PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7316

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Integrated disease management strategies for sustainable tomato cultivation in bacterial wilt-endemic region of Tamil Nadu

Sheneka R[1], Angappan K[1*], Karthikeyan M[1*], Thiribhuvanamala G[1], Karthikeyan S[2] & Kumar KK[3]

[1]Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Plant Biotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: angappan.k@tnau.ac.in, karthikeyan.m@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 20 January 2025
Accepted: 06 February 2025
Available online
Version 1.0 : 12 February 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Sheneka R, Angappan K, Karthikeyan M, Thiribhuvanamala G, Karthikeyan S, Kumar KK. Integrated disease management strategies for sustainable tomato cultivation in bacterial wilt-endemic region of Tamil Nadu. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.7316

Abstract

Bacterial wilt, caused by *Ralstonia solanacearum*, is a major threat for tomato farmers, especially in tropical areas. This study investigates the prevalence and management of bacterial wilt disease in Coimbatore district, Tamil Nadu, over three growing seasons (2020–2023). The survey found the disease occurrence in Kinathukadavu, Madukarai and other blocks with severe incidence during the Rabi season. An Integrated Disease Management (IDM) approach, incorporating soil amendment, soil application of *Bacillus subtilis*, intercropping marigold and seedling root dipping of streptocycline and drenching with copper-based fungicides, was evaluated in field trials over three consecutive years. IDM treatment (T6) consistently resulted in the lowest disease incidence, ranging from 2.67 to 4.47 % and the highest yield (394.50-404.63 q/ha) and Benefit: Cost (B: C) ratio (3.91-3.63) over the study period, demonstrating its cost-effectiveness compared to other treatments. A strong negative correlation between wilt incidence and yield was observed, with IDM T6 yielding the best results. These findings suggest that Integrated Disease Management (IDM) is an effective and sustainable approach for managing bacterial wilt disease and improving tomato yield in affected regions.

Keywords

bacterial wilt; integrated disease management; tomato; yield

Introduction

Bacterial wilt, caused by *Ralstonia solanacearum*, is a severe disease affecting many host plants, including economically significant crops like tomatoes. It is one of the most challenging diseases, causing severe damage to tomato plants throughout the world, especially in the tropical and subtropical regions and parts of the warm temperate regions (1) with yield losses exceeding 90 % (2). This disease is known as 'Green wilt' since the leaves of the infested plant stay green when the plant begins to show wilt symptoms (3). It also results in substantial losses in other crops like tomato, eggplant, potato, tobacco and banana (4). The cultivation of solanaceous crops, especially tomato and pepper, plays a significant role in many developing countries, especially in Africa and Asia these crops act as a source of income and enhance the social and nutritional status of well-being. Besides their importance, the productivity of these crops may be limited by different abiotic constraints such as low levels of irrigation, soil erosion and degradation, low levels of agrochemical input (fertilizer, pesticide and improved seeds), inadequate agricultural research and constraints in market development. In addition to that, the biotic constraints including bacterial wilt affect their productivity highly (5). *R. solanacearum* is widespread in India's major states, causing substantial crop yield losses. It is an extraordinarily diverse and complex species. The pathogen is classified into races and biovars based on its host range and metabolic characteristics. It can survive in soil and weeds and spread between fields via water, soil erosion and mechanical transmission, making its management particularly challenging (6).

Several management strategies have been developed to manage the bacterial wilt disease. Potential antagonistic agents namely *Bacillus cereus*, *Trichoderma harzianum, Calotropis gigantea* and *Pseudomonas fluorescens* were explored against *R. solanacearum* (7, 8) Despite efforts such as crop rotation, intercropping, soil amendments, biocontrol application and resistant varieties, no single control method has proven fully effective due to the pathogen's complexity and adaptability (2, 9, 10). While bacterial wilt-resistant cultivars, including Sakthi, Mukthi and Anagha, have been developed by the Asian Vegetable Research and Development Centre, their resistance was highly dependent on specific locations. Additionally, the pathogen's ability to persist in weed hosts diminishes the effectiveness of crop rotation with non-host plants (11). In addition to that physical treatment such soil solarization involves using plastic sheets to trap solar heat and raising soil temperatures to suppress soil-borne pathogens like *Ralstonia solanacearum* where its effectiveness depends on temperature and can be enhanced with additional integrated measures (12).

Historically, the incidence of this pathogen in Tamil Nadu was minimal, but its occurrence has recently been reported in major tomato and eggplant-growing regions of the state. This shift underscores the urgent need to address bacterial wilt as a critical challenge in their cultivation in affected areas.

With this view, the current study aims to conduct an extensive survey near the Kerala-Tamil Nadu border and major eggplant growing districts of Tamil Nadu over three years (2020-2023) and an integrated management experiment was conducted in disease epidemic areas.

Materials and Methods

Field survey and documentation of bacterial wilt

A roving survey was conducted during all three cropping seasons viz., the Summer (Mar -June), Kharif (July - Oct) and Rabi (Nov-Feb) from 2020 to 2023 in the major tomato growing blocks (11 blocks) of Coimbatore district *viz.,* Coimbatore South (Madukkarai, Sulur and Thondamuthur), Coimbatore North (Periyanaickenpalayam, Annur), Mettupalayam (Karamadai), Pollachi (Pollachi, Kinathukadavu, Anaimalai) and Palladam (Sultanpet) to determine the prevalence of bacterial wilt disease in the field. The plants were inspected at the nursery stage, after transplanting, at the flowering and at the fruiting stage in all the blocks. The plants were observed for the typical symptoms of bacterial wilt viz., leaf green wilting and vascular browning. The percent wilt incidence was estimated among the randomly selected plots (1 m^2) by counting the total number of plants and wilted plants (13).

Assessment of Integrated Disease Management (IDM) Protocol for Bacterial Wilt Disease

Land preparation : An experiment was conducted during the 2020-2021, 2021-2022 and 2022-2023 cropping seasons in a sick plot at Kinathukadavu block, Coimbatore district, identified as an endemic area through surveys. The soil plowed to a fine tilth, was supplemented with 25 tonnes/ha of farmyard manure as a basal application. Soil analysis was performed and lime was applied to neutralize the soil pH in the treatment plots T2 and T6. A fertilizer dose of 75:100:50 kg N: P_2O_5: K_2O per hectare was provided in the recommended split doses.

Seedling preparation : Tomato seedlings (CO-2 hybrid) were raised in a nursery using a sterile substrate. Before sowing, the seeds were treated with *Bacillus subtilis* (10 g/kg of seed) for all treatments except the control and irrigation was provided as needed. In August, 28-day-old tomato seedlings were transplanted into the experimental plots (3.0 × 2.4 m^2) for each treatment. Each plot contained 20-25 seedlings, planted at 60 × 60 cm spacing.

Experimental design and treatment details : The experiment was laid out in a Randomized Block Design (RBD) with three replications for six treatments and one control. Plant yield and disease progression were monitored under field conditions to evaluate the effectiveness of bacterial wilt management strategies.

The details of the treatment evaluated for bacterial wilt management (Table 1) are as follows, common treatment (T0) of neem cake 150kg/ha application, growing marigold (*Tagetes* spp.) as intercrop and soil application of 15 days enriched *Bacillus subtilis* @ 2.5 kg/ha + 150 kg of well decomposed FYM before transplanting was carried out. After testing the soil pH, the lime requirement of soil was calculated for each plot of 7.2 m^2 size based on the standard lime requirement given in the TNAU package of practices (https://agritech.tnau.ac.in/agriculture/agri_reosurcemgt_soil_soilcontraints.html). The pH of the soil was 6.2, hence 4.2 tons of CaCO3/acre were added to the soil (7.56kg /plot). Then the required quantity of quality lime was mixed thoroughly with the soil before transplanting seedlings in T1 and T6 treatments. The *Bacillus subtilis* strain used in this study was obtained from the Culture Collection Center of the Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore. The roots of tomato seedlings were dipped in streptocycline (2 g/10 L) for 30 min before transplanting in the case of T2 and T6 treatment. In T2, the drenching 250 mL of streptocycline 0.1g + copper oxychloride 2.5g per liter water at 15-day intervals starting from 20 days after transplanting up to 70 days. Drenching 250 mL of 0.25 % copper oxychloride per plant was done 20 days after transplanting of seedlings and it was repeated thrice at 15-day intervals in T3 treatment. In T4 treatment, drenching 250 mL of 0.25 % copper hydroxide per plant at 15-day intervals starts from 20 days after transplanting up to 70 days. In T5 treatment,

Table 1. Treatment details for Integrated disease management of tomato bacterial wilt disease

Treatments	Details
T0	Nursery Practice: Treat the seeds with talc-based formulation of *Bacillus subtilis* (10g/1000g of seeds) and soil application of antagonistic *Bacillus subtilis* (50g mixed with one kg of FYM and incorporated into the nursery bed). Application of Neem cake 150kg/ha Growing marigold (*Tagetes* spp.) as intercrop will suppress the pathogen in addition to its anti-nematode effect. Soil application of 15 days enriched *Bacillus subtilis* @ 2.5 kg / ha + 150 kg of well decomposed FYM before transplanting
T1	T0 + Soil amendment with lime depends upon the pH of the soil to make soil neutral.
T2	T0 + Seedling root dip with streptocycline @ 200ppm followed by soil drenching of streptocycline 0.1g + copper oxychloride 2.5g per litre water at 15 days intervals starting from 20 days after transplanting up to 70 days
T3	T0 + Drenching of copper oxychloride @ 2.5g per litre at 15-day intervals starting from 20 days after transplanting up to 70 days.
T4	T0 + Drenching of copper hydroxide @ 2 g per litre at 15-day intervals starting from 20 days after transplanting up to 70 days.
T5	T0 + Drenching of the liquid formulation of *Bacillus subtilis* @1% five times at 15-day intervals starting from 20 days after transplanting.
T6	T0 + IDM: Soil amendment with lime depending upon pH of the soil to make soil neutral + Seedling root dipping by streptocycline @ 200 ppm, copper oxychloride 2.5g per litre water at 20 DAT and 60 DAT and application of copper hydroxide @ 2 g per litre at 40 DAT
T7	Control

FYM -farm yard manure; kg/ha- kilogram/hectare; IDM- integrated disease management; DAT - days after transplanting

drenching of 250 mL of *Bacillus subtilis* @ 1 % per plant was done 20 days after transplanting and it was repeated thrice at 15-day intervals. T6 treatment was integration of T1, T2, T3 and T4 treatments. T7 was kept as the control plot without applying any management strategies. The incidence and severity of bacterial wilt were observed at periodical intervals starting from the 45th to the 120th day after transplanting in respective treatment blocks of the sick field.

Data collected from the field trial

Percent Bacterial wilt incidence: The percent wilt disease incidence was recorded for each treatment using the formula given in Eqn. 1 below as described (14).

Percent disease incidence (PDI) = Number of plants wilted/ Total number of plants observed ×100 (Eqn. 1)

Percent reduction over control : The percent disease reduction over control for the treatments was calculated using the formula below in Eqn. 2.

Percent reduction over control = C-T / C ×100 (Eqn. 2)

Here,

C- Percent incidence in control

T- Percent incidence in treatment

Total yield and marketable yield of tomato fruit : Periodical harvest was conducted and the total yield (kg/plot) was calculated by recording the total number and weight of the fruits per plot for each treatment, whereas the marketable yield was recorded by omitting those affected by abiotic and biotic factors. The yield was then presented for hectares and represented as quintal per hectare. The formula for yield calculation is mentioned below in Eqn. 3.

Yield (kg/ha) = Total yield per plot (kg)/ plot size (m2) ×10,000 (m2) (Eqn. 3)

Correlation between disease incidence and yield : The mean disease incidence and average yield were calculated for each treatment over three consecutive years. The values were compiled and correlation analysis was performed in Python version 3.13.1.

Benefit: cost ratio : To calculate the Incremental Cost-Benefit Ratio (ICBR), the cost of various inputs (such as seeds, fertilizers, etc.), labour wages and interest on the capital invested, for the half-life of total crop duration @ 12.5 % per year (as per the Indian government's agricultural pricing guidelines) were compared with the selling price of harvested tomato fruits at the farm level (Eqn. 4).

Incremental Cost-Benefit Ratio (ICBR) = Incremental Net Returns/ Incremental Cost of Cultivation (Eqn. 4)

Statistical analysis

The field experiments were conducted using a Randomized Block Design (RBD) with four replications per treatment. The percent disease incidence values were arcsine transformed and compared using Duncan's Multiple Range Test ($p \leq 0.05$). Graphical representations of the data were prepared using R studio software v4.4.1

Results

Documentation of tomato bacterial wilt

A survey on the bacterial wilt disease incidence in tomato growing areas of the Coimbatore district during the period of 2020-2021, 2021-2022 and 2022-2023 revealed the occurrence of the disease in Kinathukadavu block in all three growing seasons ranged from 11.7 to 27.10 percent in 2020-2021, 12.32 to 29.2 percent in 2021-2022 and 11.86 to 28.25 percent in 2022-2023 (Fig. 1, 2). The lower incidence occurs during summer while the higher incidence is recorded in the Rabi season. In the Madukarai, the Anamalai and Pollachi blocks, the disease was observed in two growing seasons viz., Kharif and Rabi seasons where disease severity was high in the Rabi season. Further, in the Thondamuthur blocks, the disease was observed during the Rabi season at around 5.25 to 6.73 percent whereas no disease incidence was recorded in Annur, Karamadai, Sultanpet and Sulur block. The results in addition revealed that the bacterial wilt incidence is progressively increasing in the case of Kinathukadavu and Madukarai blocks whereas it decreased in other blocks shown in Fig. 3.

Fig. 1. Green wilting symptoms produced by bacterial wilt on tomato crops under field conditions in Coimbatore districts.

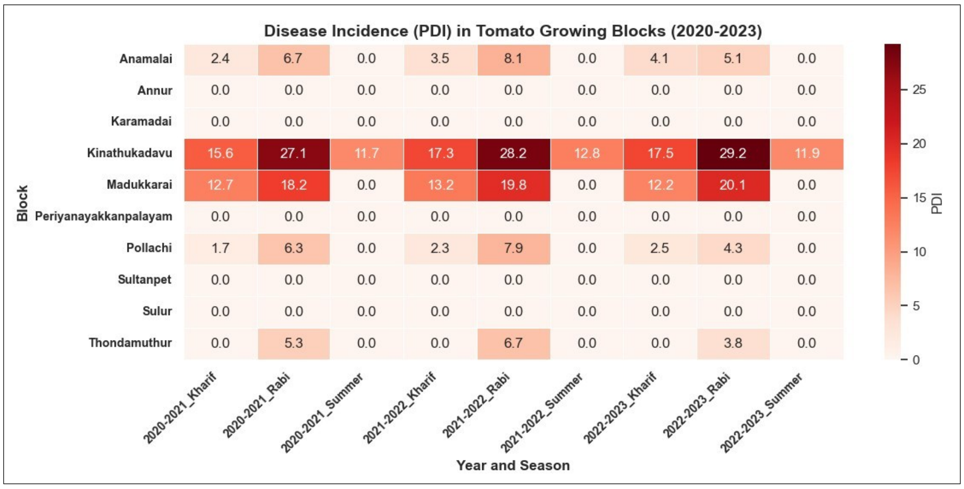

Fig. 2. Heat map depicts the Percent Disease Incidence (PDI) of bacterial wilt in tomato crops across various blocks of Coimbatore, Tamil Nadu over three years (2020-2023), segmented by seasons (Kharif, Rabi and Summer). The rows represent the blocks and the columns correspond to the year-season combinations. The colour intensity reflects the PDI value, with darker shades representing higher disease severity (PDI) and lighter shades indicating lower or no disease.

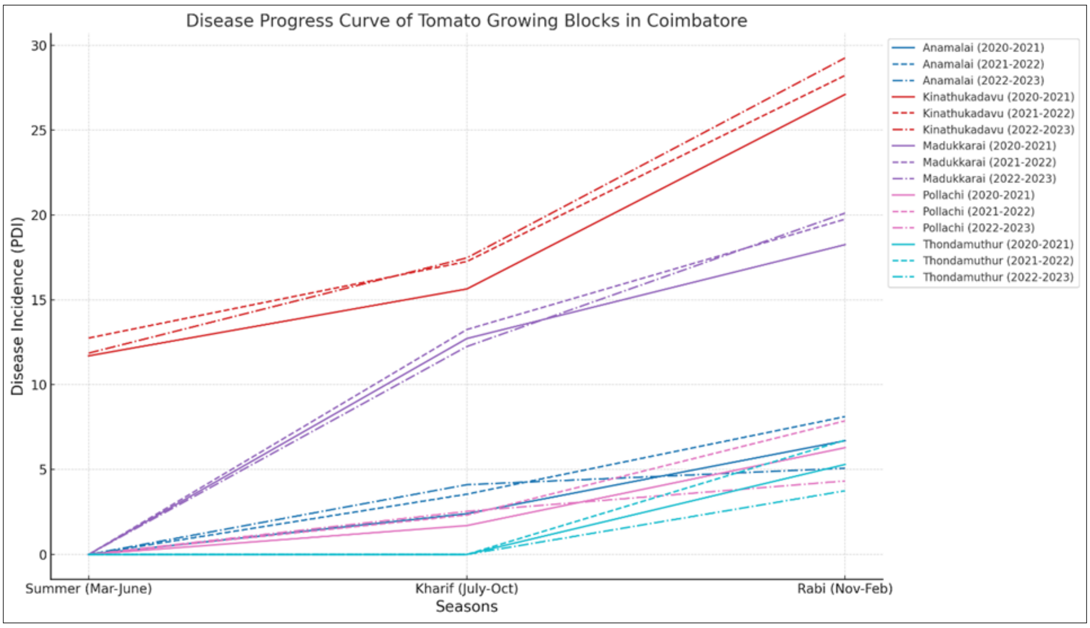

Fig. 3. The line graph shows disease progress curves of bacterial wilt disease in tomato-growing blocks of Coimbatore over three years (2020-21, 2021-22, 2022-23). Each block is represented in distinct colours, while line styles (solid, dashed, dotted) distinguish the years, highlighting variations in disease incidence (PDI) across blocks and seasons (Summer, Kharif and Rabi).

Efficacy of IDM for Bacterial wilt disease under field condition

A field experiment was conducted at Sattakalpudur village of Kinathukadavu block during the Rabi season for three consecutive years (2020-21, 2021-22, 2022-23). In all three years, the minimum disease incidence was recorded in IDM practices (T6: T0 + IDM of Soil amendment with lime depending upon pH of the soil to make soil neutral + Seedling root dipping by streptocycline @ 200 ppm, copper oxychloride 2.5g per litre water at 20 DAT and 60 DAT and application of copper hydroxide @ 2 g per litre at 40 DAT) followed by T2 as compared to control. Similarly, the maximum yield and the highest BC ratio were recorded in T6 (IDM practice) (Tables 2,3,4).

Bacterial Wilt Incidence Over Years

Treatments (T6) consistently exhibited the lowest wilt incidence across 2020-2023 (2.67, 3.85 and 4.47 percent respectively) while T7 recorded the highest incidence in all three years. There is a slight increase in wilt incidence for most treatments over the years (Fig. 4A), suggesting worsening conditions or reduced effectiveness of the treatments over time.

Total Yield Over Years

Over three years, the IDM treatment T6 produced a greater yield with a gradual increase over time by recording 404.63, 394.50 and 397.61q/ha yield during 2020-21, 2021-22 and 2022-23 respectively, indicating that this treatment apart from reducing wilt enhances the fruit yield. Further, T2 also maintained higher yields whereas T7 consistently showed the lowest yield (325.00, 314.87 and 317.98 q/ha respectively) aligning with the high wilt incidence. There, is a clear inverse relationship between wilt incidence and yield, with T6 providing the best overall performance (Fig. 4B).

Table 2. Effects of different treatments on bacterial wilt incidence and tomato yield (2020-21)

Treatments	Percent disease incidence (%)* at 120 DAT	Percent reduction over control (%)*	Total yield (q/ha)	Marketable yield (q/ha)	B:C ratio
T1	8.67^{e} (17.12)	44.67^{e} (41.94)	365.74	336.11	2.19
T2	4.33^{b} (12.71)	72.37^{b} (58.29)	404.63	383.34	3.51
T3	7.33^{d} (15.71)	53.22^{d} (46.85)	370.37	340.74	2.29
T4	5.67^{c} (13.78)	63.82^{c} (53.02)	393.52	373.15	2.41
T5	9.33^{f} (17.79)	40.46^{f} (39.50)	360.19	331.48	2.17
T6	2.67^{a} (9.40)	82.96^{a} (65.62)	436.11	404.63	3.91
T7	15.67^{g} (23.32)	0.00^{g} (0.00)	352.78	325.00	2.03
CD (p=0.05)	**2.23**		**18.3**	**17.36**	

*Values are means of four replications; values in parentheses are arcsine-transformed. This means sharing the same letter is not significantly different (DMRT, p≤0.05). DAT - days after transplanting; q/ha - quintal/ hectare; B:C ratio- Benefit: cost ratio; CD- critical difference

Table 3. Effect of different treatments on bacterial wilt incidence and tomato yield (2021-22)

Treatments	Percent disease incidence (%)* at 120 DAT	Percent reduction over control (%)*	Total yield (q/ha)	Marketable yield (q/ha)	B: C ratio
T1	9.8^{e} (18.32)	41.77^{e} (40.26)	352.32	325.98	1.87
T2	5.54^{b} (13.61)	67.08^{b} (54.99)	391.21	373.21	3.19
T3	8.52^{d} (16.97)	49.38^{d} (44.64)	356.95	330.61	1.97
T4	6.81^{c} (15.13)	59.57^{c} (50.52)	380.10	363.02	2.09
T5	10.54^{f} (18.91)	37.37^{f} (37.68)	346.77	321.35	1.85
T6	3.85^{a} (11.32)	77.12^{a} (61.42)	422.69	394.50	3.59
T7	16.83^{g} (24.22)	0.00^{g} (0.00)	339.36	314.87	1.71
CD (p=0.05)	**1.83**		**10.23**	**12.36**	

*Values are means of four replications; values in parentheses are arcsine-transformed. This means sharing the same letter is not significantly different (DMRT, p≤0.05). DAT - days after transplanting; q/ha - quintal/ hectare; B:C ratio- Benefit: cost ratio; CD- critical difference

Table 4. Effect of different treatments on bacterial wilt incidence and tomato yield (2022 -23)

Treatments	Percent disease incidence (%)* at 120 DAT	Percent reduction over control (%)*	Total yield (q/ha)	Marketable yield (q/ha)	B: C ratio
T1	10.42^{e} (18.83)	40.28^{e} (39.40)	354.94	329.09	1.91
T2	6.16^{b} (14.37)	64.69^{b} (53.54)	393.83	376.32	3.23
T3	9.14^{d} (17.60)	47.62^{d} (43.64)	359.57	333.72	2.01
T4	7.43^{c} (15.82)	57.42^{c} (49.27)	382.72	366.13	2.13
T5	11.16^{f} (19.52)	36.05^{f} (36.90)	349.39	324.46	1.89
T6	4.47^{a} (12.21)	74.38^{a} (59.59)	425.31	397.61	3.63
T7	17.45^{g} (24.69)	0.00^{g} (0.00)	341.98	317.98	1.75
CD (p=0.05)	**0.91**		**19.14**	**18.04**	

*Values are means of four replications; values in parentheses are arcsine-transformed. This means sharing the same letter is not significantly different (DMRT, p≤0.05). DAT - days after transplanting; q/ha - quintal/ hectare; B:C ratio- Benefit: cost ratio; CD- critical difference

Correlation analysis for mean wilt incidence vs mean yield

The scatter plot clearly shows a strong negative correlation between mean wilt incidence and mean yield (Fig. 4C). Pearson Correlation (-0.86) and Spearman Correlation (-1.00) confirm this relationship, indicating that higher wilt incidence consistently corresponds to lower yield. The IDM treatment T6 recorded the lowest wilt incidence and highest yield, whereas in the control treatment, T7 displayed the highest wilt incidence compared to the best treatment. This indicates that T6 is an effective IDM strategy for managing the wilt disease and improving the yields.

B: C Ratio over the year

The B: C (Benefit: Cost) ratio disclosed that the IDM treatment T6 has the highest ratio in all three consecutive years (3.91 in 2020-21, 3.59 in 2021-22 and 3.63 in 2022-23), making it the most cost-effective treatment followed by T2, which also performs well, with a relatively high B: C ratio. T7 has the lowest B: C ratio across all years, indicating it is ineffective in reducing wilt and cost-inefficient (Fig. 4D).

Discussion

The survey conducted in tomato-growing areas of the Coimbatore district to study bacterial wilt incidence revealed the spatial and temporal variation of the disease over growing seasons. It highlights the persistence and severity of disease in the Kinathukadavu block with incidence ranging from 11.7 % to 29.2 % across three years (2020-2023). This was found to be a higher incidence during the Rabi season than the kharif and summer seasons which could be attributed to favorable environmental conditions such as high soil moisture and moderate temperatures that support the survival and spread of the pathogen. In contrast, there are reduced disease occurrences in blocks like Thondamuthur and no disease in Annur, Karamadai, Sultanpet and Sulur blocks. This could be because of different soil qualities, less favorable environmental conditions and loss of virulence or due to the absence of the pathogen in these regions. These results are consistent with the previous reports of epidemiological studies that showed a steady increase in disease incidence as soil temperature rose from 30 to 35 degrees Celsius and moisture levels rose to 90 % (15-17). Further, the increasing bacterial wilt cases in the Kinathukadavu and Madukarai blocks over time is probably caused by the pathogen's slow accumulation in the soil, ideal growing conditions or ongoing production of vulnerable crops and a lack of widespread use of efficient disease control techniques. The efficacy of IDM practices (T6: lime application + soil and seed treatment with *Bacillus subtilis* + marigold intercropping + seedling root dipping by streptocycline with copper oxychloride and copper hydroxide) in managing bacterial wilt caused by *R. solanacearum* under field conditions was underscored by field experiments carried out in the Kinathukadavu block during the Rabi season. T6 continuously had the highest yield and the lowest disease incidence over all three experiments, highlighting its effectiveness in improving crop productivity and suppressing the disease. Supporting this study, previous research reported that the severity of potato bacterial wilt disease was associated with the soil acidic conditions in Ethiopia and identified the lime application of about 12 t/ha showed positive effects on soil pH while reducing the disease incidence to 10.8 percent where the incidence in control plot was recorded about 40 percent (18). A study reported that raising the soil pH from acidic conditions decreased the R. solanacearum population while promoting the growth of beneficial rhizosphere microbes,

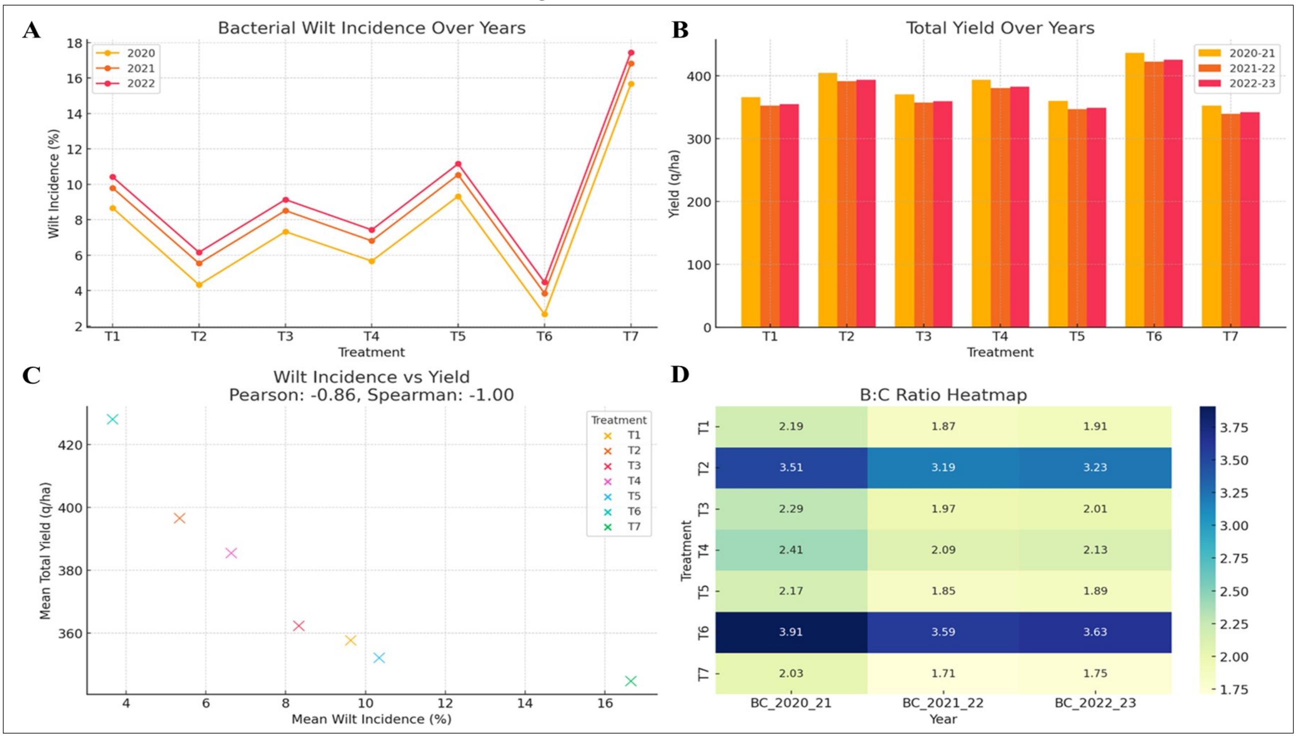

Fig. 4. A) Line chart illustrating bacterial wilt incidence (%) across seven treatments (T1-T7) over three years (2020-21, 2021-22 and 2022-23), showing peaks and drops in treatment effectiveness; B) Bar chart depicting total yield (quintal/hectare) for T1-T7 treatments over three years, color-coded as red (2020-21), green (2021-22) and blue (2022-23). C) Scatter plot showing the inverse relationship between mean wilt incidence (%) and mean total yield (quintal/hectare) for treatments (T1-T7), with data points labelled by treatment. D) A heat map displaying the Benefit: Cost (B: C) ratio for T1-T7 treatments over three years, with darker shades indicating higher B: C ratios.

particularly *Pseudomonas* and *Bacillus* (19). Additionally, research findings showed that among five different chemicals tested, the combination of Oxyrich (Copper oxychloride) + Kocide (Copper hydroxide) effectively reduced bacterial wilt incidence to 18.38 % under field conditions (20). Aligning to this, another study reported that the chili plants inoculated and treated with *Ralstonia* inoculation and copper hydroxide treatment enhance the biochemical defense pathways, helping to combat the wilt incidence by promoting disease resistance (21). In the same way, the earlier study showed that *B. amyloliquefaciens* effectively lowered the incidence of bacterial wilt disease in field settings by almost 67 % compared to untreated controls (22). Furthermore, a combination of *Pseudomonas fluorescens* and *Trichoderma viride* administered via seed, root and soil treatments dramatically increased yield (3866.77 g/plant), fruit size (337.02 g/fruit) and fruit number while lowering the incidence of bacterial wilt to 19.80 % under field conditions (23). Additionally, our findings are in line with earlier reports of IDM practices (T1: rhizome treatment with streptocycline and copper oxychloride, soil application of neem cake, drenching with bleaching powder and Metalaxyl MZ sprays at 20-day intervals, followed by a special spray on the 45th day) that showed a significant decrease in wilt incidence and increased ginger yield (24). In concordance, the author's investigations (12, 25) showed that IDM techniques, including cultural, chemical and biological measures effectively managed soil-borne pathogens like *R. solanacearum* in ginger and tomato respectively. The Pearson (-0.86) and Spearman (-1.00) coefficients demonstrate that higher disease incidence results in considerable production losses, further highlighting the strong negative association between wilt incidence and yield in this study. Higher crop yields were found to be directly correlated with a lower incidence of bacterial wilt in previous studies (12). T6 proves to be an effective treatment, continuing to have the highest yield and the lowest wilt incidence throughout the years. However, T7's continuous poor performance in terms of yield and suppression of disease shows how inadequate it is to rely on inefficient treatments when disease pressure is high. With the highest benefit-cost (B:C) ratio observed for the three years, the economic analysis provided additional evidence of T6's superiority. This suggests that IDM practices apart from its biologically effective and yield-enhancing properties, it was highly cost-efficient, making them a sustainable and practical choice for farmers with limited resources.

Conclusion

Overall, the study highlighted that bacterial wilt disease reaches its greater severity during the rabi season. Furthermore, the observed variability in disease incidence among blocks indicates that local environmental factors such as cropping practices, climatic conditions and soil type play vital roles in influencing disease dynamics. The increase in wilt incidence in Kinathukadavu and Madukkarai blocks highlights the need for regular monitoring and effective crop rotation. In addition, the findings indicate that adopting IDM practices (T6) combining soil amendment based on soil pH, border cropping of marigolds to mitigate nematode damage, application of *Bacillus subtilis* and need-based copper fungicide helps in reducing the disease incidence, preventing the further spread and promoting the crop yield. With bacterial wilt being a major constraint in tomato production, the findings of this study provide a strong basis for promoting IDM as an effective and economically viable approach to managing bacterial wilt, enhancing productivity and improving profitability for tomato growers. Future research should focus on identifying native rhizosphere antagonistic organisms to improve adaptability and long-term disease suppression. Since the pathogen primarily enters plants through the root system, exploring resistant tomato or eggplant lines that work in local conditions and integrating them into IDM practices can provide an additional layer of prevention measures for the entry of pathogen into the host systems. Understanding these elements and adjusting management strategies according to local circumstances is essential for curbing the further spread of the pathogen and ensuring sustainable disease control.

Acknowledgements

The authors acknowledge the Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore, for providing the necessary facilities to conduct this research.

Authors' contributions

SR and KM carried out the experiments, and SR wrote the original manuscript. AK reviewed and edited the manuscript and KM reviewed and carried out technical editing. TG, KS and KKK reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

References

1. Du H, Chen B, Zhang X, Zhang F, Miller SA, Rajashekara G, et al. Evaluation of *Ralstonia solanacearum* infection dynamics in resistant and susceptible pepper lines using bioluminescence imaging. Plant Dis. 2017;101(2):272-78. https://doi.org/10.1094/PDIS-05-16-0714-RE

2. Ramesh R, D'Souza M, Asolkar T, Achari G, Gupta MJ. Rootstocks for the management of bacterial wilt in eggplant (*Solanum melongena* L.) and tomato (*Solanum lycopersicum* L.) in the coastal regions of India. Adv Agric. 2022;2022(1):8594080. https://doi.org/10.1155/2022/8594080

3. Mamphogoro TP, Babalola OO, Aiyegoro OA. Sustainable management strategies for bacterial wilt of sweet peppers (*Capsicum annuum*) and other Solanaceous crops. J Appl Microbiol. 2020;129(3):496-508. https://doi.org/10.1111/jam.14653

4. Elphinstone M. The current bacterial wilt situation: a global overview in Bacterial Wilt Disease and the *Ralstonia solanacearum* Species Complex, eds C. Allen, P. Piror and A. C. Hayward (St. Paul, MN: APS Press) 2005: 9–28.

5. Du H, Yang J, Chen B, Zhang X, Xu X, Wen C, et al. Dual RNA-seq reveals the global transcriptome dynamics of *Ralstonia solanacearum* and pepper (*Capsicum annuum*) hypocotyls during bacterial wilt pathogenesis. Phytopathol. 2022 ;112 (3):630-42. https://doi.org/10.1094/PHYTO-01-21-0032-R

6. Karim Z, Hossain MS. Management of bacterial wilt (*Ralstonia solanacearum*) of potato: focus on natural bioactive compounds. JBCBM. 2018 ;4(1):73-92. https://doi.org/10.3329/JBCBM.V4I1.37879

7. Qulsum MU, Islam MM, Chowdhury ME, Hossain SM, Hasan MM. Management of bacterial wilt (*Ralstonia solanacearum*) of brinjal using *Bacillus cereus*, *Trichoderma harzianum* and *Calotropis gigantea* consortia in Bangladesh. EJBPC. 2023;33 (1):74. https://doi.org/10.1186/s41938-023-00720-0

8. Chakravarty G. Management of bacterial wilt disease of Brinjal by *P. fluorescens* based bioformulation: experimental investigation. EIAS. 2023;2:130-50. https://doi.org/10.9734/bpi/eias/v2/5978A

9. Jibat M, Terefe H, Derso E. Integrated management of bacterial wilt (*Ralstonia solanacearum)* of ginger (*Zingiber officinale*) in Southwestern Ethiopia. Arch Phytopatol Pflanzenschutz. 2018;51 (15-16):834-51. https://doi.org/10.1080/03235408.2018.1504374

10. Akter N, Islam MR, Hossain MB, Islam MN, Chowdhury SR, Hoque S, et al. Management of wilt complex of eggplant (*Solanum melongena* L.) caused by *Fusarium oxysporum*, *Ralstonia solanacearum* and *Meloidogyne* spp. Am J Plant Sci. 2021;12 (7):1155-71. https://doi.org/10.4236/ajps.2021.127080

11. Vanitha SC, Niranjana SR, Umesha S. Role of phenylalanine ammonia lyase and polyphenol oxidase in host resistance to bacterial wilt of tomato. J Phytopathol. 2009;157(9):552-57. https://doi.org/10.1111/j.1439-0434.2008.01526.x

12. Aysanew E, Alemayehu D. Integrated management of ginger bacterial wilt (*Ralstonia solanacearum*) in Southwest Ethiopia. Cogent Food Agric. 2022;8(1):2125033. https://doi.org/10.1080/23311932.2022.2125033

13. Wijayanti KS, Hidayah N, Yulianti T, Andika Y. Distribution of bacterial wilt disease (*Ralstonia solanacearum*) on tobacco in Temanggung. IOP Conf. Ser.: Earth Environ. Sci. 2021;43(1): p. 012032. https://doi.org/10.1088/1755-1315/743/1/012032

14. Xiao Y, Liu X, Meng D, Tao J, Gu Y, Yin H, et al. The role of soil bacterial community during winter fallow period in the incidence of tobacco bacterial wilt disease. Appl Microbiol Biotechnol. 2018;102:2399-412. https://doi.org/10.1007/s00253-018-8757-3

15. Li X, Liu Y, Cai L, Zhang H, Shi J, Yuan Y. Factors affecting the virulence of *Ralstonia solanacearum* and its colonization on tobacco roots. Plant Pathol. 2017;66(8):1345-56. https://doi.org/10.1111/ppa.12675

16. Lopes CA, Rossato M. History and status of selected hosts of the *Ralstonia solanacearum* species complex causing bacterial wilt in Brazil. Front Microbiol. 2018; 9:1228. https://doi.org/10.3389/fmicb.2018.01228

17. Sood D, Sharma A, Sharma M. Prevalence and epidemiology of bacterial wilt of tomato. Int J Econ Plants. 2022;9(4):328-33. https://doi.org/10.23910/2/2022.0469c

18. Tafesse S, Braam C, van Mierlo B, Lemaga B, Struik PC. Association between soil acidity and bacterial wilt occurrence in potato production in Ethiopia. Agronomy. 2021;11(8):1541. https://doi.org/10.3390/agronomy11081541

19. Zhang S, Liu X, Zhou L, Deng L, Zhao W, Liu Y, et al. Alleviating soil acidification could increase disease suppression of bacterial wilt by recruiting potentially beneficial rhizobacteria. Microbiol Spectr. 2022;10(2): e02333-21. https://doi.org/10.1128/spectrum.02333-21

20. Ghaffar A, Atiq M, Rajput NA, Fatima T, Kachelo GA, Ali S, et al. Chemotherapeutic management of *Ralstonia solanacearum* causing bacterial wilt of tomato. J Agric Sci. 2022;4(2):43-55. https://doi.org/10.56520/asj.v4i2.166

21. Kachelo GA, Sahi ST, Rajput NA, Khan MA, Atiq M. Impacts of copper hydroxide on leaf biochemical changes and on induction of resistance in chilli plants against bacterial wilt. Arch Phytopathol Pflanzenschutz. 2024:1-22. https://doi.org/10.1080/03235408.2024.2441798

22. Chou HP, Huang YC, Lin YH, Deng WL. Selection, formulation and field evaluation of *Bacillus amyloliquefaciens* PMB01 for its application to manage tomato bacterial wilt disease. Agriculture. 2022;12(10):1714. https://doi.org/10.3390/agriculture12101714

23. Kataky M. Eco friendly management of bacterial wilt of Brinjal (*Solanum melongena* L) for sustainability and livelihood of small and marginal farmers of Assam. J Krishi Vigyan. 2024;12(1):37-43. https://doi.org/10.5958/2349-4433.2024.00007.2

24. Nagaraja H, Murali R, Narayanaswamy H. Evaluation of different integrated disease management approaches for rhizome rot of Ginger (*Zingiber officinale* Roscoe.) caused by *Ralstonia solanacearum* (Smith.). Int J Environ Clim Chang. 2023;13 (11):1822-34. https://doi.org/10.9734/ijecc/2023/v13i113340

25. Ajayasree TS, Kurian PS, Rashmi CR, Cherian KA. Integrated management protocol for bacterial wilt disease of tomato in *Ralstonia solanacearum* affected soils in Kerala state. Indian J Agric Res. 2022;56(1):106-11. https://doi.org/10.18805/IJARe.A-5853