



Eco-friendly management of chickpea wilt caused by *Fusarium oxysporum* f. sp. *ciceris* using plant extracts and soil amendments

Girija Shankar*, Suresh Kumar Sahu, Ritika Samrath, Ashwarya Lalit Tandon,
Praful Kumar Soni & Nisha Thakur

Department of Plant Pathology, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya, Raipur 492 012, Chhattisgarh, India

*Correspondence: [Girija Shankar, girjasinha23@gmail.com](mailto:girjasinha23@gmail.com)

Abstract

Chickpea wilt caused by *Fusarium oxysporum* f. sp. *ciceris* is one of the most destructive soil-borne diseases limiting chickpea production. The present investigation was conducted to evaluate the efficacy of different botanical extracts and soil amendments against the pathogen under *in vitro* and pot conditions. Nine botanical extracts, namely neem, karanj, datura, lantana, tulsi, aonla, onion, garlic and ginger, were tested at 5, 10 and 15 % concentrations using the poisoned food technique. Garlic extract recorded the maximum mycelial growth inhibition (90.00 %) at 15 % concentration, followed by karanj (80.37 %) and neem (78.52 %). In pot experiments, garlic treatment resulted in the highest mean disease reduction (53.22 %), followed by karanj (43.54 %) and neem (36.01 %). Eleven soil amendments were also evaluated against wilt under pot conditions. Vermicompost + *Trichoderma* proved most effective, reducing disease incidence to 44.63 % and improving germination to 90.00 %. *Pseudomonas fluorescens* was the next best treatment with 53.57 % disease incidence. The same treatments significantly enhanced plant height, root length, nodulation and biomass accumulation. The study demonstrated that garlic, karanj, neem, vermicompost + *Trichoderma* and *P. fluorescens* can be effectively utilised as eco-friendly components for integrated management of chickpea wilt.

Keywords: chickpea wilt; plant extracts; *Pseudomonas fluorescens*; soil amendments; *Trichoderma*

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1. Introduction

Chickpea (*Cicer arietinum* L.) is one of the most important grain legumes cultivated in India and other semi-arid regions of the world because of its high nutritional value and ability to improve soil fertility through biological nitrogen fixation (1, 2). Wilt caused by *Fusarium oxysporum* f. sp. *ciceris* is one of the most destructive diseases of chickpea and is responsible for considerable yield losses under favourable environmental conditions. The pathogen invades the root system, colonises the vascular tissues, blocks xylem vessels and ultimately causes wilting and death of infected plants (2– 4). The long-term survival of the pathogen as chlamydospores in soil and infected crop residues makes its management difficult using a single control strategy (3, 5).

The extensive use of synthetic fungicides for the management of soil-borne pathogens has raised concerns regarding environmental contamination, fungicide resistance and adverse effects on beneficial microorganisms. Therefore, sustainable disease management approaches based on botanicals, biological control agents and organic soil amendments are receiving increasing attention (5, 6). Botanical

extracts contain diverse bioactive compounds, including phenolics, flavonoids, terpenoids and sulfur-containing metabolites, which possess broad-spectrum antifungal activity against several phytopathogenic fungi. Similarly, organic amendments can contribute to the suppression of soil-borne pathogens by improving soil physicochemical properties and stimulating beneficial microbial communities. Their decomposition provides substrates that enhance the activity and abundance of antagonistic microorganisms, which can suppress pathogens through competition for nutrients and infection sites, antibiosis, mycoparasitism and production of inhibitory metabolites. Organic amendments may also promote microbial diversity and improve soil structure and nutrient availability, thereby enhancing plant vigour and resistance to pathogen infection (7, 8).

Beneficial microorganisms such as *Trichoderma* spp. and *Pseudomonas fluorescens* suppress *F. oxysporum* f. sp. *ciceris* through multiple mechanisms, including competition for nutrients and space, antibiosis, mycoparasitism, production of lytic enzymes and induction of systemic resistance in host plants. These mechanisms improve seedling establishment, reduce wilt incidence and promote plant growth, making them

important components of integrated disease management strategies (8, 9). The present investigation was therefore undertaken to evaluate the efficacy of selected botanical extracts and different soil amendments against *F. oxysporum* f. sp. *ciceris* under laboratory and pot conditions for developing eco-friendly management strategies for chickpea wilt.

2. Materials and Methods

The pathogen isolate was identified as *F. oxysporum* f. sp. *ciceris* based on its characteristic colony morphology and microscopic features, including the production of hyaline, septate mycelium, characteristic macroconidia and microconidia. The pathogenicity of the isolate was confirmed by inoculating healthy chickpea plants and observing typical wilt symptoms, followed by re-isolation of the pathogen from symptomatic tissues, thereby fulfilling the essential steps of Koch's postulates. Chickpea cultivar JG-62, a highly susceptible cultivar to *F. oxysporum* f. sp. *ciceris*, was used for the pathogenicity and subsequent disease-management experiments.

The pot experiment was conducted to manage the wilt of chickpea by artificial inoculation techniques under greenhouse condition. For the soil inoculation technique, the soil was autoclaved at approximately 121 °C for 60 min for one time, before use the soil was separated in two groups for inoculation and non-inoculated. Each pot was filled with sterile soil. Wheat substrate (100 g) was placed in a 250 mL Erlenmeyer flask and autoclaved at 121 °C for 30 min before inoculation. The inoculated cultures were incubated at 25 ± 1 °C for 7 days under complete darkness. After 30 days of incubation, infested wheat brans were applied to the soil (10). For inoculated treatment, the pathogen-infested pots were prepared by using the inoculum of the pathogen at 25 g/kg soil. The inoculum of mass multiplied on wheat grain media each isolate was added to the sterilised soil. Two kg mixture was placed in a (35.6 × 30 × 28.6 cm L × W × H) size plastic pot containing sterile soil. Chickpea seeds of susceptible variety (JG-62) were surface sterilised with 1 % sodium hypochlorite (NaOCl) for 1 min, followed by 3 washes with sterile water. Ten seeds were placed in 1 pot and 3 replications of each isolate were maintained. Plants were maintained at room temperature (25–28 °C) and watered to saturation after planting. Observation to be recorded as germination per cent and per cent mortality. Germination per cent was recorded to observe the effect of botanical extract on seed germination of chickpea.

Germination per cent was calculated according to standard procedures of the International Seed Testing Association (11).

$$\text{Germination \%} = \frac{\text{Number of germinated seeds}}{\text{Total number of seeds tested}} \times 100$$

Eq. (1)

The per cent mortality was calculated using standard plant pathology methodology (12).

$$\text{Mortality \%} = \frac{\text{Number of wilted plant}}{\text{Total number of plant tested}} \times 100$$



HePG

Eq. (2)

The present study evaluated three botanical extracts, namely garlic, neem and karanj, for their antifungal activity against *F. oxysporum* f. sp. *ciceris*. In addition, the soil amendments evaluated under pot conditions included vermicompost, farmyard manure (FYM), poultry manure, bone meal, neem cake, mustard cake, vermicompost + *Trichoderma*, FYM + vermicompost, *P. fluorescens* and neem cake + FYM, with an untreated control for comparison.

Preparation of botanical extracts

Fresh plant materials of neem (*Azadirachta indica* A.Juss.), karanj (*Pongamia pinnata* (L.) Pierre), datura (*Datura stramonium* L.), Jarayan (*Lantana camara* L.), tulsi (*Ocimum* sp.), aonla (*Embllica officinalis* Gaertn.), onion (*Allium cepa* L.), garlic (*Allium sativum* L.) and ginger (*Zingiber officinale* Roscoe) were thoroughly washed, crushed with sterile distilled water and filtered through muslin cloth. The filtrates were used for preparing 5, 10 and 15 % concentrations (8, 13).

In vitro evaluation of botanicals

The poisoned food technique was employed. Appropriate quantities of botanical extracts were mixed with sterilised potato dextrose agar (PDA) before pouring into Petri plates (14). After solidification, 5 mm discs from actively growing cultures of *F. oxysporum* f. sp. *ciceris* were placed at the center of each plate. Plates without extracts only PDA served as control. Radial mycelial growth was measured after incubation and per cent inhibition was calculated using the standard formula.

Pot evaluation

The pot experiments were conducted under controlled greenhouse conditions. The plants were maintained at a temperature of approximately ($25 \pm$ °C), with relative humidity of (80–90 %) and a natural photoperiod of approximately (12 hr light/12 hr dark). Pots were maintained under uniform light exposure and were periodically repositioned to minimise variation in light and temperature among treatments. Irrigation was applied uniformly to all treatments as required to maintain adequate soil moisture without waterlogging. The environmental conditions were monitored throughout the experimental period.

A pot experiment was conducted in a completely randomised design with 3 replications using chickpea cultivar JG-62. Seeds were treated with botanical extracts and sown in pathogen-infested soil. Germination per cent and wilt incidence were recorded. The pathogen-inoculated untreated control, plants were maintained under artificially inoculated conditions without any disease-management treatment.

Experimental design

The pots were arranged in a completely randomised design (CRD). In 10 treatment allocations with 3 replications, the pots were randomly positioned in the greenhouse using a random-number sequence, with equal spacing between pots. Pot positions were periodically rearranged to minimise the effects of spatial

variation in light, temperature and other environmental conditions.

Soil amendments

The pots were arranged in a CRD. In 11 treatment allocation with 3 replications, the pots were randomly positioned in the greenhouse using a random-number sequence, with equal spacing between pots. Pot positions were periodically rearranged to minimise the effects of spatial variation in light, temperature and other environmental conditions.

Eleven treatments comprising vermicompost, FYM, poultry manure, bone meal, neem cake, mustard cake, vermicompost + *Trichoderma*, FYM + vermicompost, *P. fluorescens*, neem cake + FYM and an untreated control were evaluated under pot conditions. Sterilised soil was mixed with the respective amendments before sowing (15).

Observations on germination, disease incidence, plant height, root length, nodules, shoot and root fresh weight and shoot and root dry weight were recorded (15, 16).

Randomisation of pot experiment

Pots representing all treatments were randomly assigned to positions within the experimental area for each replication. The positions of the pots were randomised to minimise potential positional effects arising from variation in light, temperature, humidity and other environmental conditions. All pots were maintained under uniform experimental conditions and were managed similarly throughout the experiment.

Statistical analysis

The *in vitro* and pot experiments were conducted in a CRD, with 3 replications. Data were subjected to analysis of variance (ANOVA). Treatment means were compared using the critical difference (CD) test at a 1 % level of significance ($p \leq 0.01$) for CRD experiments (17).

3. Results and Discussion

Efficacy of plant extracts against mycelial growth of *Fusarium oxysporum* f. sp. *ciceris* under *in vitro* conditions

Significant differences were observed among the botanical extracts, with all treatments exhibiting concentration-dependent inhibition of mycelial growth. In general, increasing the extract concentration from 5 % to 15 % resulted in greater suppression of fungal growth. The results are presented in Table 1, Plate 1 and Fig. 1.

At the highest concentration (15 %), garlic (*A. sativum*) clove extract was the most effective treatment, restricting radial mycelial growth to 9.00 mm and recording the highest inhibition (90.00 %) compared with the untreated control (90.00 mm). Karanj (*P. pinnata*) leaf extract ranked second, with 17.67 mm radial growth and 80.37 % inhibition, followed by neem

(*A. indica*) leaf extract, which recorded 19.33 mm radial growth and 78.52 % inhibition.

Moderate antifungal activity at 15 % concentration was observed with datura (*D. stramonium*) (28.67 mm radial growth; 68.14 % inhibition) and tulsi (*Ocimum* sp.) (30.67 mm radial growth; 65.92 % inhibition). Comparatively lower inhibition was recorded with *L. camara* (34.67 mm radial growth; 61.48 % inhibition) and onion (*A. cepa*) (36.33 mm radial growth; 59.63 % inhibition).

A similar trend was observed at 10 % concentration, where garlic remained the most effective treatment, recording 13.67 mm radial growth and 84.81 % inhibition. Karanj and neem also showed appreciable antifungal activity, with radial growth of 25.33 mm and 36.67 mm, corresponding to 71.86 % and 59.26 % inhibition, respectively.

At the lowest concentration (5 %), garlic continued to exhibit the greatest inhibitory effect, restricting mycelial growth to 28.33 mm with 68.52 % inhibition. In contrast, ginger (*Z. officinale*) was the least effective treatment at this concentration, recording 67.33 mm radial growth and only 25.19 % inhibition.

The superior antifungal activity of garlic, followed by karanj and neem, may be attributed to the presence of bioactive compounds with antifungal properties that inhibit mycelial growth of *F. oxysporum* f. sp. *ciceris*. The concentration-dependent increase in inhibition observed across all botanical extracts indicates that their efficacy is influenced by the quantity of active phytochemicals available in the extract. Therefore, it was concluded that while all the plant extracts possessed inherent fungitoxic properties, Garlic, Karanj and Neem were exceptionally effective in retarding the radial growth of *F. oxysporum* f. sp. *ciceris* *in vitro*.

Evaluation of different plant extracts against wilt of chickpea under pot conditions

Significant differences among the botanical treatments were observed for seed germination and disease incidence. The pathogen-inoculated untreated control recorded the lowest seed germination (55.00 %) and the highest disease incidence, reaching 94.44 % during 2024–25 and 100.00 % during 2025–26, indicating severe wilt infection under uninoculated conditions. The results are presented in Table 2, Plate 2 and Fig. 2. Among the tested botanicals, garlic (*A. sativum*) was the most effective treatment. It improved seed germination to 75.00 % and reduced wilt incidence to 45.83 % during 2024–25 and 45.04 % during 2025–26, resulting in the highest mean disease reduction (53.22 %) over the control. Karanj (*P. pinnata*) was the second most effective treatment, recording 70.00 % seed germination and disease incidences of 54.17 % and 55.56 % during 2024–25 and 2025–26, respectively, with a mean disease reduction of 43.54 %. Neem (*A. indica*) also reduced disease incidence, recording 62.10 % and 62.22 % wilt incidence during the two experimental seasons and a mean disease reduction of 36.01 %.



Table 1. Efficacy of different plant extracts on mycelial growth of *Fusarium oxysporum* f. sp. *ciceris* under *in vitro* condition

Sl. No.	Plant extract	5 % Concentration		10 % Concentration		15 % Concentration	
		Growth (mm)	Inhibition (%)	Growth (mm)	Inhibition (%)	Growth (mm)	Inhibition (%)
1	Aonla (<i>Emblica officinalis</i>)	64.67	28.14	47.33	47.41	33.00	63.33
2	Datura (<i>Datura stramonium</i>)	51.00	43.33	42.00	53.33	28.67	68.14
3	Karanj (<i>Pongamia pinnata</i>)	36.33	59.63	25.33	71.86	17.67	80.37
4	Jarayan (<i>Lantana camara</i>)	60.33	32.97	47.33	47.41	34.67	61.48
5	Neem (<i>Azadirachta indica</i>)	43.67	51.48	36.67	59.26	19.33	78.52
6	Tulsi (<i>Ocimum sp.</i>)	56.00	37.78	43.33	51.86	30.67	65.92
7	Onion (<i>Allium cepa</i>)	66.00	26.67	46.33	48.52	36.33	59.63
8	Garlic (<i>Allium sativum</i>)	28.33	68.52	13.67	84.81	9.00	90.00
9	Ginger (<i>Zingiber officinale</i>)	67.33	25.19	49.33	45.19	31.33	65.19
10	Control	90.00	0.00	90.00	0.00	90.00	0.00
	C.D. ($p = 0.01$)	3.15		2.88		2.45	
	SE(m) $\pm$	1.05		0.96		0.82	

In vitro inhibition recorded at 5 %, 10 % and 15 % concentrations. Mean values from 3 replications.

**Plate 1.** Efficacy of different plant extracts against mycelial growth of *Fusarium oxysporum* f. sp. *ciceris* under *in vitro* condition.

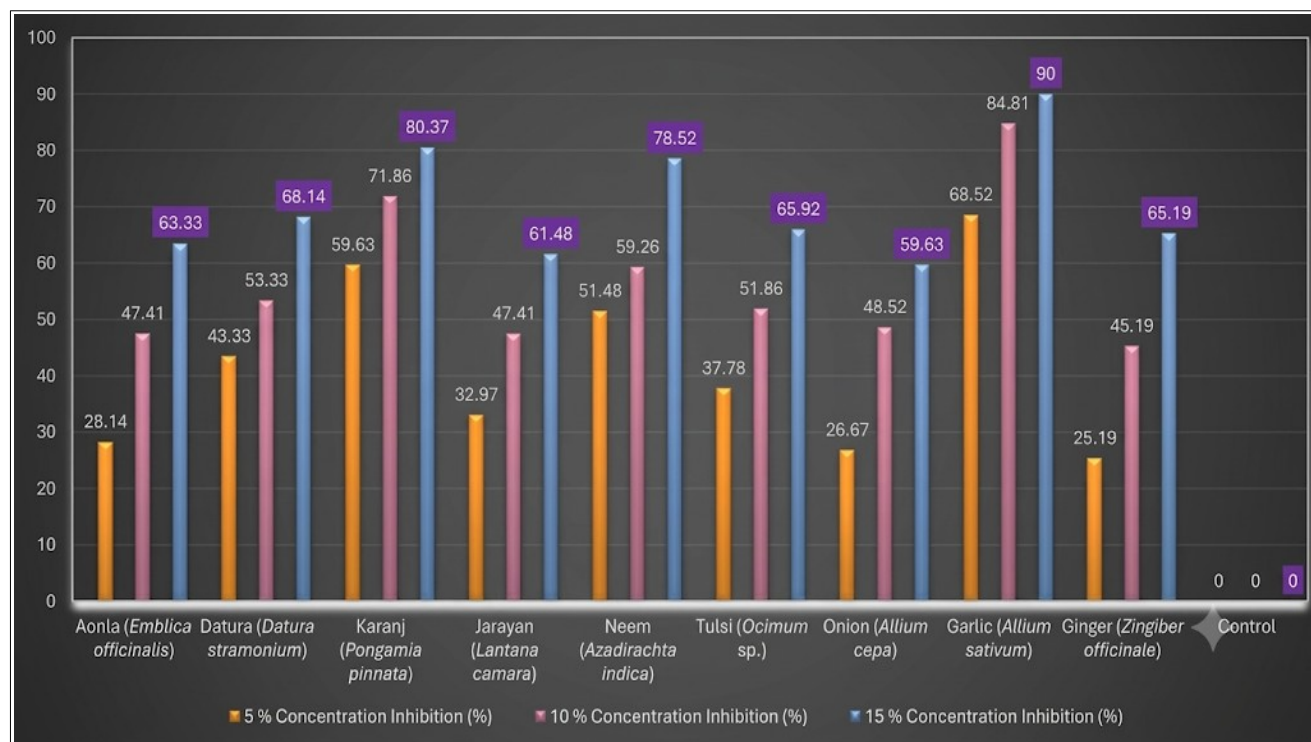


Fig. 1. Efficacy of plant extracts against mycelial growth of *Fusarium oxysporum* f. sp. *ciceris* under *in vitro* condition.

In contrast, jarayan (*L. camara*) was the least effective botanical, with a mean disease reduction of 12.03 % and disease incidence reaching 88.89 % during 2025–26. Similarly, ginger (*Z. officinale*) and onion (*A. cepa*) provided comparatively lower disease suppression, resulting in mean disease reductions of 14.95 % and 17.77 %, respectively. The enhanced disease suppression and improved seed germination observed with garlic, karanj and neem may be attributed to the presence of antifungal phytochemicals that inhibit pathogen growth and support early seedling establishment. The consistency of their performance under both *in vitro* and pot conditions suggests their potential as eco-friendly components of integrated management strategies for chickpea wilt.

Effect of soil amendments on germination and disease incidence of wilt disease of chickpea

The effect of different soil amendments on seed germination and wilt disease incidence caused by *F. oxysporum* f. sp. *ciceris* was evaluated under pot conditions during the 2024–25 and 2025–26 seasons. The results are presented in Table 3, Plate 3 and Fig.3. Significant differences among the treatments were observed for both seed germination and disease incidence.

The untreated control recorded the lowest mean seed germination (50.00 %) and the highest mean disease incidence (85.75 %), indicating severe disease pressure in the absence of soil amendments. Among the evaluated treatments, vermicompost enriched with *Trichoderma* was the most effective, resulting in the highest mean seed germination (90.00 %) and the

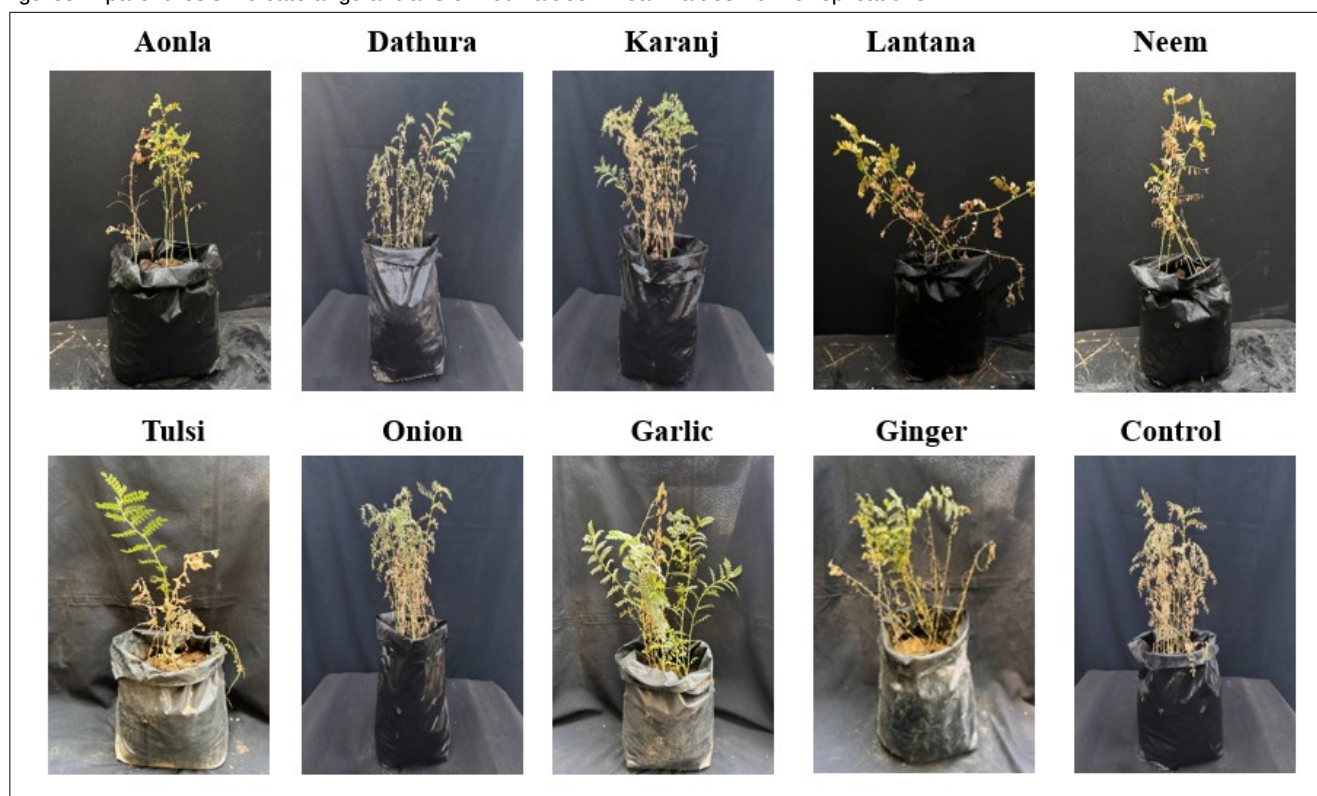
lowest disease incidence of 42.96 % during 2024–25 and 46.30 % during 2025–26, with an overall mean of 44.63 %. Application of *P. fluorescens* was the second most effective treatment, improving mean seed germination to 75.00 % while reducing the overall mean disease incidence to 53.57 %. Neem cake combined with FYM also improved crop establishment and reduced disease, recording a mean germination of 70.00 % and a mean disease incidence of 67.56 %.

In contrast, sole application of organic amendments such as bone meal and poultry manure was less effective in suppressing wilt, with mean disease incidences of 78.33 % and 76.11 %, respectively. Although these amendments provided some improvement over the untreated control, their efficacy was lower than that of the bioagent-based treatments. The superior performance of vermicompost + *Trichoderma* and *P. fluorescens* observed in the present study may be associated with the disease-suppressive and plant-growth-promoting properties reported for these biological inputs. Vermicompost-associated disease suppression has been linked to enhanced microbial activity, competition with pathogens, antibiosis and induction of plant defence responses, whereas *P. fluorescens* can suppress soil-borne pathogens through rhizosphere colonisation, competition for nutrients and space, production of antimicrobial metabolites and induction of systemic resistance. However, these mechanisms were not directly evaluated in the present experiment and therefore are proposed as possible explanations for the observed disease suppression rather than as experimentally confirmed mechanisms (18).

Table 2. Effect of different plant extracts on wilt incidence and seed germination of chickpea (*Cicer arietinum*)

Sl. No.	Plant extracts	Germination %		Mean	Disease incidence %		Mean	Disease incidence reduction %		Mean
		2024–25	2025–26		2024–25	2025–26		2024–25	2025–26	
1	Aonla (<i>Embllica officinalis</i>)	66.67	60.00	63.34	75.40 (60.27)	78.25 (62.20)	76.83 (61.24)	20.16	21.72	20.94
2	Datura (<i>Datura stramonium</i>)	66.67	60.00	63.34	65.87 (54.25)	83.02 (65.67)	74.45 (59.96)	30.25	16.98	23.62
3	Karanj (<i>Pongamia pinnata</i>)	73.33	66.67	70.00	54.17 (47.39)	55.56 (48.19)	54.87 (47.79)	42.64	44.44	43.54
4	Jarayan (<i>Lantana camara</i>)	56.67	53.33	55.00	82.22 (65.06)	88.89 (70.53)	85.56 (67.80)	12.94	11.11	12.03
5	Neem (<i>Azadirachta indica</i>)	70.00	53.33	61.67	62.10 (52.00)	62.22 (52.07)	62.16 (52.04)	34.24	37.78	36.01
6	Tulsi (<i>Ocimum</i> sp.)	66.67	56.67	61.67	65.87 (54.25)	88.89 (70.53)	77.38 (62.39)	30.25	11.11	20.68
7	Onion (<i>Allium cepa</i>)	66.67	63.33	65.00	70.63 (57.18)	89.68 (71.26)	80.16 (64.22)	25.21	10.32	17.77
8	Garlic (<i>Allium sativum</i>)	80.00	70.00	75.00	45.83 (42.61)	45.04 (42.15)	45.44 (42.38)	51.47	54.96	53.22
9	Ginger (<i>Zingiber officinale</i>)	76.67	73.33	75.00	78.57 (62.42)	86.90 (68.78)	82.74 (65.60)	16.80	13.10	14.95
10	Control	56.67	53.33	55.00	94.44 (76.36)	100.00 (90.00)	97.22 (83.18)	0.00	0.00	0.00
	C.D. ($p = 0.01$)	4.11	3.94	3.42	6.02	6.48	5.67			
	SE(m)±	1.42	1.36	1.18	2.08	2.24	1.96			

Figures in parenthesis indicate angular transformed values. Mean values from 3 replications.

**Plate 2.** Evaluation of different plant extracts against on wilt disease of chickpea under pot condition.

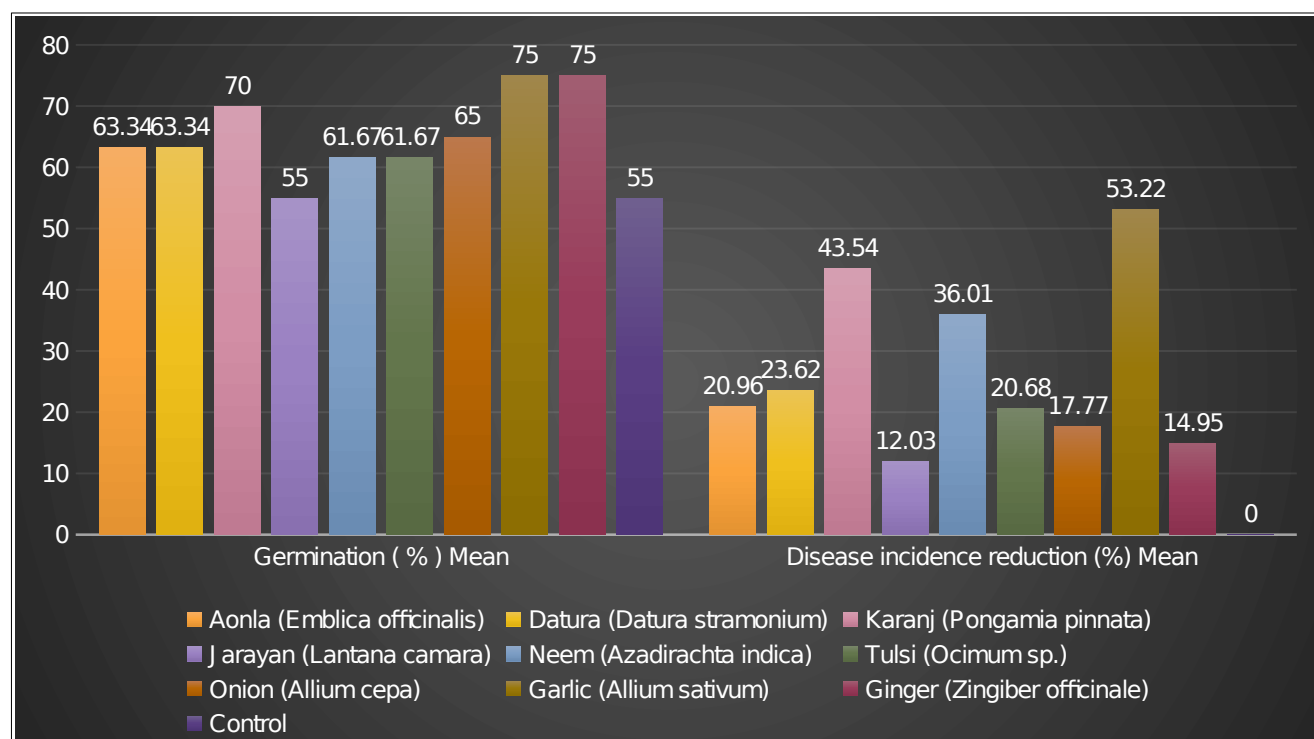


Fig. 2. Evaluation of different plant extracts against on wilt disease of chickpea under pot condition.

Table 3. Effect of different soil amendments on wilt incidence and seed germination of chickpea (*Cicer arietinum*)

Sl. No.	Amendments	Germination (%)			Disease incidence (%)			Disease incidence reduction (%)		
		2024–25	2025–26	Mean	2024–25	2025–26	Mean	2024–25	2025–26	Mean
1	Vermicompost	76.67	76.67	76.67	73.81 (59.22)	75.40 (60.27)	75.20 (60.13)	20.58	24.60	22.65
2	FYM	80.00	76.67	78.33	71.03 (57.44)	74.40 (59.60)	72.72 (58.51)	24.79	25.60	25.20
3	Poultry manure	56.67	53.33	55.00	76.67 (61.12)	75.56 (60.37)	76.11 (60.74)	18.82	24.44	21.71
4	Bone meal	63.33	56.67	60.00	78.33 (62.26)	78.33 (62.26)	78.33 (62.26)	17.06	21.67	19.43
5	Neem cake	40.00	43.33	41.67	67.22 (55.07)	75.56 (60.37)	71.39 (57.66)	28.82	24.44	26.57
6	Mustard cake	50.00	53.33	51.67	74.60 (59.74)	71.11 (57.49)	72.86 (58.60)	21.01	28.89	25.06
7	Vermicompost + <i>Trichoderma</i>	93.33	86.67	90.00	42.96 (40.95)	46.30 (42.88)	44.63 (41.92)	54.51	53.70	54.09
8	FYM + Vermicompost	76.67	73.33	75.00	69.64 (56.56)	73.21 (58.83)	71.43 (57.69)	26.26	26.79	26.53
9	<i>Pseudomonas fluorescens</i>	76.67	73.33	75.00	48.21 (43.97)	58.93 (50.14)	53.57 (47.05)	48.95	41.07	44.90
10	Neem Cake + Farmyard manure	73.33	66.67	70.00	75.00 (60.00)	61.31 (51.54)	67.56 (55.28)	21.84	38.69	30.51
11	Control	53.33	46.67	50.00	94.44 (76.36)	100.00 (90.00)	97.22 (83.18)	0.00	0.00	0.00
	C.D. ($p = 0.01$)	3.94	3.72	3.24	5.45	5.63	5.10			
	SE(m)±	1.36	1.28	1.12	1.88	1.94	1.76			

Figures in parentheses indicate angular transformed values. Mean values from 3 replications.

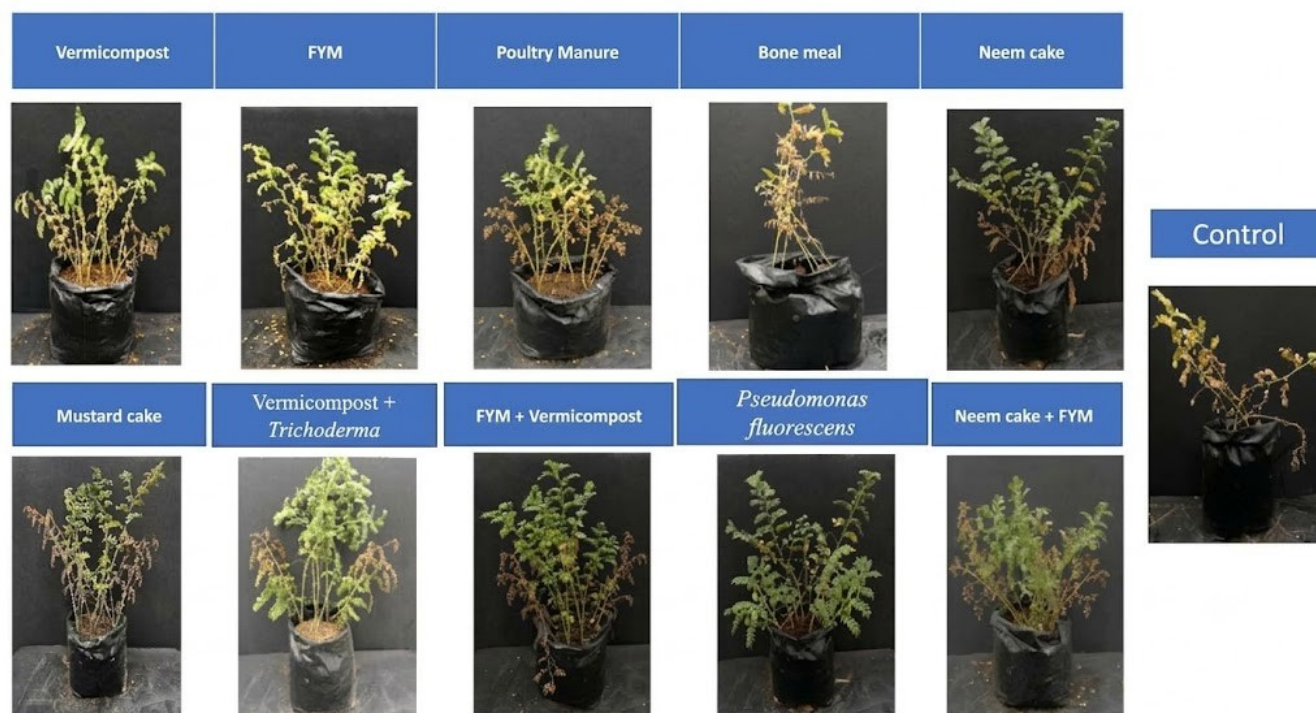


Plate 3. Effect of different soil amendments on disease incidence of wilt disease of chickpea.

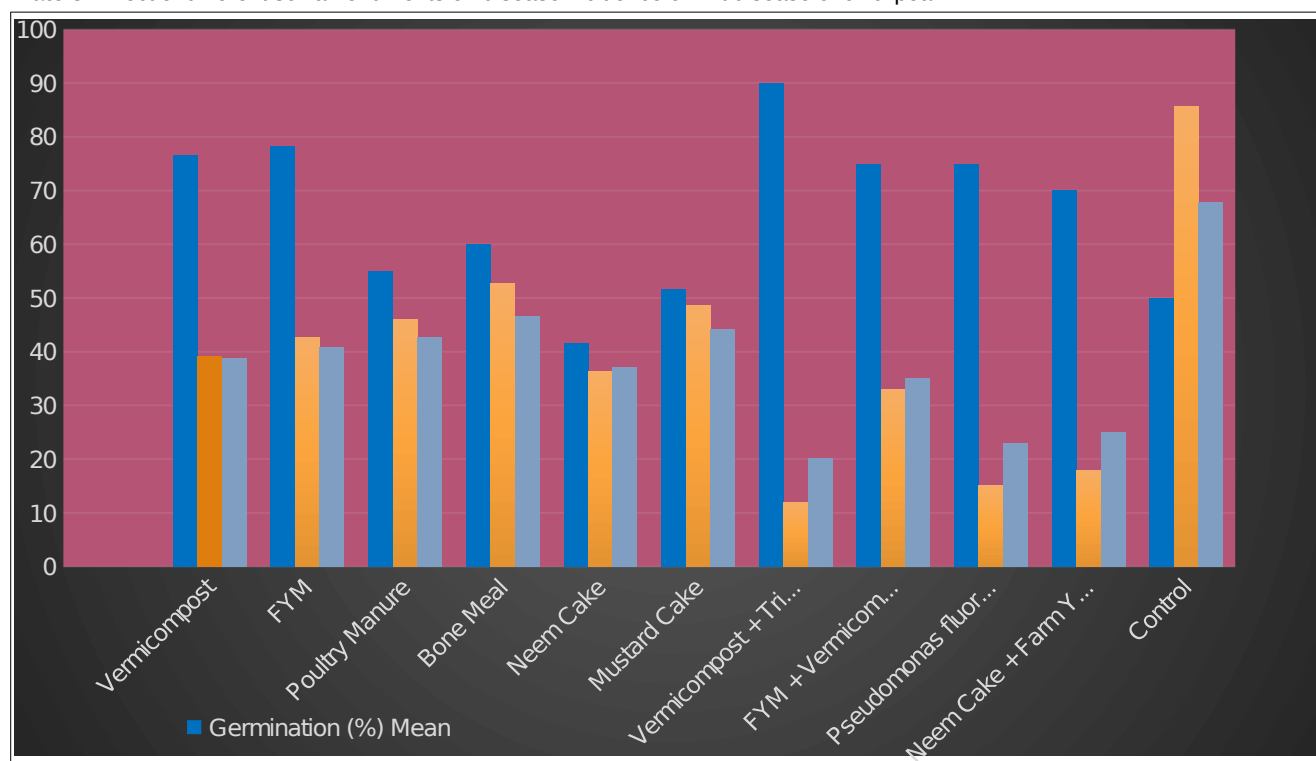


Fig. 3. Effect of different soil amendments on disease incidence of wilt disease of chickpea.

Effect of soil amendments on plant height, root parameters and biomass

The effect of different soil amendments on plant growth and biomass of chickpea under *F. oxysporum* infection is presented in Table 4, Plate 4 and Fig. 4. Significant

differences were observed among the treatments for all growth and biomass parameters.

The untreated control recorded the lowest values for all measured traits due to severe root rot and vascular wilt caused by *F. oxysporum*. Control plants exhibited a

mean plant height of 21.75 cm, root length of 9.10 cm, no root nodules, shoot fresh weight of 6.25 g, shoot dry weight of 1.60 g and poor root biomass.

Among the treatments, vermicompost enriched with *Trichoderma* was the most effective in improving overall plant growth. It recorded the highest plant height (43.00 cm), shoot fresh weight (16.85 g), root fresh weight (6.65 g) and shoot dry weight (4.90 g). The treatment also significantly increased root length (17.25 cm) and produced three root nodules per plant compared with the untreated control. The *P. fluorescens* treatment also showed substantial improvement in plant growth and was particularly effective in enhancing root development. It produced the greatest root length (19.25

cm) and the highest number of root nodules (6 per plant), along with a height of 40.00 cm, shoot fresh weight of 15.40 g and root dry weight of 1.70 g. The improved plant growth and biomass observed in the biological treatments may be attributed to enhanced nutrient availability, suppression of the pathogen in the rhizosphere and stimulation of plant growth through microbial activity. Vermicompost provides a nutrient-rich substrate that supports the establishment and proliferation of beneficial microorganisms such as *Trichoderma*, while *P. fluorescens* promotes root growth and nodulation through plant growth-promoting mechanisms, resulting in improved root architecture and biomass accumulation under disease stress.

Table 4. Effect of soil amendments on wilt disease of chickpea shoot and root parameters

Sl. No.	Amendments	Plant height	Root length	Nodules	Fresh Weight		Dry Weight	
					Shoot	Root	Shoot	Root
1	Vermicompost	30.75	14.10	0	11.75	4.65	3.17	1.25
2	Farmyard manure (FYM)	28.25	10.55	2	10.50	4.35	2.90	1.15
3	Poultry manure	25.75	9.20	0	10.30	4.45	2.95	1.20
4	Bone meal	36.75	13.33	0	12.65	3.90	3.80	0.95
5	Neem cake	33.25	15.60	0	11.40	4.95	2.95	1.35
6	Mustard cake	32.75	11.00	0	9.20	4.10	2.75	1.05
7	Vermicompost + <i>Trichoderma</i>	43.00	17.25	3	16.85	6.65	4.90	1.85
8	FYM + Vermicompost	33.25	15.55	2	12.25	5.15	3.70	1.45
9	<i>Pseudomonas fluorescens</i>	40.00	19.25	6	15.40	6.15	4.55	1.70
10	Neem Cake + FYM	38.00	14.45	3	14.50	5.95	4.30	1.60
11	Control	21.75	9.10	0	6.25	2.65	1.60	0.65
	C.D. ($p = 0.01$)	2.49	1.39	0.99	1.22	0.61	0.52	0.26
	SE(m)±	0.86	0.48	0.34	0.42	0.21	0.18	0.09

Data recorded for agronomic biomass parameters. Mean values from 3 replications.



Plate 4. Effect of soil amendments on wilt disease of chickpea shoot and root parameters.

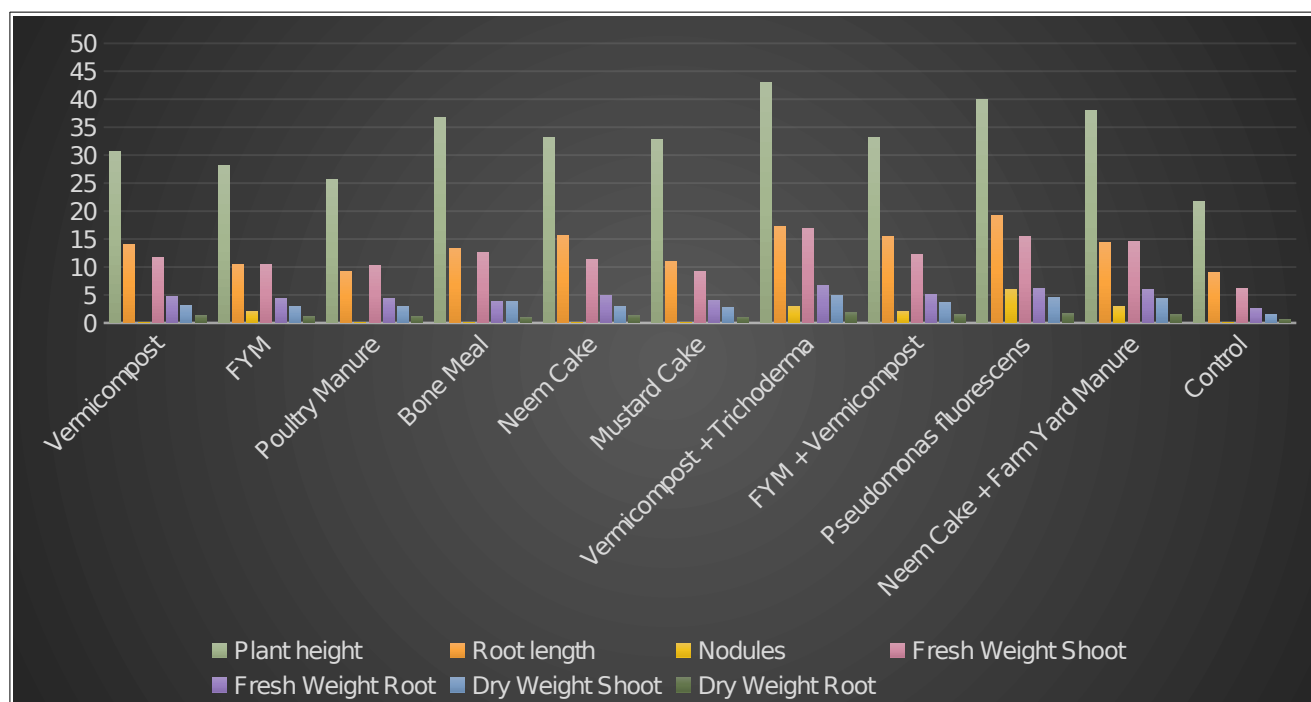


Fig. 4. Effect of soil amendments on wilt disease of chickpea shoot and root parameters.

4. Discussion

The present study demonstrated that garlic clove extract was the most effective botanical against *F. oxysporum* f. sp. *ciceris* under *in vitro* conditions, with efficacy increasing with increasing extract concentration. The strong antifungal activity of garlic may be attributed to sulfur-containing compounds, particularly allicin, which inhibit spore germination, disrupt fungal cell membranes and suppress mycelial growth. Similar observations have been reported by earlier workers, who documented the superior fungitoxic activity of garlic and other plant extracts against vascular wilt pathogens (7, 13). The concentration-dependent inhibition observed in the present study also agrees with previous reports indicating that higher concentrations of plant extracts suppress fungal growth more effectively due to increased availability of bioactive secondary metabolites (19, 20). These findings support the potential of locally available plant extracts as environmentally safe alternatives for the sustainable management of chickpea wilt in central India (16, 21).

The pot experiment further confirmed that botanical treatments effectively reduced wilt incidence and improved seed germination compared with the untreated control. Garlic clove extract exhibited concentration-dependent antifungal activity against *F. oxysporum* f. sp. *ciceris*, with the 15 % concentration showing the highest inhibition. This treatment was statistically superior to the lower concentrations tested, confirming that increasing the concentration of garlic extract enhanced its inhibitory effect on fungal growth. The improved plant establishment may be attributed to the suppression of soil-borne inoculum around the

germinating seed and protection of emerging roots from infection by *F. oxysporum* f. sp. *ciceris*. Similar results have been reported for the organic management of chickpea wilt, where plant-derived products significantly reduced disease incidence and seedling mortality while enhancing crop establishment (13, 16, 22–24). These findings demonstrate that the antifungal activity observed under laboratory conditions can be effectively translated into disease suppression under pot conditions.

Among the organic and biological treatments, bioagent-based soil management markedly reduced *Fusarium* wilt incidence and improved plant growth. The enhanced disease suppression may be attributed to reduced pathogen inoculum density in the rhizosphere through microbial competition, antibiosis and niche exclusion. Previous studies have shown that beneficial microorganisms modify the rhizosphere environment, limiting nutrient availability to the pathogen and thereby reducing its ability to infect host roots (15, 25). In addition, organic amendments such as neem cake and farmyard manure release antimicrobial compounds during decomposition and improve soil microbial activity, contributing to the suppression of soil-borne pathogens (26).

The present study demonstrated that *P. fluorescens* produced greater nodulation than several organic amendments. This response may be related to the plant-growth-promoting effects of rhizobacteria, which can enhance root development and create conditions favourable for nodulation and biological nitrogen fixation. However, nitrogen fixation and rhizobacterial colonisation were not directly quantified in the present study; therefore, this mechanism should be considered a

possible explanation rather than a confirmed finding. These beneficial effects are attributed to the production of phytohormones such as indole-3-acetic acid (IAA), which stimulate root elongation, lateral root formation and root hair development, thereby enhancing nutrient uptake (27). The compatibility of *P. fluorescens* with symbiotic rhizobia also promotes biological nitrogen fixation and increases nodulation. Furthermore, the production of siderophores and other antimicrobial metabolites restricts pathogen development by limiting iron availability and suppressing pathogen colonisation of the root system (27, 28). The improved plant growth, dry matter accumulation and reduced disease incidence observed in the present study are therefore consistent with the well-established mechanisms of plant growth-promoting rhizobacteria. The increases of 61.9–127 % in root length and 69.3–92.2 % in aerial-part length following *Trichoderma asperellum* treatment of *Fusarium*-infected chickpea. Similarly, a recent field study reported 44 % and 27 % increases in shoot length and plant dry weight, respectively, with a *Trichoderma harzianum* bioformulation compared with the inoculated control (29). The pronounced antifungal activity of garlic extract may be associated with its rich content of bioactive organosulfur compounds, particularly allicin, which is rapidly generated from alliin following disruption of garlic tissues. Allicin is highly reactive toward cysteine residues and thiol-containing proteins and can consequently interfere with essential cellular processes, including redox homeostasis, energy metabolism and enzyme activity. Recent evidence in plant-pathogenic fungi demonstrated that allicin could cause hyphal abnormalities, impair plasma-membrane integrity, reduce ATP production and alter oxidative-stress and energy-metabolism pathways, providing a mechanistic basis for its antifungal activity (30–32).

The disease-suppressive activity of *Trichoderma* spp. may involve multiple complementary mechanisms, including mycoparasitism, antibiosis, competition for nutrients and infection sites, effective rhizosphere colonisation and induction of plant defence responses. *Trichoderma* can produce cell-wall-degrading enzymes and antimicrobial secondary metabolites while stimulating systemic defence pathways in plants, thereby restricting pathogen establishment and promoting plant growth (33–35). However, these mechanisms were not directly evaluated in the present study and are therefore proposed as possible explanations for the observed results.

Overall, the integration of botanicals, organic amendments and beneficial microorganisms represents a promising eco-friendly strategy for the sustainable management of chickpea wilt and improved crop productivity.

5. Conclusion

Garlic extract showed the strongest antifungal activity against *Fusarium oxysporum* f. sp. *ciceris* under both *in vitro* and pot conditions, while karanj and neem also showed considerable activity. Among the soil

amendments and biocontrol treatments, vermicompost + *Trichoderma* and *Pseudomonas fluorescens* effectively reduced wilt incidence and improved plant growth. These findings indicate that botanical extracts and biocontrol-based approaches have potential for sustainable management of chickpea wilt and may help reduce reliance on chemical fungicides. Future research should validate the most promising treatments under multi-location field conditions, optimise their application rates and timing and evaluate their long-term efficacy and compatibility within integrated disease-management programs. Molecular characterisation of the effective *Trichoderma* isolates and further investigation of their mechanisms of pathogen suppression are also warranted.

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Authors' contributions

GS contributed to conceptualisation, study design, experimentation, data collection and analysis, statistical analysis, interpretation of results and writing – original draft. SKS contributed to supervision, technical guidance, data interpretation and critical review and editing. RS contributed to data interpretation, review and editing and final approval. ALT contributed to study design, research guidance, review and editing and final approval. PKS contributed to critical revision, organisation of content and improvement of scientific clarity and coherence. NT contributed to revision and editing in response to the reviewers' comments. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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