



RESEARCH ARTICLE

Integrated eco-friendly and chemical strategies for managing bacterial wilt of tomato in eastern India

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Abstract

Tomato production is severely constrained by bacterial wilt caused by *Ralstonia solanacearum*, particularly under warm and humid conditions. Conventional chemical control methods, although effective under laboratory conditions, are often limited in field applications due to environmental hazards, the risk of resistance development and potential residue accumulation in soil and produce. Therefore, the present study evaluated eco-friendly and chemical-based management strategies under both *in vitro* and field conditions in Odisha. *In vitro* results showed that streptomycin (10 µg) exhibited the highest inhibition (11.20 mm), while the combination of streptomycin (200 ppm) and copper oxychloride (500 ppm) yielded maximum inhibition (28.5 mm) with complete suppression of the pathogen. Among biological agents, *Pseudomonas fluorescens* (OD11) showed the highest antagonistic activity (26.52 mm). Botanical extracts such as garlic (21.98 mm) and neem (19.77 mm) were also effective. Organic amendments, particularly karanj cake, reduced wilt incidence to 27.64 % at 90 days after transplanting (DAT), representing a 60.03 % disease reduction. Field evaluation revealed that integrated treatment significantly reduced wilt incidence (25.23 %), delayed disease onset (35.67 days) and increased yield (245.25 g plant⁻¹) compared to the control (78.46 % wilt; 96.40 g plant⁻¹). The study highlights that integrated disease management (IDM) practices that combine biological agents, botanicals, organic amendments and limited, judicious chemical use are more effective, sustainable and environmentally safe than sole reliance on chemicals. Adoption of IDM not only minimises ecological risks but also enhances soil health, improves plant resistance and ensures stable tomato productivity in wilt-prone regions.

Keywords: bacterial wilt; integrated disease management; *Pseudomonas fluorescens*; *Ralstonia solanacearum*

Introduction

Tomato (*Solanum lycopersicum* Mill.) is a widely cultivated vegetable crop valued for its nutritional richness and importance as a high-value cash crop. The fruit is a rich source of vitamins, minerals and antioxidants and plays a significant role in human nutrition. However, tomato productivity is frequently constrained by several factors, including poor seed quality, inadequate agronomic practices, severe pest and disease pressure and a range of abiotic stresses such as drought, heat, salinity and suboptimal nutrient or water availability. Among these constraints, bacterial wilt caused by the soil-borne bacterium *Ralstonia solanacearum* (Smith) is considered one of the most destructive diseases affecting tomato production (1, 2).

Ralstonia solanacearum (Smith), formerly classified as *Pseudomonas solanacearum* (Smith) Smith and later as *Burkholderia solanacearum*, is a devastating vascular pathogen and is ranked as the second most important bacterial plant pathogen

worldwide (3). The pathogen has a wide host range, infecting more than 200 plant species belonging to over 50 botanical families. In India, it affects several economically important crops, including tomato, potato, eggplant, chilli, banana and groundnut. In tomato, the disease usually starts with wilting of the upper leaves, quickly leading to complete plant collapse. Infected plants show brown discolouration of the vascular tissue and a milky white bacterial ooze is often visible when cut stems are suspended in water. Yield losses caused by *R. solanacearum* vary widely depending on crop species, cultivar susceptibility, environmental conditions, soil characteristics and pathogen strain. Reported yield losses range from 0–91 % in tomato, 33–90 % in potato, 10–30 % in tobacco, 80–100 % in banana and up to 20 % in groundnut (4).

Various strategies have been explored to manage bacterial wilt, including host resistance, cultural practices, biological control and chemical approaches. Host resistance is generally considered the most economical and sustainable method; however, achieving stable resistance under tropical conditions characterised by high

temperature and humidity remains difficult, largely due to broad pathogen variability (including diverse races and strains) and the temperature-sensitive expression of many resistance genes, which can break down or weaken under the intense heat and moisture common in these environments (5). Cultural practices such as intercropping with non-host crops and incorporating organic amendments have shown potential to suppress the disease (6, 7). Crop rotation with green manure crops such as sunhemp (*Crotalaria juncea* L.) and mungbean (*Vigna radiata* L.) has been reported to significantly reduce the incidence of bacterial wilt (8). Green manure crops, such as *Mucuna* and *Crotalaria*, suppress bacterial wilt while enhancing soil nitrogen levels (9).

Biological control has also gained considerable attention as an environmentally sustainable strategy for managing soil-borne pathogens. Plant growth-promoting rhizobacteria (PGPR) play a crucial role in suppressing plant diseases through mechanisms such as antibiosis, competition for nutrients and ecological niches and induction of systemic resistance in plants (10). Several studies have demonstrated the potential of antagonistic bacteria to manage bacterial wilt in tomato (11). Among these, fluorescent pseudomonads have been widely studied for their ability to suppress soil-borne diseases. Significant reductions in bacterial wilt and bacterial blight of potato have been reported with the application of *Pseudomonas fluorescens* (12). Moreover, *P. fluorescens* has been reported to enhance seed quality and reduce bacterial spot disease in tomato under field conditions (13). Numerous greenhouse and field studies have confirmed the effectiveness of *P. fluorescens* in plant disease management (14, 15).

Soil amendments have also been explored to suppress bacterial wilt. The S-H mixture developed in Taiwan, which contains agricultural and industrial by-products such as bagasse, rice husk, oyster shell powder, urea, potassium nitrate, calcium superphosphate and mineral ash, has been reported to reduce pathogen populations and disease severity in several crops (16, 17). Incorporation of this mixture into soil significantly reduces populations of *R. solanacearum* and lowers disease incidence (18).

Despite the availability of various management options, bacterial wilt remains difficult to control due to the pathogen's complex ecology and high genetic variability. Resistant cultivars developed by the Asian Vegetable Research and Development Center (AVRDC) have shown promising results, but their effectiveness is often location-specific and influenced by environmental conditions and pathogen strain variability. Chemical control measures are generally ineffective or impractical; antibiotics such as streptomycin, ampicillin, tetracycline and penicillin have shown limited success and in some cases, streptomycin treatment has even increased disease incidence (19, 20).

Under such conditions, integrated disease management (IDM) approaches that combine biological agents, cultural practices and chemical treatments offer a more sustainable and effective strategy for managing bacterial wilt in tomato. Therefore, the present study was undertaken to evaluate eco-friendly and chemical-based management strategies for the suppression of bacterial wilt and improvement of tomato yield under field conditions in Odisha.

Materials and Methods

Experimental site and pathogen

The study was conducted at the Department of Plant Pathology, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India (approx. 20°15' N, 85°50' E; altitude about 11 m above sea level), under a tropical climate characterised by hot, humid summers and moderate rainfall during the kharif season. The bacterial wilt pathogen, *R. solanacearum*, was isolated from wilt-infected tomato plants and maintained on King's B agar medium under laboratory conditions.

In vitro evaluation of antibiotics, chemicals, biocontrol agents and botanicals

The inhibitory effects of various antibiotics, chemicals, biocontrol agents and botanical extracts against *R. solanacearum* were evaluated under laboratory conditions. A standardised bacterial suspension ($\approx 1 \times 10^6$ cfu mL⁻¹), adjusted spectrophotometrically to a defined optical density at 600 nm and confirmed by serial dilution and plate count, prepared from a 48-hr culture, was spread uniformly on sterilised King's B agar plates.

For antibiotic and chemical evaluation, the disk diffusion technique was employed by placing sterile antibiotic discs or filter paper discs impregnated with different concentrations of chemical solutions on the inoculated agar surface. Plates were incubated at 28 ± 1 °C for 24–48 hr and the diameter of the inhibition zone (mm) was recorded. Biocontrol agents, including isolates of *P. fluorescens*, *Bacillus subtilis*, *Trichoderma harzianum* and *Trichoderma viride*, were evaluated using the disk diffusion method with bacterial suspensions (1×10^6 cfu mL⁻¹) or fungal suspensions (1×10^8 spores mL⁻¹).

Botanical extracts were prepared from dried plant materials (10 g, w/v) extracted in a methanol–water solvent (e.g., 70:30, v/v) and filtered through Whatman No. 1 filter paper. The antibacterial activity was assessed using the well diffusion method, in which 50 µL of botanical extract was added to wells on pathogen-inoculated agar plates. After incubation at 28 ± 1 °C for 24 hr, inhibition zones were measured. Botanicals tested included tulsi (*Ocimum tenuiflorum*), bael (*Aegle marmelos*), marigold (*Tagetes erecta*), garlic (*Allium sativum*), onion (*Allium cepa*), neem (*Azadirachta indica*), dhatura (*Datura stramonium*) and castor (*Ricinus communis*). All laboratory experiments were conducted in a completely randomised design (CRD) with three replications.

Evaluation of organic amendments

A pot culture experiment was conducted to evaluate the effects of different organic amendments on the incidence of bacterial wilt in tomato. Organic materials — neem cake, karanj cake, groundnut cake, mustard cake, farmyard manure (FYM), vermicompost, castor cake and poultry manure — were incorporated into the potting soil at their respective recommended doses (neem cake, karanj cake, groundnut cake, mustard cake and castor cake at 2 t ha⁻¹; vermicompost at 7 t ha⁻¹; poultry manure at 5 t ha⁻¹; and FYM at 25 t ha⁻¹) before transplanting. Healthy tomato seedlings of 25–30 days old were transplanted into the amended soil and maintained under uniform agronomic practices throughout the experimental period. Wilt incidence was recorded at 30, 60 and 90 days after transplanting (DAT) and expressed as a percentage of wilted plants using the formula:

$$\text{Wilt (\%)} = (\text{Number of wilted plants} / \text{Total number of plants}) \times 100$$

(Eqn. 1)

Wilt reduction over the uninoculated control was calculated as:

$$\text{Wilt reduction (\%)} = [(\text{Wilt \% in control} - \text{Wilt \% in treatment}) / \text{Wilt \% in control}] \times 100$$

(Eqn. 2)

Field evaluation of integrated management strategies

Field experiments on integrated management of bacterial wilt were conducted during the Rabi seasons of 2023–24 and 2024–25 in a wilt-sick plot at Odisha University of Agriculture and Technology (OUAT), Bhubaneswar. The experiment was laid out in a randomised block design (RBD) with 12 treatments and three replications using the susceptible tomato variety Pusa Ruby.

Treatments included soil application of bleaching powder and lime; seed treatment and root dipping with streptomycin or *P. fluorescens*; drenching with copper oxychloride; application of *Trichoderma asperellum*; organic amendments; garlic extract treatments; and integrated combinations of these practices. Standard crop management practices were followed uniformly.

Observations and statistical analysis

Growth parameters, including plant height, shoot length and root length, were recorded at the harvest stage (90 DAT) using a standard measuring scale, with values expressed in centimetres (cm). Fruit yield was recorded treatment-wise at final harvest and expressed in quintals per hectare (q ha^{-1}), calculated using the formula:

$$\text{Yield (q ha}^{-1}\text{)} = (\text{Total fruit weight per plot} / \text{Plot area}) \times 10000 \text{ (Eqn. 3)}$$

All data were subjected to one-way analysis of variance (ANOVA) using OPSTAT statistical software developed at Chaudhary Charan Singh Haryana Agricultural University, Hisar and treatment means were compared using the critical difference (CD) test at the 5 % level of probability ($p \leq 0.05$). Data expressed as percentages,

such as wilt incidence, were subjected to arcsine square root transformation prior to statistical analysis to normalise the distribution and back-transformed means are presented in the tables.

Results

In vitro efficacy of antibiotics against *Ralstonia solanacearum*

The tested antibiotics differed significantly in their inhibitory activity against *R. solanacearum* under *in vitro* conditions (Table 1). Streptomycin (10 μg ; T10) recorded the highest zone of inhibition (11.20 mm) and was categorised as highly susceptible (HS). This was followed by ampicillin (10 μg ; 8.20 mm), chloramphenicol (30 μg ; 7.40 mm), levofloxacin (5 μg ; 7.40 mm), tetracycline (30 μg ; 7.30 mm), azithromycin (15 μg ; 6.80 mm) and vancomycin (30 μg ; 6.25 mm), all of which were categorised as susceptible (S). In contrast, rifampicin (5 μg ; 0.25 mm), amikacin (30 μg ; 0.12 mm), penicillin (10 units; 1.10 mm) and erythromycin (15 μg ; 0.48 mm) produced negligible inhibition zones and were categorised as resistant (R). Overall, streptomycin was the most effective antibiotic against *R. solanacearum* under laboratory conditions.

In vitro efficacy of chemicals and antibiotic-copper combinations

Marked variation was observed among chemical and combination treatments in their ability to suppress *R. solanacearum* (Table 2). The combination of streptomycin (200 ppm) and copper oxychloride (500 ppm) produced the largest inhibition zone (28.5 mm) and resulted in 100 % inhibition of bacterial growth. This was followed by streptomycin (100 ppm) + copper oxychloride (1000 ppm) with a 24.2 mm inhibition zone and 84.91 % inhibition and streptomycin (100 ppm) + copper oxychloride (500 ppm) with a 20.5 mm inhibition zone and 71.93 % inhibition. Among individual antibiotics,

Table 1. Efficacy of different antibiotics on the inhibition of *Ralstonia solanacearum*

Sl. No.	Treatment	Concentration	Zone of inhibition (mm)	Susceptible / Resistance reaction
T1	Chloramphenicol	30 mcg	7.40	S
T2	Rifampicin	5 mcg	0.25	R
T3	Amikacin	30 mcg	0.12	R
T4	Tetracycline	30 mcg	7.30	S
T5	Azithromycin	15 mcg	6.80	S
T6	Ampicillin	10 mcg	8.20	S
T7	Penicillin	10 units	1.10	R
T8	Erythromycin	15 mcg	0.48	R
T9	Levofloxacin	5 mcg	7.40	S
T10	Streptomycin	10 mcg	11.20	HS
T11	Vancomycin	30 mcg	6.25	S
T12	Control	–	–	–

Table 2. *In vitro* efficacy of different chemicals on the growth of *Ralstonia solanacearum*

Sl. No.	Treatment	Concentration (ppm)	Zone of inhibition (mm)	% inhibition
1	Streptomycin + Copper oxychloride	200 + 500	28.5 (5.39) ^a	100.0 (90.0)
2	Streptomycin + Copper oxychloride	100 + 1000	24.2 (4.97) ^b	84.91 (77.98)
3	Streptomycin + Copper oxychloride	100 + 500	20.5 (2.05) ^c	71.93 (65.94)
4	Streptomycin sulphate	500	19.9 (4.50) ^c	69.82 (64.37)
5	Kasugamycin	200	14.4 (3.84) ^d	50.53 (45.48)
6	Streptomycin + Copper oxychloride	100 + 250	18.8 (4.41) ^d	65.96 (61.45)
7	Streptomycin sulphate	200	17.7 (4.34) ^e	62.11 (58.61)
8	Copper oxychloride	1000	15.4 (3.96) ^f	54.04 (47.35)
9	Copper oxychloride	500	13.2 (3.68) ^g	46.32 (42.91)
10	Ampicillin + Copper oxychloride	200 + 1000	12.9 (3.64) ^g	45.26 (42.34)
11	Streptomycin sulphate	100	12.3 (3.57) ^g	43.16 (41.07)
12	Ampicillin	200	11.2 (3.43) ^h	39.30 (38.57)
13	Copper oxychloride	250	10.1 (3.27) ^h	35.44 (36.31)
14	Azoxystrobin	500	8.3 (2.96) ⁱ	29.12 (32.03)
15	Control	–	0.0 (0.71) ^j	–
	SEm ($\pm$)		0.89	1.58
	CD (5 %)		2.57	4.58

streptomycin (500 ppm) performed well (19.9 mm; 69.82 % inhibition), whereas kasugamycin (200 ppm) showed moderate inhibition (14.4 mm; 50.53 % inhibition). Copper oxychloride alone resulted in comparatively lower inhibition (15.4 mm at 1000 ppm and 13.2 mm at 500 ppm). The lowest efficacy among active treatments was observed with azoxystrobin (500 ppm), at 8.3 mm (29.12 % inhibition), while the control (distilled water) showed no inhibition.

In vitro efficacy of biocontrol agents

All biocontrol agents tested showed variable antagonism against *R. solanacearum* (Table 3). *Pseudomonas fluorescens* OD11

Table 3. In vitro efficacy of different bio-control agents on the growth of *Ralstonia solanacearum*

Sl. No.	Treatment	Concentration	Zone of inhibition (mm)
T1	<i>Pseudomonas fluorescens</i> OD11	1×10^6	26.52 (5.20) ^a
T2	<i>Pseudomonas fluorescens</i> OD01	1×10^6	20.38 (4.58) ^b
T3	<i>Bacillus subtilis</i> ODB1	1×10^6	8.67 (3.08) ^d
T4	<i>Trichoderma asperellum</i> ISO 1	1×10^8	23.41 (4.93) ^{ab}
T5	<i>Trichoderma harzianum</i> ISO 2	1×10^8	14.47 (3.89) ^c
T6	<i>Trichoderma viridae</i> ISO II	1×10^8	15.20 (4.00) ^c
T7	<i>Bacillus subtilis</i> ODB2	1×10^6	9.35 (3.16) ^d
T8	Control	–	0.00 (0.71) ^e
		SEm (±)	0.78
		CD (5 %)	2.34

(1×10^6 cfu mL⁻¹) recorded the highest inhibition zone (26.52 mm), followed by *Trichoderma asperellum* ISO 1 (1×10^8 spores mL⁻¹) (23.41 mm) and *P. fluorescens* OD01 (1×10^6 cfu mL⁻¹) (20.38 mm). Moderate inhibition was observed with *Trichoderma viride* ISO 2 (15.20 mm) and *T. harzianum* ISO 2 (14.47 mm). *Bacillus subtilis* isolates were comparatively less effective, with ODB2 (9.35 mm) and ODB1 (8.67 mm). The control recorded 0.00 mm inhibition.

In vitro efficacy of botanicals

Botanical extracts differed significantly in their ability to suppress *R. solanacearum* (Table 4). Garlic clove extract (*A. sativum*) recorded the maximum inhibition zone (21.98 mm), followed by neem leaf extract (*A. indica*) (19.77 mm) and onion bulb extract (*A. cepa*) (18.52 mm). *Datura* leaf extract (*D. stramonium*) showed moderate inhibition (14.65 mm), followed by marigold leaf extract (*T. erecta*) (12.49 mm). Lower inhibition was recorded with bael leaf (*A. marmelos*) (8.52 mm), tulsi leaf (*O. tenuiflorum*) (7.28 mm) and turmeric (*Curcuma longa*) (5.42 mm). The control recorded 0.00 mm.

Table 4. Effect of different botanicals on the pathogen's growth inhibition

Sl. No.	Treatment	Scientific name	Zone of inhibition (mm)
T1	Tulsi leaf	<i>Ocimum tenuiflorum</i>	7.28 (2.84) ^{cd}
T2	Turmeric	<i>Curcuma longa</i>	5.42 (2.44) ^d
T3	Bael leaf	<i>Aegle marmelos</i>	8.52 (3.01) ^{cd}
T4	Marigold leaf	<i>Tagetes erecta</i>	12.49 (3.58) ^{bc}
T5	Garlic clove	<i>Allium sativum</i>	21.98 (4.76) ^a
T6	Onion bulb	<i>Allium cepa</i>	18.52 (4.37) ^{ab}
T7	Neem leaf	<i>Azadirachta indica</i>	19.77 (4.47) ^{ab}
T8	Dhatura leaf	<i>Datura stramonium</i>	14.65 (3.89) ^b
T9	Control	–	0.00 (0.71) ^e
		SEm (±)	1.32
		CD (5 %)	3.91

Effect of organic amendments on bacterial wilt incidence

Organic amendments reduced bacterial wilt incidence compared with the untreated control, with differences in magnitude across treatments (Table 5). Karanj cake (2 t ha⁻¹) recorded the lowest wilt incidence across stages (18.55 % at 30 DAT, 23.67 % at 60 DAT and 27.64 % at 90 DAT) and achieved the highest wilt reduction (60.03 %). Neem cake (2 t ha⁻¹) was next best, recording 20.64 %, 26.09 % and 33.82 % wilt at 30, 60 and 90 DAT, respectively, with 53.91 % wilt reduction. Groundnut cake provided moderate suppression, while FYM and vermicompost resulted in comparatively higher wilt incidence than oilseed cakes. Overall, oilseed cakes—particularly karanj and neem cakes—were more effective than FYM and vermicompost at reducing bacterial wilt.

Field evaluation of integrated management strategies under sick plot (pooled for Rabi 2023–24 and 2024–25)

Significant differences were observed among management strategies under sick plot conditions during Rabi 2023–24 (Table 6). The earliest wilt appearance occurred in the untreated control (T12) at 18.33 days, which also recorded the highest wilt incidence (78.46 %) at 90 DAT and the lowest yield (96.40 g plant⁻¹).

Among individual treatments, soil application of bleaching powder (T1) delayed the first infection to 32.33 days, reduced wilt incidence to 31.26 % and achieved a 60.15 % disease reduction, along with improved growth and yield (202.29 g plant⁻¹). Lime amendment (T2) and streptomycin root dip (T3) provided moderate suppression (wilt incidence 39.01 % and 39.96 %, respectively). Copper oxychloride drenching alone (T4) and *P. fluorescens* seed treatment + root dip (T5) were less effective, with wilt incidence of 50.71 % and 51.81 %, respectively.

Table 5. Effect of different organic amendments against the bacterial wilt of tomato

Sl. No.	Treatment	Dose	Wilt (%) at 30 DAT	Wilt (%) at 60 DAT	Wilt (%) at 90 DAT	Wilt reduction (%)
T1	Neem cake	2 t ha ⁻¹	20.64 (27.02)	26.09 (30.72)	32.83 (35.56)	53.91
T2	Karanj cake	2 t ha ⁻¹	18.55 (25.51)	23.67 (29.11)	27.64 (31.72)	60.03
T3	Groundnut cake	2 t ha ⁻¹	23.53 (29.02)	29.56 (32.94)	35.97 (36.85)	51.75
T4	Mustard cake	2 t ha ⁻¹	25.61 (30.40)	35.68 (36.68)	41.18 (39.92)	44.51
T5	Farmyard manure	25 t ha ⁻¹	23.26 (28.83)	31.08 (33.88)	39.39 (38.87)	45.80
T6	Vermicompost	7 t ha ⁻¹	23.61 (29.07)	34.02 (35.68)	38.96 (38.62)	46.25
T7	Castor cake	2 t ha ⁻¹	26.94 (31.27)	36.94 (37.43)	44.28 (41.72)	38.74
T8	Poultry manure	5 t ha ⁻¹	29.47 (32.88)	43.32 (41.16)	51.97 (46.13)	31.96
T9	Control	–	44.23 (41.69)	62.05 (51.97)	81.21 (64.31)	–
		SEm (±)	1.45	1.62	1.85	
		CD (5 %)	4.20	4.80	5.90	

Table 6. Field evaluation of various management strategies against bacterial wilt of tomato (Pusa Ruby) caused by *Ralstonia solanacearum* during 2023–24 and 2024–25

Sl. No.	Days of 1st infection	Wilt incidence (%) at 90 DAT	Plant height (cm)	Root growth (cm)	Shoot growth (cm)	Yield (q ha ⁻¹)	Disease reduction (%)
T1	29.33	37.48 (37.75)	90.65	38.14	83.63	212.90	55.17
T2	32.17	43.79 (41.43)	90.58	34.94	80.06	195.30	47.46
T3	32.17	41.93 (40.36)	88.45	31.92	76.61	206.22	49.51
T4	26.50	53.49 (47.00)	88.43	29.61	72.21	192.22	35.61
T5	28.67	56.14 (48.53)	80.92	28.39	69.96	177.36	32.52
T6	26.17	47.70 (43.68)	80.14	27.76	65.96	184.51	42.70
T7	35.83	27.26 (31.48)	79.97	25.21	58.76	245.44	67.02
T8	30.17	30.86 (33.75)	79.84	24.31	57.38	229.58	63.06
T9	31.00	56.84 (48.93)	78.55	22.02	56.01	156.35	31.45
T10	30.67	64.31 (53.31)	75.29	20.98	54.98	137.26	22.38
T11	24.83	66.04 (54.36)	70.63	18.96	48.71	131.71	20.34
T12	16.67	83.10 (65.72)	66.93	13.99	32.36	93.31	–
SEm (±)	1.57	1.89	2.55	1.05	2.51	8.89	2.12
CD (5 %)	4.73	5.12	7.08	2.99	7.81	25.19	6.39

The best performance was recorded under integrated treatments. T7 (bleaching powder + lime + streptomycin root dip + copper oxychloride drenching) recorded the maximum delay in first infection (35.67 days), the lowest wilt incidence (25.23 %) and the highest disease reduction (67.47 %), along with the highest yield (245.25 g plant⁻¹). This was closely followed by T8, which also delayed the first infection (35.33 days) and maintained a low wilt incidence (26.12 %), with a 66.70 % disease reduction and a high yield (231.28 g plant⁻¹).

Discussion

The current study demonstrates significant variation in the efficacy of antibiotics, chemical combinations, biocontrol agents and botanical extracts against *R. solanacearum*, the causal agent of bacterial wilt of tomato, under both *in vitro* and field conditions. Among the antibiotics screened, streptomycin (10 µg) recorded the highest zone of inhibition (11.20 mm) and was categorised as HS, while rifampicin, amikacin and erythromycin showed negligible inhibition and were categorised as R. Among the chemical combinations, streptomycin (200 ppm) + copper oxychloride (500 ppm) achieved complete suppression of *R. solanacearum*, with a 28.5 mm inhibition zone and 100 % inhibition *in vitro*. Among biocontrol agents, *P. fluorescens* OD11 recorded the highest antagonism (26.52 mm), followed by *T. asperellum* ISO 1 (23.41 mm), while garlic clove extract (*A. sativum*) was the most effective botanical (21.98 mm). Under field conditions, the IDM strategy comprising bleaching powder + lime + streptomycin root dip + copper oxychloride drenching (T7) was the most effective, recording the lowest wilt incidence (25.23 % at 90 DAT), the highest disease reduction (67.47 %) and the maximum yield (245.25 g plant⁻¹), clearly establishing the superiority of integrated approaches over individual treatments in managing this recalcitrant soil-borne pathogen. The superior performance of streptomycin in inhibiting *R. solanacearum* under *in vitro* conditions corroborates earlier reports that bactericides, particularly antibiotics, exhibit strong antibacterial activity against plant-pathogenic bacteria. However, despite their effectiveness in laboratory conditions, their field applicability remains limited due to environmental concerns and the development of resistance (21). Similarly, researchers have reported inconsistent or even adverse effects of antibiotics, such as streptomycin, under field conditions, highlighting that reliance solely on antibiotics is not a sustainable management strategy (22).

The significantly higher inhibition observed in antibiotic-

copper combinations, particularly streptomycin + copper oxychloride, suggests a synergistic interaction between these compounds. This finding is consistent with earlier studies in which combined chemical treatments enhanced disease suppression compared with individual applications. Such synergism may be attributed to multiple modes of action, including disruption of bacterial cell membranes and interference with metabolic processes (23). However, excessive dependence on chemical control should be avoided due to environmental risks and potential residue accumulation, reinforcing the importance of IDM strategies (24).

Among biocontrol agents, *P. fluorescens* isolates exhibited the highest antagonistic activity, followed by *Trichoderma* spp., while *Bacillus subtilis* showed comparatively lower efficacy. These findings are in strong agreement with previous reports indicating that fluorescent pseudomonads are among the most effective biological control agents against bacterial wilt due to their ability to produce antimicrobial metabolites, compete for nutrients and induce systemic resistance in plants (25). Similarly, another study demonstrated that *Trichoderma* and *Bacillus* species significantly reduced disease incidence and pathogen populations in soil, although their effectiveness varied by isolate (26). The comparatively lower performance of *Bacillus subtilis* in the present study may be due to strain-specific differences in antagonistic potential.

The effectiveness of botanical extracts, particularly garlic (*A. sativum*) and neem (*A. indica*), observed in this study supports earlier findings that plant-derived compounds possess antimicrobial properties due to the presence of bioactive secondary metabolites such as alkaloids, flavonoids and phenolic (27). Another study reported that plant extracts and powders can significantly inhibit *R. solanacearum* and reduce disease severity, offering an eco-friendly alternative to synthetic chemicals (28). These natural products are biodegradable, non-phytotoxic and suitable for sustainable agriculture.

The overall trend observed in this study—where integrated approaches outperform individual treatments—is consistent with several previous studies across crops such as tomato, brinjal and pepper. Integrated disease management strategies combining biological agents, plant extracts and chemical treatments have been shown to significantly reduce bacterial wilt incidence and improve crop yield (29, 30). The inability of any single method to provide complete control is mainly due to the complex nature of *R. solanacearum*, which can survive in soil, water and plant debris and infect a wide range of hosts (31).

Conclusion

From this study, it can be observed that effective management of bacterial wilt in tomato caused by *R. solanacearum* cannot be achieved through a single strategy; rather, an integrated approach is essential. While antibiotics and chemical combinations showed high inhibitory capacity in *in vitro* conditions, they have limited field applicability due to environmental concerns and the potential for resistance development. However, environmentally friendly approaches utilising biological agents (such as *P. fluorescens*), botanicals (such as garlic and neem extracts) and organic sources (such as karanj and neem cake) demonstrated significant potential in reducing disease incidence and severity. Notably, IDM treatments that incorporated any of these environmentally friendly measures were found to outperform other treatment methods in delaying disease occurrence, minimising disease incidence and improving crop yield.

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Authors' contributions

SSP conceptualised and designed the study, conducted field experiments, collected the data, and drafted the original manuscript. SS contributed to the experimental design, interpreted the data, and critically revised the manuscript. AM provided methodological guidance and assisted with manuscript editing. AD performed the statistical analysis and supported data interpretation. BJ, DM and LS contributed to data analysis, interpretation, and provided technical inputs. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT to assist with language editing and to improve the clarity of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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