataka, and Odisha. It significantly contributes to the agricultural economy but faces threats from various fungal and bacterial diseases at different growth stages. The most significant castor disease now affecting India is castor wilt (*Fusarium oxysporum* f. sp. *ricini*) (Nanda and Prasad, 1974). The disease is characterized by the appearance of symptoms like interveinal necrosis, progressive yellowing, drooping of leaves and blackening and necrosis of the roots, prominently noticeable during the flowering and spike/raceme development stages (Dange et al., 2006) leading to significant yield losses.

Seed treatment involves applying chemical or biological agents before planting to protect against disease. While chemical fungicides control wilt pathogens well (Chaudhari et al., 1992) they leave chemical residues in crops and the environment, as well as problems with toxicity and resistance, have highlighted the need for biological methods. Biological seed treatments, which administer natural beneficial microorganism directly to seeds for targeted disease protection during early growth, have become a viable, residue-free alternative (McKinney, 1923). Kumar et al. (2020) identified multiple *Trichoderma* species, including *T. harzianum*, *T. viride*, *T. asperellum*, and others, using morphomolecular methods. Identification was based on colony traits, growth rate, and microscopic features like conidiophore branching and spore characteristics. Chattopadhyay and Varaprasad investigated the use of *Trichoderma viride* for controlling wilt disease in castor plants. *Trichoderma* species are common saprophytic fungi found in the soil and many studies have focused on their ability to reduce the incidence of the disease caused by plant pathogenic fungi (Elad, 2000; Freeman et al., 2004; Dubey et al., 2007).

The effectiveness of the biological control fungus *Trichoderma harzianum* was established by Prasad et al. (2002) reported that *T. harzianum* soil application limited root rot to 4.9% at 30 days and 1.2% at 60 days, compared to 16.4% and 17.0% in untreated controls. *T. virens* PDBCTVs 12 was found to be effective against fusarium wilt, whereas *T. harzianum* PDBCTH 10 was found to be an efficient biological control agent against rhizoctonia root rot and sclerotium collar rot (Rudresh 2005). Bardia and Rai (2007) who tested against *Fusarium oxysporum* f. sp. *cumini.*, Ravichandran and Hegde (2015) against *Fusarium oxysporum* f. sp. *ciceri*, Singh (2016) against *Fusarium oxysporum* and *Fusarium solani.*

Biological seed treatments, especially with biocontrol agents like *Trichoderma harzianum*, have gained attention for their eco-friendly properties and effectiveness (Villela et al., 2010). Suresh et al. (2012) assessed the efficacy of native isolates of *Trichoderma* and *Pseudomonas* in managing safflower wilt, a disease caused by *Fusarium oxysporum* f. sp. *carthami*. Chattopadhyay et al. (2001) found that *T. harzianum* reduced the castor wilt incidence by 93.78% in pot culture experiments. Sharma et al. (2014) reported that seed treatment and soil application with *Trichoderma* isolates significantly reduced cumin wilt incidence (58–85%). Navaneetha et al. (2015) reported that seed treatment with *Trichoderma harzianum* and foliar application of *Trichoderma* effectively decrease disease severity to about 55–65% against gray mold of castor.

Current research aims to evaluate the impact of chemical and biological seed treatments on controlling soil-borne wilt pathogen in castor crop, focusing on disease incidence, plant health, and overall yield outcomes. This study aims to explore sustainable seed treatment strategies to improve disease management, minimize dependence on chemical inputs, and faster healthier, more resilient castor crops.

## 2. Materials and Methods

### *2.1. Pathogen and the bioagent*

The experiment was conducted during January, 2024 to March, 2025 at ICAR-IIOR, plant pathology section. The biocontrol agent *Trichoderma harzianum* Th4d strain (Plate 1) and the castor wilt pathogen, *Fusarium oxysporum* f. sp. *ricini* were sourced from the ICAR-IIOR Pathology Laboratory and was maintained through regular sub culturing on Potato Dextrose Agar (PDA).

To prepare the pathogen for experimental use, single spores from each *F. oxysporum* f. sp. *ricini* isolate (Palte 2) were transferred onto PDA medium and incubated at 25±1°C. Mycelial plugs (5 mm in diameter) were taken from 7-day-old cultures of each isolate and subsequently inoculated onto fresh PDA plates, which were incubated at 25±2°C for 7 days. The morphological and cultural characteristics of the colony included a pinkish-white mycelial color, a fluffy texture, smooth margins, rapid growth, and high sporulation, consistent with observations reported by Aravind et al. (2024).

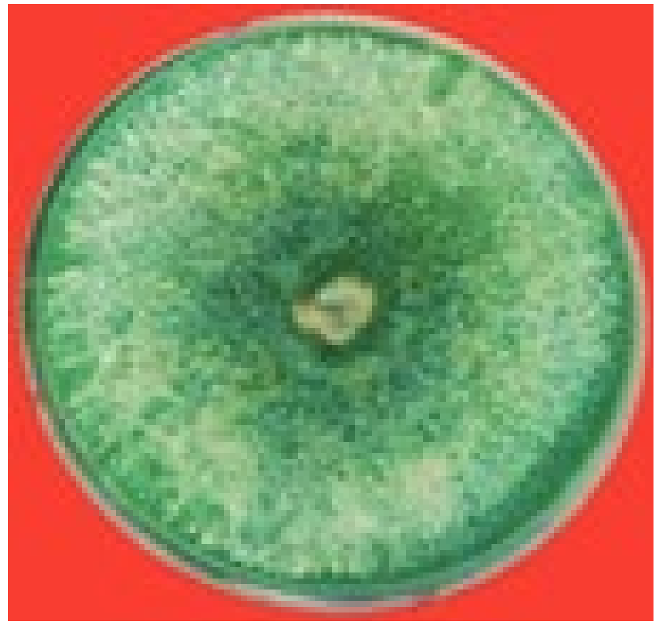

Plate 1: *Trichoderma harzianum* (Th4d) on PDA media

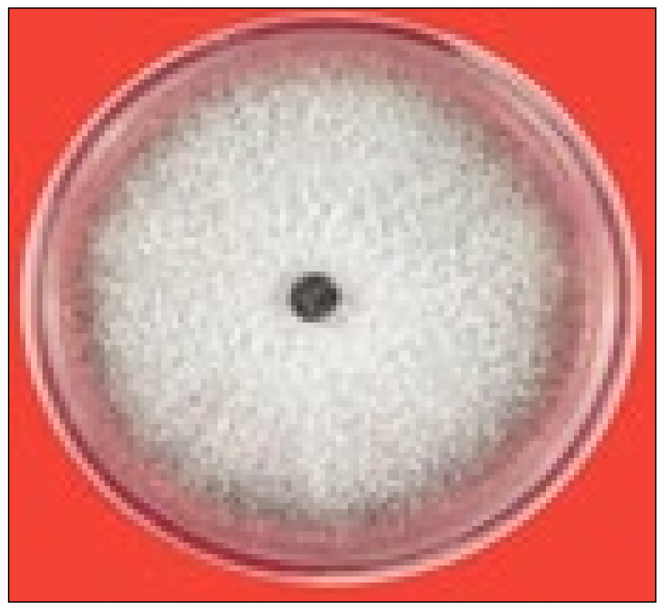

Plate 2: *Fusarium oxysporum* fsp. *ricini* on PDA media

### *2.2. Symptoms of fusarium wilt in castor*

Castor plants are highly susceptible to wilt disease throughout their growth stages, with symptoms often appearing in patches. The disease becomes most pronounced during flowering and spike formation but detected early at the seedling stage, particularly when the plant has 2–3 leaves. Root infections result in blackening and necrosis, often localized to one side of the root system, ultimately leading to significant reductions in plant growth and poor-quality seed production or failure to bear capsules.

### *2.3. In vitro antifungal activity of different seed treatment chemicals and Trichoderma, Th4d on Fusarium wilt of castor in paper towel method*

Figure 1: Typical symptoms of castor wilt: yellowing, wilting, stunted growth, black necrosis of stem tissues, defoliation

*2.3.1. Rolled paper towel method*

The effectiveness of various seed coating treatments on castor seeds against wilt infection was evaluated using the rolled paper towel method (ISTA, 1996). Additionally, the impact of biological and chemical treatments used (Table 1) on seed quality parameters was assessed in 5 replications under *in vitro* conditions.

Table 1: Details of chemical (fungicides) and biological agent used in *in vitro* studies (rolled paper towel method)

| Treatment No. | Treatment details | Trade name |
|---|---|---|
| $T_1$ | Carboxin 37.5%+thiram 37.5% WS at 3.0 g kg$^{-1}$ | Vitavax |
| $T_2$ | *Trichoderma harzianum*, Th4d 1.5% WP at 10.0 g kg$^{-1}$ | Triguard Th – WP |
| $T_3$ | Penflufen 13.28% w/w+ trifloxystrobin 13.28% w/w FS at1.0 ml kg$^{-1}$ | Evergol xtend |
| $T_4$ | Pathogen control (*Fusarium oxysporum* f. sp. *ricni*) | - |
| $T_5$ | Control | - |

*2.3.2. Effect of biological and chemical treatment on seed germination and seedling vigour*

Castor seeds were surface sterilized with 2% sodium hypochlorite solution and subsequently washed in distilled water three times and dried at room temperature under shade. Surface sterilized seeds were coated with different treatments as presented in Table 1 and then treated with conidial suspension. Coated seeds were placed on autoclaved germination paper towels (10 seeds paper towel$^{-1}$) and rolled tightly without disturbing the seed placing and moistened with water. Germination was checked after 7 days of incubation in growth chamber at 25±2°C. Data on seedling vigour was recorded after 15 days. The germination percentage, vigour index and disease incidence were calculated by using the formulae mentioned below;

Germination (%)=(Number of germinated seeds/Total number of seeds)×100

Vigour index-i= Germination (%)×Seedling length

Seedling length (cm)=(Shoot length+Root length)

Vigour index-ii=Germination (%)×Seedling dry weight (g)

*2.4. In vivo antifungal activity of different seed treatments against castor wilt pathogen*

*2.4.1. Preparation of Fusarium inoculum and pot culture test*

The standard sick pot inoculation technique, as described by Shaw et al. (2016), was employed to test the pathogenicity of *Fusarium oxysporum* f. sp. *ricini* isolates on castor plants. Wilt pathogen was mass multiplied on sorghum grains. The sorghum grains were soaked overnight in a 2% sucrose solution, then boiled in fresh water for 30 minutes. Excess water was drained, and the grains were transferred to conical flasks and autoclaved at 15 psi for 15 minutes. After sterilization, each flask was inoculated with a 5 mm mycelial disc from a 7-day old *F. oxysporum* f. sp. *ricini* culture grown on Potato Dextrose Agar (PDA) and incubated at 25°C for 10 to14 days. The inoculum was prepared by transferring a portion of the infected sorghum grains into sterile water and mixing thoroughly using a magnetic stirrer. The spore suspension was then adjusted to a concentration of $1\times10^6$ spores ml$^{-1}$, determined using a haemocytometer.

Plastic pots (4 kg capacity) were filled with a mixture of sterilized soil (3 parts red soil and 1 part black soil) and inoculated with 4 g kg$^{-1}$ of *F. oxysporum* f. sp. *ricini* inoculum. After inoculation, the pots were watered and placed in a glasshouse for 2–3 days. Seeds of five different castor treatments were sown in the inoculated soil to ensure uniform distribution of the pathogen. Seedlings were monitored for disease development, and wilt incidence was recorded as the number of wilted plants out of the total number inoculated, up to 30 days after sowing. The experiment was conducted under glasshouse conditions at ICAR-IIOR using sterilized red soil treated with a 2% formaldehyde solution. Castor seeds, treated with various treatments, were sown in pots filled with the sterile red soil. The treatments included fungicides carboxin 37.5%+thiram 37.5% WS and penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS) and a talc-based formulation of *Trichoderma harzianum*, which served as chemical and biological control treatments, respectively in 5 replications. Additionally, pathogen-inoculated and uninoculated controls were included. Each treatment was replicated three times and disease incidence (%) was recorded.

Disease incidence (%)=(Number of infected plants/Total number of plants)×100

*2.5. Statistical analysis*

*In vitro* antifungal activity experimental results were represented as mean+standard error. The statistical data was analyzed by one-way ANOVA using SPSS software (version 22, IBM Corporation, USA).

## 3. Results and Discussion

### *3.1. Impact of seed treatment on castor seeds*

In castor, seed treatment is essential because it supports strong seedling establishment, increases germination rates and shields plants from soil-borne diseases like Fusarium wilt. Effective disease management achieved with chemical solutions such as carboxin+thiram and penflufen+trifloxystrobin, while biological agents like *Trichoderma harzianum* offer environmentally friendly pathogen suppression and support soil health.

Castor wilt caused by *Fusarium oxysporum* f. sp. *ricini* is an economically important and major disease in castor growing areas of Telangana. The present study was undertaken to determine the impact of seed treatment of castor seeds against *Fusarium oxysporum* f. sp. *ricini* causing wilt in castor (*Ricinis communis* L.) at Indian Institute of Oilseeds Research, Hyderabad during 2024 to 2025 through rolled paper towel method and pot culture study. The results of experiments presented in Plate 3 and Plate 4.

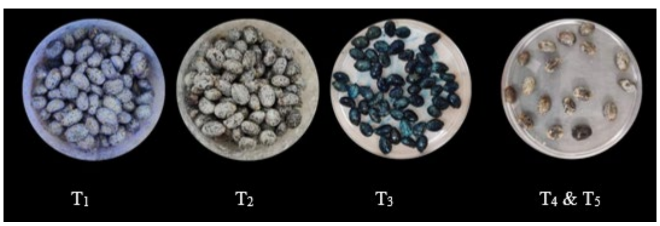


Plate 3: Castor seed treated with different chemicals and bioagent; $T_1$: Carboxin 37.5%+thiram 37.5% WS at 3.0 g kg$^{-1}$; $T_2$: *Trichoderma harzianum*; Th4d 1.5% WP at 10.0 g kg$^{-1}$; $T_3$: Penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS at 1.0 ml kg$^{-1}$; $T_4$: Pathogen control (*Fusarium oxysporum* f. sp. *ricini*); $T_5$: Control

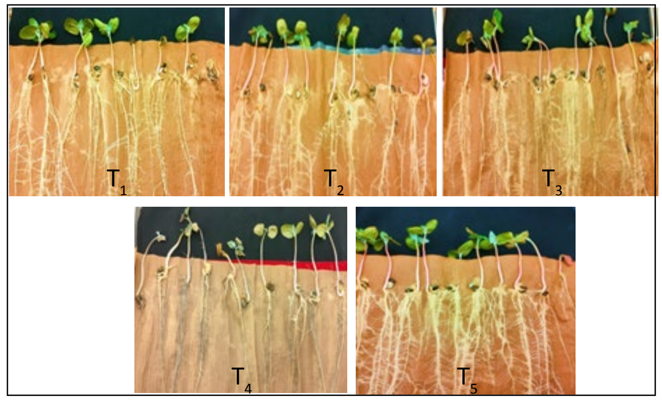


Plate 4: Efficacy of biological and chemical treatments of castor seed against *Fusarium oxysporum* f.sp. *ricni* through rolled paper towel method. $T_1$: Carboxin 37.5%+thiram 37.5% WS at 3.0 g kg$^{-1}$; $T_2$: *Trichoderma harzianum*; Th4d 1.5% WP at 10.0 g kg$^{-1}$; $T_3$: Penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS at 1.0 ml kg$^{-1}$; $T_4$: Pathogen control (*Fusarium oxysporum* f. sp. *ricini*); $T_5$: Control

The evaluation of different seed treatments based on parameters like seed germination, vigour, growth indices and disease incidence, enhanced the germination and all growth parameters compared with uncoated and other treated seeds in uninoculated condition (Table 2). The parameter wise impact of the seed treatments was detailed herewith.

#### *3.1.1. Seed vigour index-I (SVI)*

Highest seed vigour index was recorded in *Trichoderma* Th4d WP (3493.3) followed by penflufen 13.28% w/w+ trifloxystrobin 13.28% w/w FS treated seed (3460), carboxin 37.5% + thiram 37.5% WS treated seed (3390) and untreated seeds (3286). The least seed vigour index was recorded in Pathogen treated seed (3116). The treatment $T_2$ having a superior vigour index provides a faster germination and improved growth of castor seeds. The length of the roots aids

Table 2: Efficacy of biological and chemical treatments of castor seed against *Fusarium oxysporum* f. sp. *ricini* through rolled paper towel method

| | Germination (%) | Seed viability | Seed vigour index -1 | Seed vigour index-2 | Average Root length (cm) | Average Shoot length (cm) | Fresh weight (g) | Dry weight (g) | Disease Incidence (%) |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 100 | 100 | (3390)$^{a}$ | (133)$^{c}$ | 23.7 (4.91)$^{a}$ | 10.1 (3.25)$^{bc}$ | 12.5 (3.60)$^{a}$ | 1.25 (1.32)$^{a}$ | 36.7 (37.2)$^{d}$ |
| $T_2$ | 100 | 100 | (3493)$^{a}$ | (134)$^{c}$ | 24.8 (5.03)$^{a}$ | 11.2 (3.41)$^{a}$ | 12.6 (3.61)$^{a}$ | 1.26 (1.33)$^{a}$ | 26.1 (30.7)$^{a}$ |
| $T_3$ | 100 | 100 | (3460)$^{a}$ | (123)$^{b}$ | 23.9 (4.94)$^{a}$ | 10.7 (3.34)$^{ab}$ | 12.3 (3.57)$^{a}$ | 1.23 (1.31)$^{a}$ | 32.4 (34.6)$^{c}$ |
| $T_4$ | 100 | 100 | (3116)$^{a}$ | (106)$^{a}$ | 20.7 (4.60)$^{b}$ | 9.4 (3.14)$^{c}$ | 10.1 (3.25)$^{b}$ | 1.07 (1.25)$^{b}$ | 100.0 (90.0)$^{e}$ |
| $T_5$ | 100 | 100 | (3286)$^{b}$ | (167)$^{d}$ | 21.5 (4.69)$^{b}$ | 10.0 (3.23)$^{bc}$ | 10.6 (3.33)$^{b}$ | 1.43 (1.38)$^{c}$ | 0.0 (0.0)$^{b}$ |
| SEm± | | | 0.09 | 1.62 | 0.26 | 0.12 | 0.16 | 0.02 | 0.74 |
| CV (%) | | | 3.87 | 3.52 | 1.86 | 1.84 | 3.62 | 3.69 | 3.85 |
| CD (*p*=0.0.5) | | | 0.27 | 4.58 | 0.77 | 0.34 | 0.47 | 0.06 | 2.13 |

*Values represented are mean of five replications. Values in parantheses in arc sine transformation (Disease Incidence) and remaining values in square root transformed values in more water and nutrients can be absorbed from the soil *via* deeper roots and impacts in well-established plant stand. Highest root length was recorded in Th4d WP (24.8) followed by penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS treated seed (23.9), carboxin 37.5%+thiram 37.5% WS treated seed (23.7) and untreated seeds (21.5). The least seed root length was noticed with Pathogen treated seed (20.7). The Th4d WP treated seeds shown longest root length (23.9 cm), indicative of faster root development, contributing to higher seedling vigour. Highest shoot length was recorded in Th4d WP (11.2) followed by Evergol treated seed (10.7), carboxin 37.5%+thiram 37.5% WS treated seed (10.1) and untreated seeds (10.0). The least seed root length was noticed with Pathogen treated seed (9.4). The Th4d WP treated seeds provide longest shoot length (11.2 cm) contributing to higher seedling vigour

*3.1.2. Seed vigour index- II (SV II)*

Seed vigour index having a prominent impact on overall seed quality. Highest seed vigour index was recorded in *Trichoderma* Th4d WP (134.00) followed by carboxin 37.5%+thiram 37.5% WS treated seed (133), penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS treated seed (123) and untreated seeds(167). The least seed vigour index was recorded in Pathogen control (106). The treatment $T_2$ with a seed vigor index ensures that seeds germinate evenly and quickly, producing robust seedlings that boost crop establishment, yield potential, and performance in harsh environment. Dry weight is typically regarded as a more accurate measure of biomass and plant development. Fresh weight was recorded highest in *Trichoderma* Th4d WP treated seeds (11.2) followed by carboxin 37.5%+thiram 37.5% WS (12.5), penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS (12.3) and then untreated seeds (10.6), least fresh weight was observed in pathogen treated seeds (10.1). Similarly, highest dry weight was observed in Th4d WP treated seeds (1.26) followed by carboxin 37.5%+thiram 37.5% WS (1.25) and penflufen 13.28% w/w+ trifloxystrobin 13.28% w/w FS (1.23) and then untreated seeds (1.43), least fresh weight was observed in pathogen treated seeds (1.43).

*3.1.3. Disease incidence*

Disease incidence was recorded highest in pathogen control (100.0%). The least disease incidence was recorded in Th4d WP treated seeds (26.1%) and followed by moderate disease incidence with penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS (32.4%) and carboxin 37.5%+thiram 37.5% WS (36.7%). In untreated seeds i.e., healthy control exhibited 0.0% disease incidence was observed (Plate 5).

Efficacy of different treatments on wilt incidence mentioned in Table 3. In pathogen control, 100% disease incidence was observed compared to healthy control with free disease incidence followed by carboxin 37.5%+thiram 37.5% WS treated seeds (31.0% disease incidence). Carboxin 37.5%+thiram 37.5% WS recorded with less effective in disease

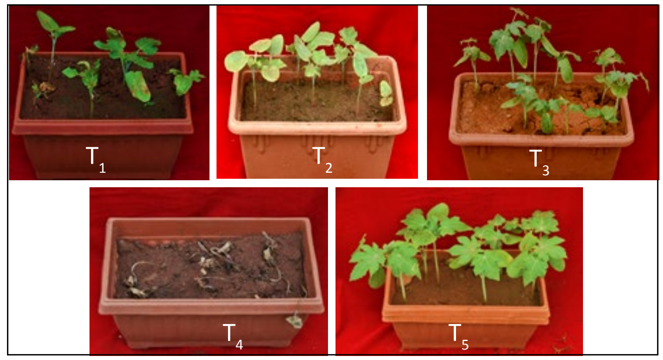


Plate 5: Evaluation of the different seed treatments of castor seeds against *Fusarium oxysporum* f. sp. *ricini* in castor under pot culture study; $T_1$: Carboxin 37.5%+thiram 37.5% WS at 3.0 g kg$^{-1}$; $T_2$: *Trichoderma harzianum*; Th4d 1.5% WP at 10.0 g kg$^{-1}$; $T_3$: Penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS at 1.0 ml kg$^{-1}$; $T_4$: Pathogen control (*Fusarium oxysporum* f. sp. *ricini*); $T_5$: Control

Table 3: Evaluation of the different seed treatments of castor seeds against *Fusarium oxysporum* f. sp. *ricini* in castor under pot culture study

| Treat-ment No. | Treatment details | Disease incidence (%) |
|---|---|---|
| $T_1$ | Carboxin 37.5%+thiram 37.5% WS at 3.0 g kg$^{-1}$ | 31.0 (33.8)$^{b}$ |
| $T_2$ | *Trichoderma harzianum*, Th4d 1.5% WP at 10.0 g kg$^{-1}$ | 28.1 (32.0)$^{a}$ |
| $T_3$ | Penflufen 13.28% w/w+ trifloxystrobin 13.28 % w/w FS at 1.0 ml kg$^{-1}$ | 29.4 (32.8)$^{ab}$ |
| $T_4$ | Pathogen control (*Fusarium oxysporum* f. sp. *ricni*) | 100.0 (90.0)$^{c}$ |
| $T_5$ | Healthy seed | 0.0 (0.0)$^{d}$ |
| SEm± | | 0.35 |
| CV (%) | | 3.92 |
| CD ($p$=0.05) | | 0.98 |

*Values represented here are mean of five replications; Values in parenthesis are arc sine transformed values

control compared to biological treatments, as chemical treatments sometimes face limitations in providing long-term protection. The *Trichoderma* Th4dWP treated seeds showed 28.1% disease incidence providing a protection against disease enhances the immune system and promoting the overall plant health by reducing more than 72.0% disease reduction. In penflufen 13.28% w/w+trifloxystrobin 13.28% w/w FS treated seeds showing least% disease incidence (29.4%) resulted in most effective management of wilt disease.

Rolled Paper Towel and Pot Culture methodologies were used to assess the management strategies for *Fusarium oxysporum f. sp. ricini*-causing castor wilt as mentioned in

Figure 2. Treatment $T_1$, which involved a combination of carboxin 37.5% and thiram 37.5% as a wettable powder, demonstrated moderate control with disease incidence rates of 31% and 36.7% in the two respective methods. In contrast $T_2$, *Trichoderma harzianum* as a biocontrol agent, achieved superior results with disease incidence of 28.1% and 26.1%. $T_3$, a mixture of penflufen 13.28% and trifloxystrobin 13.28% as a flowable concentrate, exhibited slightly lower effectiveness, with DI of 29.4 and 32.4, compared to $T_2$. Treatments $T_4$ (pathogen control) with higher disease severity, thereby underscoring the relative advantages of biological and integrated disease management approaches.

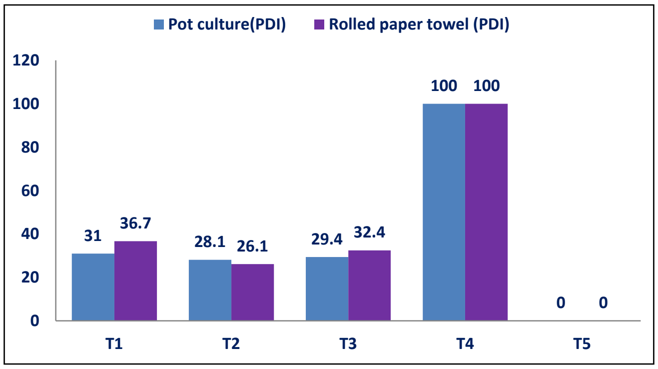


Figure 2: Wilt disease incidence under rolled paper towel and pot culture experiments

Seed treatments with both biological (Th4d) and chemical agents reduced wilt incidence in castor. According to Azad et al. (2025), the best bioagent for controlling seedling illnesses was a combination of seed treatment with Trichoderma *harzianum* strain PBAT 21 and Pseudomonas fluorescens strain PBAP 27 at 10 g $kg^{-1}$ with highest seed germination rate (43.88%), lowest seedling mortality (35.82%) and maximum seedling vigor index (759.00). *T. harzianum* PBAT-21 by itself came next, and in comparison to other treatments, it likewise demonstrated better seed germination (41.52%) and lower seedling mortality (39.82%).

These results agree with the findings of Singh et al. (2023), who reported that *Trichoderma harzianum* isolate Th Azad showed strong antagonistic activity against *Fusarium oxysporum* f. sp. *lentis*, was able to improve seed quality attributes in the field and limit pathogen development by 69.2% under *in vitro*. Th Azad showed synergistic benefits with the fungicide vitavax, increasing lentil seed germination by 8.26% when compared to untreated controls. The isolate was suitable for field use as a seed treatment at 5 g $kg^{-1}$ seed since it demonstrated resilience to abiotic stressors.

In the present study *Trichoderma harzianum* (Th4d WP) consistently gave the best results for castor seed treatments. It improved seed vigour, root and shoot length, and plant biomass, while also reducing disease incidence. Seeds treated with Th4d WP showed the strongest seedling growth. Chemical treatments like penflufen+trifloxystrobin and carboxin+thiram were also helpful, but slightly less effective than the biological treatment. Untreated seeds and those exposed to the pathogen had weaker growth and higher disease levels, showing the importance of seed treatment for healthy crop establishment. These findings similar with results using *in vitro*, Sumi and Tiameren (2015) documented the efficacy of three *Trichoderma* species- *Trichoderma harzianum*, *T. viride* and *T. virens* against *Sclerotium rolfsii*, the causative agent of sunflower stem rot.

Suresh et al. (2023), who found that native *Trichoderma* from chickpea fields controlled Fusarium wilt more effectively than commercial products. Similarly, Rakesh et al. (2017) showed that *Trichoderma* treatments increased germination and vigour, while reducing disease to just 15.40%.

In pot culture study, seed treatments significantly reduced wilt incidence in castor, highlighting their importance in disease management. Among chemical treatments, carboxin + thiram reduced disease to 31.0%, and penflufen + trifloxystrobin was slightly better at 29.4%. However, *Trichoderma harzianum* (Th4d WP) showed the best results with only 28.1% disease incidence over 72% reduction proving more effective than chemicals, likely due to its long-term protection and lower risk of resistance. According to Khatso et al. (2023) The highest reduction in plant mortality (4.2.%) under field conditions was achieved by treating seeds with *T.viride* @ 4g 10 $ml^{-1}$ of water $kg^{-1}$ of seed. This was followed by increases in disease control (84.9%), plant stand over control (32.8.%), plant height (48.9 cm), number of tillers (18.0) and yield (10.5 kg $plot^{-1}$), respectively.

In a similar study Singh et al. (2023) found that the TH3 isolate, which was isolated from a soil sample of the Bilgram block of the Hardoi district, had the highest suppression of *F. oxysporum* f.sp. *ciceri* mycelial growth, measuring 55.08%. $TH_1$ had the highest inhibition of 60.26% myccelial growth against *Fusarium* lentis, whereas the $TS_5$ isolate of Lainbua block of Sitapur was determined to be 39.76% least effective against the parasite.

Jangir et al. (2023), reported over 78% fungal inhibition by *T. harzianum*. In both paper towel and pot studies, *T. harzianum* outperformed chemical treatments, suggesting its superiority as a biocontrol agent. Other researcher studies also support current findings Altinok and Erdogan (2015) found that *T. harzianum* inhibited *Fusarium* growth by 72.6%. Massod et al. (2020) reported an 85.9% reduction in *Fusarium* using *T. harzianum*, improving plant growth in strawberries. Kripalini et al. (2018) found that combining seed and soil treatment with *Trichoderma* gave the best disease control. Dubey et al. (2013) showed that using *T. harzianum* with chemical fungicides in chickpea improved germination and reduced wilt. Islam et al. (2010) and Nayaka et al. (2010) also reported reduced wilt incidence and better plant growth in tomato and maize with *Trichoderma*.

## 4. Conclusion

In comparison to chemical treatments such as penflufen 13.28%+trifloxystrobin 13.28% FS and carboxin 37.5% + thiram 37.5% WS, the study showed that *Trichoderma harzianum* Th4d WP (biological treatment) produced the highest seedling vigour indices (VI-I, VI-II), root/shoot length, biomass, and the lowest disease incidence in rolled paper towel and pot culture assays. In contrast to chemical treatments, which have historically been successful but have limits related to fungicide resistance concerns and variable environmental compatibility, Th4d WP probably increased seedling resilience by triggering natural defense mechanisms against diseases like *Fusarium*.

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