



RESEARCH ARTICLE

Exploiting antagonistic bacteria and botanical oils for systemic resistance-mediated management of papaya anthracnose complex

A Muthukumar^{1*}, M Sunil Suriya¹, M Rajesh², S Ranjith Raja Ram³, V K Satya⁴, T Suthin Raj⁵, P Renganathan¹, L Vengadeshkumar⁶, T Balaji⁷ & N Rajinimala⁸

¹Department of Plant Pathology, Faculty of Agriculture, Annamalai University, Annamalai Nagar, Chidambaram 608 002, Tamil Nadu, India

²Department of Plant Pathology, Tapioca and Castor Research Station, Yethapur 636 119, Salem, Tamil Nadu, India

³Department of Plant Breeding and Genetics, Tapioca and Castor Research Station, Tamil Nadu Agricultural University, Yethapur 636 119, Salem, Tamil Nadu, India

⁴Department of Plant Pathology, Anbil Dharmalingam Agricultural College and Research Institute, Trichy 620 027, Tamil Nadu, India

⁵Department of Plant Pathology, Regional Research Station, Vridhachalam 606 001, Tamil Nadu, India

⁶Department of Plant Pathology, Agricultural College and Research Institute, Keezhvelur, Nagapattinam 611 105, Tamil Nadu, India

⁷Soil Science and Agricultural Chemistry (SS & AC), Krishi Vigyan Kendra, Ramanathapuram, Kuyavankudi, 623 536, Tamil Nadu, India

⁸Department of Plant Pathology, V O Chidambaram Agricultural College and Research Institute, Killikulam 628 252, Tamil Nadu, India

*Correspondence email - muthuragulajay@gmail.com

Received: 20 April 2026; Accepted: 01 June 2026; Available online: Version 1.0: 06 July 2026

Cite this article: Muthukumar A, Sunil SM, Rajesh M, Ranjith Raja Ram S, Satya VK, Suthin RT, Renganathan P, Vengadeshkumar L, Balaji T, Rajinimala N. Exploiting antagonistic bacteria and botanical oils for systemic resistance-mediated management of papaya anthracnose complex. Plant Science Today. 2026; 13(sp5): 1-16 <https://doi.org/10.14719/pst.15125>

Abstract

Chemical pesticides are widely used to control plant diseases but pose risks to human health and the environment. Essential oils and antagonistic bacteria, which are effective in managing plant diseases, offer a safer alternative to synthetic fungicides. This study aimed to evaluate papaya anthracnose control using antagonists and plant oils. *In vitro* screening of 9 bacterial strains demonstrated varying inhibitory effects against both *Lasiodiplodia theobromae* and *Colletotrichum papayae*. The most potent suppression of *L. theobromae* was attributed to isolate *Pseudomonas fluorescens* (PfP1), which restricted fungal development to 28.33 mm (a 67.68 % reduction relative to the control) and established a clear 11.00 mm zone of inhibition. Similarly, isolate *Bacillus subtilis* (BsP1) proved most effective against *C. papayae*; it limited mycelial proliferation to just 21.33 mm, creating an 11.67 mm inhibition zone and achieving a 75.94 % growth decline compared to the untreated check. *In vitro* evaluation of essential oils was carried out to assess the mycelial growth of *C. papayae* and *L. theobromae*. Of these, *Eucalyptus* oil showed minimum inhibitory concentration of 0.05 % against the growth of both pathogens. Enhanced disease suppression was achieved through a combined fruit-dipping treatment consisting of 0.05 % *Eucalyptus* oil integrated with *P. fluorescens* (PfP1) and *B. subtilis* (BsP1), both applied at a 0.02 % (v/v) with a bacterial population of approximately 10^8 cfu mL⁻¹ concentration. Following challenge inoculation with the pathogen, this consortium effectively curtailed infection levels. By the 8th day post-inoculation 8 days after inoculation (DAI), the treatment demonstrated a 95.75 % reduction in disease severity compared to the control. Notably, these results were statistically comparable to the efficacy of the synthetic chemical intervention, which yielded a 97.50 % reduction (1.90). The treatment also enhanced defence-related enzymes like peroxidase (PO), polyphenol oxidase (PPO) and phenylalanine ammonia-lyase (PAL). These findings suggest that the consortium of *Eucalyptus* oil and bacterial bioagents has strong potential as an eco-friendly biofungicide for the management of papaya anthracnose.

Keywords: bioagents; *Colletotrichum papayae*; essential oils; *Lasiodiplodia theobromae*

Introduction

Papaya (*Carica papaya* L.) is one of the most economically important fruit crops of the family Caricaceae. While its ancestral roots are found in Southern Mexico and the adjacent territories of Central America, its cultivation has expanded extensively throughout tropical and subtropical corridors. Papaya is widely cultivated across Asia, Africa and the Americas. In India, papaya cultivation contributes significantly to the nation's fruit production, with Tamil Nadu being one of the leading producers. During

2023–24, papaya production in Tamil Nadu reached 219208 metric tonnes, representing a slight increase compared to 217769 metric tonnes recorded in the previous year (1). India is the world's largest producer of papaya, contributing about 44 % to the global output (2). In Tamil Nadu, papaya cultivation is concentrated in regions such as Coimbatore, Madurai and Dindigul, where the favourable climate and soil conditions support the growth of high-yielding and quality varieties like Red Lady and Taiwan Red Lady 786. Other key papaya-growing states in India include Andhra Pradesh, Gujarat, Karnataka and Madhya Pradesh.

Despite its popularity, the marketability of papaya is frequently compromised by its rapid perishability and sensitivity to post-harvest decay, driven by significant physiochemical transitions during ripening (3). The fruit is particularly vulnerable to a broad spectrum of fungal pathogens, including *Alternaria* fruit rot, black spot, chocolate spot and collar rot. However, anthracnose remains the most economically devastating challenge at both the pre-harvest and storage phases. This disease is primarily attributed to a pathogenic complex involving *Colletotrichum papayae* (Penz.) Penz & Sacc. and *Lasiodiplodia theobromae* (Pat.) Griffon & Maubl. Symptomatically, anthracnose manifests as sunken, circular brown lesions, which may eventually develop salmon-coloured conidial masses; notably, *Colletotrichum* species possess the ability to breach the fruit cuticle directly (4).

While synthetic fungicides have traditionally served as the primary management strategy, concerns regarding chemical residues have necessitated the exploration of safer alternatives. Biological control agents offer a sustainable solution by disrupting fungal metabolic pathways and reducing the risk of pathogen resistance development (5), often demonstrating efficacy comparable to or exceeding that of traditional chemicals (6–8). Furthermore, the antimicrobial properties of essential oils such as *Eucalyptus*, lemongrass, cinnamon and thyme have shown significant promise in inhibiting *C. papaya* and *L. theobromae* across various horticultural crops (9–11). In light of these considerations, this research was designed with the following aims: i) to conduct a survey and isolate the specific pathogens responsible for papaya anthracnose; ii) to evaluate the *in vitro* inhibitory potential of various antagonists and essential oils against *C. papayae* and *L. theobromae*; and iii) to assess the effectiveness of integrated botanical and biological treatments in suppressing fruit anthracnose while monitoring the induction of defence-related enzymes.

Materials and Methods

Crop and variety

Papaya varieties CO-1, CO-2, CO-3 and Red Lady were used throughout the study.

Market survey for the assessment of loss due to anthracnose in papaya

A systematic market survey was conducted during 2022–23 across different agro-climatic regions of Tamil Nadu, viz., Chidambaram, Peelamedu, Karur, Tiruchengodu and Salem to assess anthracnose incidence and associated fruit loss. In each location, 5 samples comprising 20 fruits each were randomly collected from retail markets and disease severity was assessed using the standard disease grade chart (12).

Three fruits were randomly harvested from the middle whorl of the crown from each treated plant at the appropriate harvesting stage. The harvested fruits were washed, cleaned and allowed to air-dry for 30 min on a laboratory bench. They were then stored at room temperature, wrapped in paper and placed on cardboard layers, following traditional farmer storage practices. Only fruits showing progressive anthracnose lesion development were selected for subsequent disease severity assessment using a predefined severity scale. The severity of anthracnose was assessed manually using a predefined severity scale.

Disease severity scale

Disease severity was assessed using a 0–4 rating scale based on the percentage of fruit surface exhibiting symptoms. A score of 0 indicated 0–5 % of the fruit surface showing symptoms, 1 represented 6–10 % symptom development, 2 corresponded to 11–25 % of the fruit surface affected, 3 denoted 26–50 % symptom coverage and 4 indicated more than 50 % of the fruit surface showing disease symptoms.

Disease assessment

Disease assessment in different varieties was estimated by using the different scale and percent disease index was calculated using the following the formula.

$$DSI = \frac{\text{Sum of individual disease rating}}{\text{Number of samples}} \times \frac{100}{\text{Maximum disease grade}}$$

$DSI = (\text{Sum of individual disease ratings} \times 100) / (\text{Number of samples} \times \text{Maximum disease grade})$

During market survey the variety Red Lady showed the maximum anthracnose incidence. Hence, this variety was used for further study.

Sampling and isolation of anthracnose pathogens

To isolate the causal agents of papaya anthracnose, symptomatic fruit samples from varieties including CO-1, CO-2, CO-3 and Red Lady were procured from various retail markets across Tamil Nadu during the 2022–23 period. Infected tissues (1 cm²) were subjected to surface sterilisation using a 2 % (v/v) sodium hypochlorite (NaOCl) solution for 5 min, followed by a triple rinse in deionised water and air-drying under aseptic conditions. After trimming the sterilised margins, the tissue segments were inoculated onto potato dextrose agar (PDA) medium and incubated at 28 ± 2 °C for 5–7 days. Emerging fungal colonies were subsequently transferred to fresh PDA plates. Pure cultures were established using either the single hyphal tip or single spore isolation technique and preserved on PDA slants for further use (13).

Out of the 12 resulting cultures, nine were identified as *Lasiodiplodia theobromae* (designated LT₁ through LT₉), while three were identified as *C. papayae* (designated CP₁ through CP₃). Notably, the Red Lady variety consistently yielded the highest frequency of both pathogens. The identity of these isolates was verified through detailed microscopic examination, aligning with the taxonomic descriptions established by previous researchers (14–16). Following preliminary pathogenicity assays, the most virulent strains LT₁ and CP₁ were selected for all subsequent experimental trials.

Isolation of bacterial antagonists

Isolation and maintenance of antagonistic bacteria following the standard protocol, beneficial bacterial strains were recovered from the exocarp of papaya fruits (17). Specifically, sections of the fruit peel were immersed in 5 mL of sterile distilled water and subjected to continuous agitation on a rotary shaker for 30 min. A 1 mL aliquot of the resulting suspension was then plated onto nutrient agar (NA) and maintained at an ambient temperature of 28 ± 2 °C for a 48 hr incubation period. Individual colonies were subsequently purified through sub-culturing using the single-colony isolation technique on NA. For long-term preservation, stock cultures were maintained on NA slants and stored under refrigeration at 4 °C.

A total of 9 bacterial isolates were successfully retrieved and characterised in accordance with Bergey's Manual of Systematic Bacteriology. Morphological and physiological assessments revealed that 7 of these isolates belonged to the genus *Pseudomonas fluorescens*; these were designated as Pfp₁, Pfp₂, Pfp₃, Pfp₄, Pfp₅, Pfp₆ and Pfp₇. Likewise, 2 isolates were identified as *Bacillus subtilis* and named as Bsp₁ and Bsp₂ respectively.

In vitro testing of bacterial antagonists

The antagonistic activity of nine bacterial isolates against *L. theobromae* (LT₁) and *C. papayae* (CP₁) was tested by dual culture technique separately (18) using PDA medium. The antagonistic potential of the bacterial isolates was evaluated using the dual culture technique on PDA. Specifically, an 8 mm mycelial plug, sourced from an actively growing 7-day-old culture of either *L. theobromae* or *C. papayae*, was positioned 1.5 cm from the periphery of a Petri dish containing 15 mL of solidified medium. On the opposite side of the plate, at an equivalent distance from the centre, a 48 hr old bacterial culture was applied as a 1 cm linear streak under aseptic conditions. Control treatments consisted of plates inoculated solely with the respective fungal pathogens. All experimental units were maintained at an incubation temperature of 28 ± 2 °C. Following the incubation period, the radial expansion of the fungal colonies was quantified in millimetres. The most proficient biocontrol candidates were identified based on their capacity to significantly suppress the mycelial development of the pathogens compared to the untreated controls. The percent inhibition of mycelial growth as calculated (19).

To determine the biocontrol efficiency of each isolate, the percentage of growth inhibition (I) was calculated using,

$$\text{Percent inhibition (I)} = [(C - T) / C] \times 100$$

In this equation, C represents the radial expansion of the pathogen in the control plates, while T denotes the radial growth observed in the presence of the bacterial antagonist. Based on the results obtained from these dual culture assays, the isolates Pfp₁ and Bsp₁ demonstrated the highest level of inhibitory activity and were consequently selected for all subsequent experimental phases (20).

Inhibitory influence of botanical essential oils on *Lasiodiplodia theobromae* (LT₁) and *Colletotrichum papayae* (CP₁)

solid bioassay

The fungistatic and fungicidal potential of various essential oils against *L. theobromae* and *C. papayae* was determined using the poisoned food assay. The botanical oils were evaluated across a concentration gradient ranging from 0.02–0.1 %. To prepare the treatment media, specific volumes of each oil were incorporated into 50 mL aliquots of molten, sterile PDA to achieve the desired concentrations. The enriched medium was then decanted into sterile Petri dishes and agitated gently to ensure homogenous distribution of the oil throughout the agar.

Control units consisted of PDA medium devoid of any botanical extracts. Each plate was inoculated with an 8 mm mycelial plug, harvested from the actively growing margins of a 7-day-old fungal colony. These experimental units were maintained in an incubator at 28 ± 2 °C for a duration of 7 days. To ensure statistical reliability, the experiment was conducted with 3 independent replicates for each treatment level. All laboratory procedures were performed under strict aseptic conditions to prevent contamination.

Liquid bioassay

To corroborate the findings from the solid media assays, oils that exhibited high efficacy at minimal concentrations were further evaluated in a liquid broth system. For this purpose, 100 mL Erlenmeyer flasks containing 50 mL of potato dextrose broth (PDB) were sterilised via autoclaving at 121 °C for 20 min. The selected botanical oils were introduced into the broth to achieve a concentration gradient of 0.02–1.0 % (v/v). To facilitate the uniform dispersion of the hydrophobic essential oils within the aqueous medium, Tween 80 was incorporated as a surfactant at a concentration of 0.01 %. Additionally, a Tween 80 only treatment (without botanical oil) was maintained as a surfactant control.

The flasks were placed on a rotary shaker at 28 ± 2 °C to ensure thorough homogenisation. Subsequently, an 8 mm mycelial plug of the anthracnose pathogen was aseptically transferred into each flask. After a 7 day incubation period, the resulting fungal biomass was harvested by filtration through pre-weighed Whatman No. 1 filter papers. The recovered mycelia were washed thrice with deionised water to remove residual media and then dried to a constant weight in a hot air oven at 60 °C for 36 hr. The degree of growth suppression was quantified by calculating the percentage of inhibition based on the dry mycelial weight relative to the control, following the standard methodology (21).

$$\text{Percent inhibition (MIC)} = \frac{(C - I) - (T - I) \times 100}{C - I}$$

Where,

T = mean weight of mycelium in the treatments

C = mean weight of mycelium in control

I = mean weight of initial inoculum

The lowest concentration resulting in complete fungal growth inhibition for each treatment was documented. In instances where the essential oils achieved total growth suppression, the fungal plugs were moved to non-amended PDA plates and incubated for an additional 7 days. Subsequently, these discs were immersed in a 1 % 2, 3, 5-triphenyl tetrazolium chloride (TTC) solution for 30 min to evaluate cellular viability.

In vivo efficacy of botanical extracts and biocontrol agents against papaya anthracnose

To determine the effectiveness of essential oils and bacterial biocontrol agents against papaya anthracnose, an *in vivo* assay was performed using 'Red Lady' variety fruits obtained from the field. The fruits underwent thorough washing with tap water, followed by air-drying and surface disinfection using 2 % sodium hypochlorite (NaOCl). To facilitate infection, the fruit surfaces were wounded using a sterile needle via the pin-prick technique. The inoculum was prepared by harvesting conidia from 7-day-old cultures of *L. theobromae* (LT₁) and *C. papayae* (CP₁), which were suspended in sterile distilled water. The spore density was standardised to 10⁵ conidia/mL using a hemacytometer and this suspension was applied to the fruits as a spray. Following a 12 hr stabilisation period, the fruits were monitored, while those inoculated with only sterile distilled water served as the control group. Following the initial phase, the papayas were immersed in various treatment solutions: *P. fluorescens* (Pfp₁) at 0.2 %, *B. subtilis* (Bsp₁) at 0.2 % and *Eucalyptus* oil at 0.05 %. Additionally, a combined consortium was tested, containing both *P. fluorescens* and *B. subtilis* (each at 0.2 %) along

with 0.05 % Eucalyptus oil. For the chemical reference, Thiabendazole was applied at a concentration of 1000 ppm. The trial was maintained at an ambient room temperature of approximately 28 °C, with the treated fruits being incubated for a total of 12 days.

Site selection and field preparation

The trial took place in Karungalpalayam, within the Erode district, to assess the growth and performance of the 'Red Lady' papaya cultivar. Field preparation was initiated three weeks before the scheduled planting. The layout followed a specific spacing of 2.5 m both between individual plants and between rows.

Excavations for the planting holes were standardised at 45 × 45 × 45 cm, which were then enriched with 5 kg of compost integrated with topsoil. One week prior to transplanting, basal fertilisers were added to these holes according to established protocols. The design included 1.5 ft pathways to distinguish between different experimental blocks. Finally, vigorous one-month-old seedlings were sourced from the nursery and established in the designated planting sites.

Preparation of treatment for pretreatment spraying in field condition

Lemongrass oil, citronella oil, palmarosa oil, Eucalyptus oil and geranium oil were procured from commercial suppliers (Table 1). Emulsions of these oils were prepared at a concentration of 1000 µL L⁻¹ in sterile water using Tween 80 (0.05 %) as a surfactant, following the standard methodology (7).

Table 1. Treatment schedule for each block for each treatment

Block/ Stages	Flower bud initiation	Fruit setting	Fruit maturation	Harvesting
A	Yes	No	No	No
B	Yes	Yes	No	No
C	Yes	Yes	Yes	No
D	Yes	Yes	Yes	Yes

Treatment schedule

The experiment consisted of eight treatments to evaluate their efficacy against disease development. T1 comprised application of *P. fluorescens* (PfP1) at 0.2 %, while T2 involved *B. subtilis* (BsP1) at 0.2 %. T3 consisted of a combination of T1 and T2, whereas T4 included application of Eucalyptus oil at 0.05 %. T5 represented the combined treatment of T3 and T4. T6 involved application of the fungicide Thiabendazole at 1000 ppm. T7 served as the inoculated control, while T8 was maintained as the healthy control.

Biological management of anthracnose disease of papaya (without pathogen inoculation)

To remove soil and dust, 'Red Lady' papaya fruits were cleaned with tap water, surface-sterilised using 2 % NaOCl and subsequently rinsed twice with sterile distilled water. Following this, the fruits were subjected to various treatments as outlined in the treatment schedule, without artificial pathogen inoculation, to evaluate the preventive efficacy of biological and botanical treatments against naturally occurring anthracnose infection and to assess their potential role in extending postharvest shelf life under ambient storage conditions. The treatment procedure involved immersing the fruits for 20 min in suspensions of *P. fluorescens* (PfP₁) at 0.2 %, *B. subtilis* (BsP₁) at 0.2 %, or a combined consortium treatment consisting of 0.2 % of each bacterial strain along with 0.05 % Eucalyptus oil. Thiabendazole at 1000 ppm served as the chemical check, while healthy control fruits received sterile distilled water alone without pathogen inoculation or treatment application. After

dipping, the fruits were air-dried for 5 min and stored undisturbed under ambient conditions for 12 days. Each treatment was performed in triplicate. After the 12 day storage period, observations on anthracnose disease incidence, lesion diameter, disease severity, shelf life and fruit quality parameters were recorded and the resulting data were subjected to statistical analysis.

Collection of plant samples

To study induced resistance mechanisms, samples were collected from treated and untreated papaya fruits at different time intervals (1, 3, 6, 9 and 12 days) following artificial pathogen inoculation. This experiment was conducted separately to evaluate the induction of defence-related enzymes in response to pathogen challenge after treatment application.

Enzyme extraction

For the quantification of peroxidase (PO) and polyphenol oxidase (PPO), enzymes were extracted using a 0.1 M sodium phosphate buffer at pH 7.0. One gram of each sample was homogenised with 1 mL of this buffer using a chilled mortar and pestle. The resulting mixture was centrifuged at 15000 rpm for 15 min at 4 °C and the resulting supernatant was collected as the enzyme source. For the determination of phenylalanine ammonia-lyase (PAL) activity, the enzyme extraction was performed using a 0.1 M sodium borate buffer at pH 7.0.

Assay of peroxidase activity (PO)

The assay was conducted using a reaction mixture containing 1.5 mL of 0.05 M pyrogallol, 0.5 mL of the enzyme extract and 0.5 mL of 1 % H₂O₂. This mixture was maintained at an incubation temperature of 28 ± 2 °C. Absorbance fluctuations were measured at 420 nm at 30 sec intervals over a 3 min duration. A blank was prepared using a boiled enzyme sample for comparison. Enzyme activity was subsequently calculated and reported as change in absorbance per minute per gram of fresh tissue weight (22).

Assay of polyphenol oxidase (PPO)

The assessment of PPO activity followed established protocols (23). The assay was prepared by combining 0.2 mL of the enzyme extract with 1.5 mL of 0.1 M sodium phosphate buffer maintained at pH 6.5. To initiate the reaction, 0.2 mL of 0.01 M catechol was introduced. Absorbance shifts were monitored at 495 nm at 30 sec intervals for a total duration of 3 min. The resulting enzyme activity was quantified and reported as the change in absorbance per minute per gram of fresh tissue weight.

Assay of phenylalanine ammonia lyase (PAL)

For the extraction process, one-gram samples were homogenised in one mL of chilled 25 mM borate-HCl buffer (pH 8.8) supplemented with 0.4 mL of 5 mM mercaptoethanol L⁻¹. This mixture was centrifuged at 15000 rpm for 15 min, with the resulting supernatant serving as the enzyme source.

The assay was prepared using 0.2 mL of the enzyme extract, 1.3 mL of water and 0.5 mL of borate buffer (pH 8.8). To start the reaction, 1 mL of 0.1 M L-phenylalanine was added and the mixture was incubated at 32 °C for 1 hr. The process was terminated by adding 0.5 mL of 2 N HCl. For the blank, phenylalanine was introduced only after the addition of the 2 N HCl. Phenylalanine ammonia lyase activity was quantified based on the conversion rate of L-phenylalanine to trans-cinnamic acid, measured at 290 nm. The final activity was reported as µmol of cinnamic acid per minute per gram of fresh tissue weight (24).

Design of the experiment

All treatments were applied at different concentrations to evaluate their effectiveness under a standardised pre-treatment schedule. The experiment included 5 treatments and a control: T1 (lemongrass oil), T2 (citronella oil), T3 (palmarosa oil), T4 (Eucalyptus oil), T5 (geranium oil) and T6 (control, distilled water). Treatments were administered at 4 distinct fruit development stages (Blocks A, B, C and D), corresponding to specific application timings. Each treatment was applied separately at the designated fruit development stages, covering various stage combinations. A randomised complete block design (RCBD) was implemented following a two-factor factorial arrangement with three biological replicates. The experimental site comprised 90 plants, divided into 3 replicates, with each replicate containing 30 plants subjected to the 6 selected treatments (including the control) according to the pre-treatment schedule. Individual plants served as the experimental units. Block A received a single application at one fruit development stage, Block B received 2 applications at different developmental stages, Block C received 3 applications and Block D received applications at all 4 fruit development stages (2²). Statistical analyses were carried out using IRRISTAT software (version 92-1), developed by the Biometrics Unit at the International Rice Research Institute (IRRI), Philippines (25). The data were subjected to analysis of variance (ANOVA) and treatment means were compared using Duncan's multiple range test (DMRT) at a significance level of $p \leq 0.05$.

Results and Discussion

Market survey for anthracnose disease in the common cultivation of papaya (2022–23)

The systemic survey conducted during the year 2022–23 in retail markets of Chidambaram, Peelamedu, Karur, Tiruchengode and Salem revealed that the percent disease index (PDI) ranged from 11.00–20.33 in papaya fruits. Among 3 varieties surveyed, of the 3 varieties surveyed, Red Lady recorded a higher anthracnose incidence in all retail markets and recorded maximum of 20.33 PDI in Chidambaram retail market followed by Co-1 16.72 %. The variety Co-2 recorded least disease index of 11.00 % (Table 2). Anthracnose symptoms observed in infected papaya fruits initially appeared as small, circular dark spots on the ripening regions, which progressively enlarged into slightly depressed, water-soaked lesions with distinct dark margins and blackened centres. Under high-humidity conditions, pinkish conidial masses were observed on the lesion surface, often arranged in concentric rings (Fig. 1–3).

Field and market survey revealed that the endemic nature of anthracnose disease incidence ranging from 11.10–43.67 % of leaf infection and 10.00–24.60 of fruit infection, respectively (26). However, anthracnose rot attains serious status during transit, storage and market causing considerable economic losses (27). The variation in the extent of the disease incidence observed in the present study might be due to the prevalence of the isolates of the pathogen differing in their virulence. In all the market surveyed the var. Red Lady was found to be highly susceptible to anthracnose

Table 2. Market survey and isolation of pathogen associated with papaya anthracnose disease (2022–23)

District	Market locality	Variety	Percent disease index (%)	Isolate number	
				<i>Lasiodiplodia theobromae</i>	<i>Colletotrichum papaya</i>
Cuddalore	Chidambaram	Red Lady	20.33 ^f (26.80)	LT ₁	CP ₁
		Co-1	16.72 ^e (24.13)	LT ₂	-
Coimbatore	Peelamedu	Red Lady	16.66 ^e (24.08)	LT ₃	-
		Co-3	14.33 ^{cd} (22.24)	LT ₄	-
Karur	Karur	Red Lady	12.32 ^b (20.54)	LT ₅	CP ₂
Namakkal	Tiruchengode	Red Lady	18.62 (25.56)	LT ₆	-
		Co-2	11.00 ^a (19.36)	LT ₇	-
Salem	Salem	Red Lady	18.00 (25.10)	LT ₈	CP ₃
		Co-1	13.66 ^c (21.69)	LT ₉	-

Mean of three replications. Values in each column followed by the same letter are not significantly different according to DMRT method ($p = 0.05$).

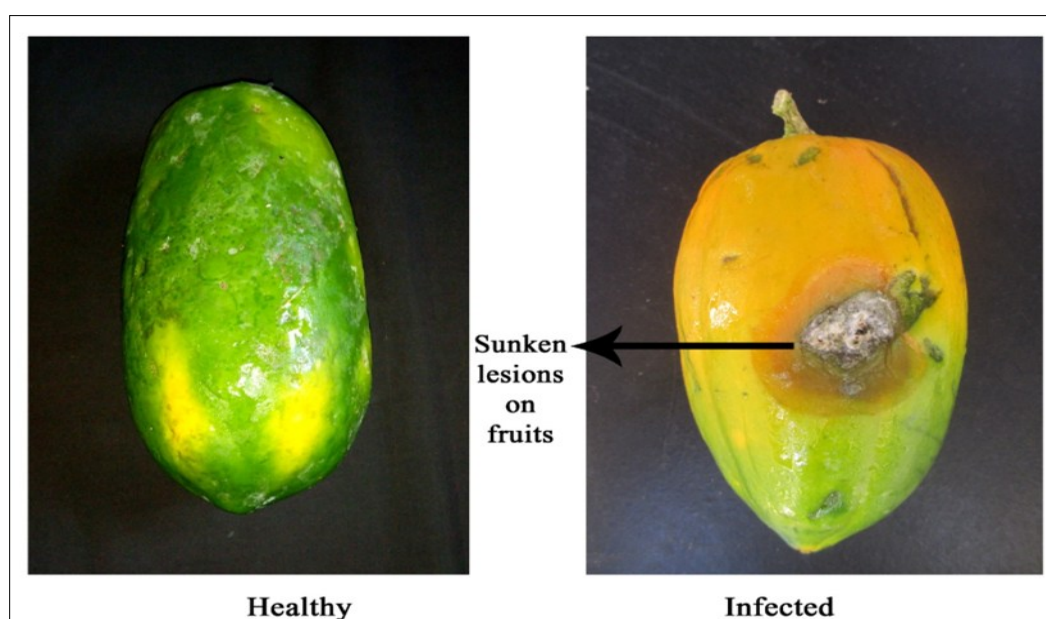


Fig. 1. Symptoms of papaya anthracnose.

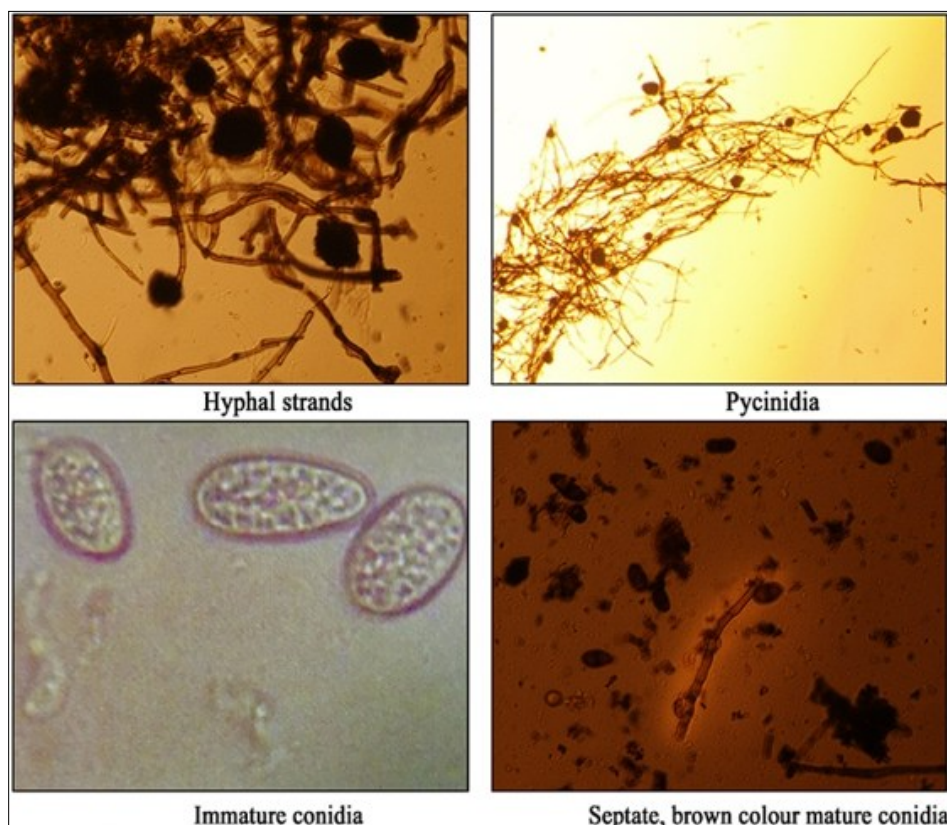


Fig. 2. Culture characteristics of *Lasiodiplodia theobromae*.

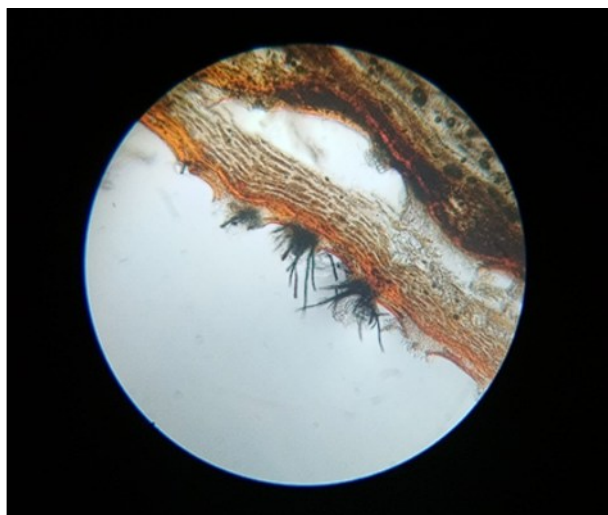


Fig. 3. Culture characteristics of *Colletotrichum papayae*.

which was followed by CO-1. At retail and consumer level the papaya fruits were in the stage of ripening or fully ripe stage. Hence, this type of disease incidence may be due to the decline in the fungal inhibitors in fruits during the ripening process (28).

Isolation of pathogens associated with papaya anthracnose

Pathogen isolation from various infected papaya cultivars showed that both *L. theobromae* and *C. papayae* were present in the 'Red Lady' variety sourced from the Chidambaram and Peelamedu markets. In contrast, only *L. theobromae* was recovered from the Co-1, Co-2 and Co-3 varieties. Consequently, the 'Red Lady' cultivar was selected for all further experimental trials (Table 2).

In the present study, the pathogenicity test reproduced typical anthracnose symptoms in papaya fruits, characterised by water-soaked, sunken lesions with dark margins, followed by the development of pinkish spore masses arranged in concentric rings, ultimately leading to fruit rot (Fig. 4). Similar symptom expression in

papaya anthracnose has been reported by previous researchers, who described the disease as initially appearing as small water-soaked lesions that gradually enlarge into sunken necrotic areas with concentric sporulation under humid conditions (29, 30). The consistency between the symptoms observed in the present study and earlier reports confirms the pathogenic potential of the isolated fungal species associated with papaya anthracnose.

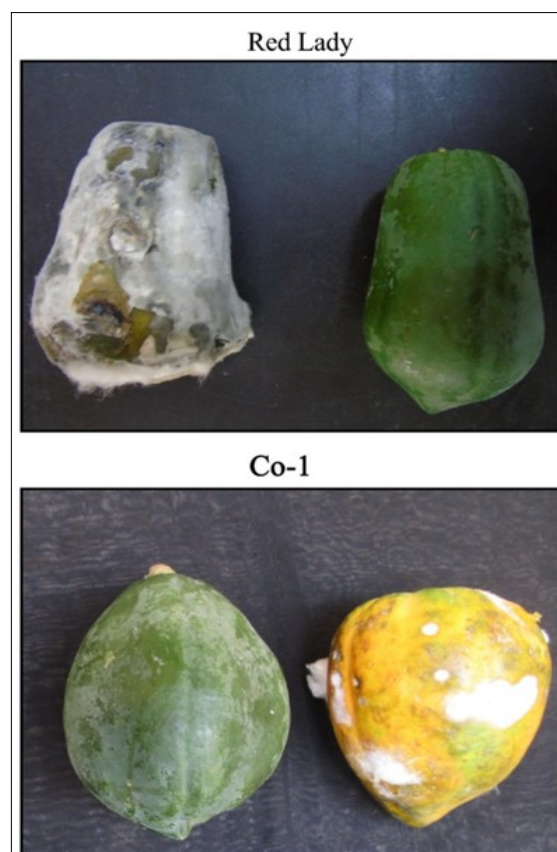


Fig. 4. Pathogenicity on papaya fruit.

In vitro inhibition of mycelial growth of *Lasiodiplodia theobromae* (LT₁) and *Colletotrichum papayae* (CP₁) by selected bacterial isolates

All nine bacterial isolates exhibited diverse levels of antagonistic activity against both *L. theobromae* and *C. papayae* (Fig. 5 and 6). Among the candidates, isolate PfP1 demonstrated the highest efficacy, producing an inhibition zone of 11.00 mm and restricting the mycelial growth of *L. theobromae* to just 28.33 mm. This represents a 67.68 % reduction in growth compared to the control.

Similarly, PfP1 achieved an 11.67 mm inhibition zone against *C. papayae*, with a minimum mycelial growth of 21.33 mm, resulting in a 75.94 % reduction over the control. The isolate BsP₁ followed PfP₁ in terms of effectiveness. In a parallel evaluation of five established biocontrol agents using the dual culture technique, *P. fluorescens* and *B. subtilis* showed potent antagonism toward *L. theobromae*, suppressing mycelial development by 75.83 % and

70.50 %, respectively (31). The significant inhibition of *B. theobromae* was achieved through the application of *P. fluorescens* and *B. subtilis* (32). Among these, *B. subtilis* demonstrated the greatest suppressive effect against *L. theobromae*, producing an inhibition zone of 0.71 cm. In comparison, *P. fluorescens* also significantly restricted the pathogen's development, yielding an inhibition zone of 0.42 cm. All the three bacterial isolates showed varying degree of antagonism against *C. papayae*. Among the antagonists tested in this study, *Bacillus* sp. (BSP1) showed the high level of suppression of *C. papayae* (papaya anthracnose) (47.83 %) followed by BSP2 which recorded 46.83 %. The biocontrol agents *Bacillus* spp. significantly inhibited the growth of *Colletotrichum* by producing clear inhibition zone than sp. (33). Among all the microbial biological control agents (MBCAs) *B. subtilis* LB22 showed highest inhibition (85.00 %) on mycelial growth of *Colletotrichum capsici* followed by *P. fluorescens* (84.33 %) and *Bacillus vallismortis* (83.22 %). Several bacterial bioagents evaluated under *in vitro* conditions against the mycelial

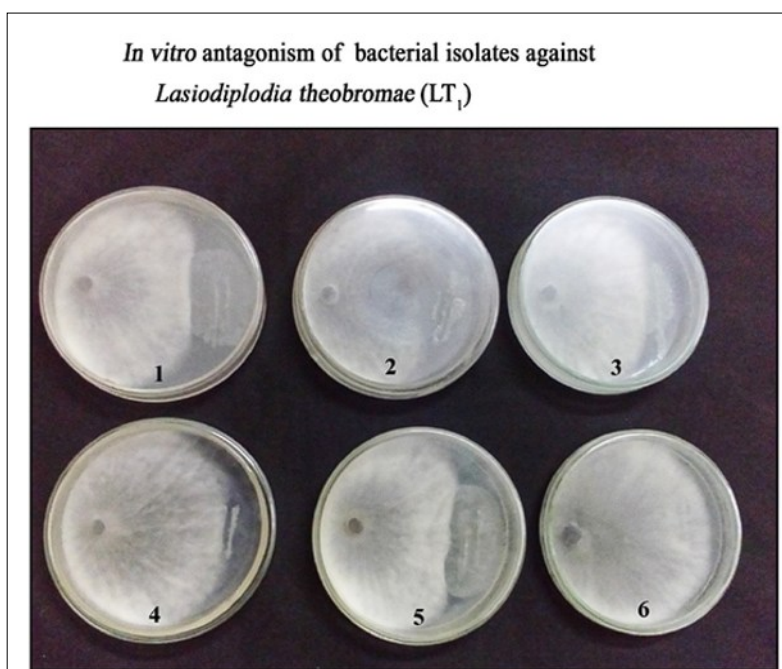


Fig. 5. *In vitro* antagonism of bacterial isolates against *Lasiodiplodia theobromae*.

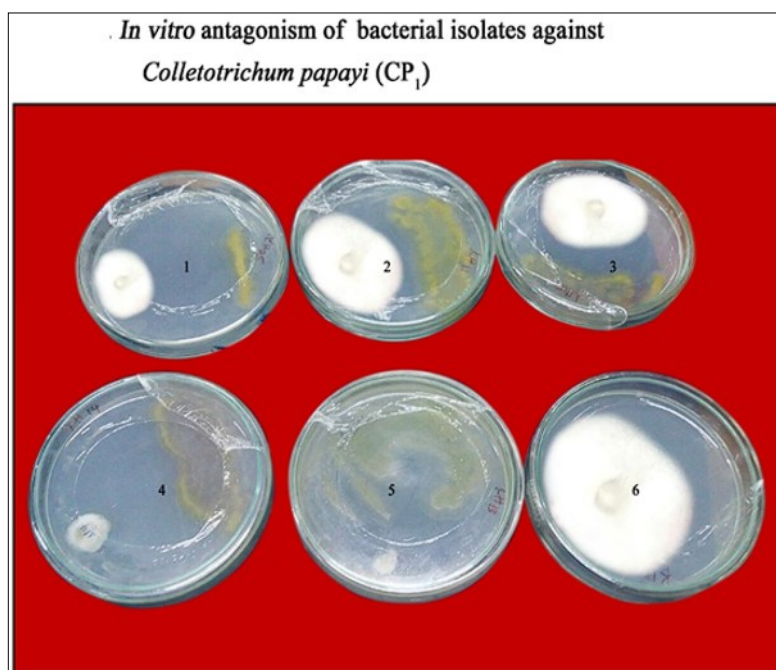


Fig. 6. *In vitro* antagonism of bacterial isolates against *Colletotrichum papayae*.

growth of *Colletotrichum gloeosporioides* revealed that bacterial bioagents viz., UHSBS-1 showed maximum inhibition of mycelial growth followed by UHSBS-9 and UHSBS-21 isolates of *B. subtilis* (34). Among the 74 bacterial endophytes isolated from healthy chilli plants, *Bacillus amyloliquefaciens* (ENLB 4) exhibited the most pronounced antagonistic effect against the chilli anthracnose pathogen *Colletotrichum acutatum*. *In vitro* tests revealed that ENLB 4 inhibited the pathogen's growth by 56.43 % (35).

The synthesis of siderophores and the secretion of chitinases represent two key mechanisms that likely contribute to the efficacy of biological control agents. Indeed, it is known that chitinolytic activity and siderophore production, solubilising phosphate and producing Indole-3-acetic acid (IAA) are correlated with antifungal activity against *L. theobromae* and *C. papayae* (36, 37).

Furthermore, *Pseudomonas* species are recognised for their ability to synthesise a wide array of broad-spectrum antibiotics, such as phenazine, which is produced by specific *Pseudomonas* strains. B-109 in tomato (38). 2, 4-diacetylphloroglucinol (2,4-DAPG) by *Pseudomonas* sp. 28r/96 in wheat (39). Pyoluteorin by *P. fluorescens* CHAO in tobacco, Pyrrolnitrin by *P. fluorescens* BL 915 in cotton (40). Viscosinamide by *P. fluorescens* D1254 in sugarbeet (41) and Zwittermycin A by *B. cereus* UW in alfalfa (42) which proved to be a major mechanism involved in their biocontrol activity. The presence of surfactins, iturin and fengycin in the culture filtrates of *B. subtilis* and *B. amyloliquefaciens* which were previously reported to inhibit spore germination of certain plant pathogens may be responsible for the strong antagonistic activity against *C. acutatum* (42). All these earlier results lend support to the present findings.

In vitro inhibition of plant oils against *Lasiodiplodia theobromae* (LT₁) and *Colletotrichum papaya* (CP₁)

Among the eight plant oils evaluated, *Eucalyptus* oil exhibited superior antifungal efficacy against both *L. theobromae* and *C. papayae* under *in vitro* conditions. *Eucalyptus* oil recorded the lowest minimum inhibitory concentration (MIC) of 0.05 % against *L. theobromae*, followed by lemongrass oil (0.06 %). Similarly, against *C. papayae*, *Eucalyptus* oil showed a minimum inhibitory concentration (MIC) of 0.05 % and minimum lethal concentration (MLC) of 0.1 %, whereas lemongrass oil exhibited the next best performance (MIC: 0.06 %; MLC: 0.08 %) (Table 3, 4). Therefore, *Eucalyptus* oil was selected for subsequent compatibility and integrated disease management studies owing to its comparatively superior antifungal performance. (Fig. 7 and 8). Similarly, the essential oils viz., thyme oil, *Eucalyptus* oil, lemongrass oil (each at 0.05 and 0.1 %) and cinnamon oil at 0.1 % concentration was highly effective against *C. capsici* which was followed by cinnamon oil (88.51 %), neem oil (55.55 %), winter green oil (66.66 %) with the maximum percent mycelial growth inhibition over the untreated control (43).

However, in contrast to the present study reported that palmarosa oil, tulsi oil, geranium oil and lemongrass oil showed antifungal activities (*L. theobromae* and *Collectotrichum musae*) even at the least concentration of 0.04 % under *in vitro* condition (44). The lemongrass oil was found to be more effective and caused complete growth inhibition of *L. theobromae* even at 0.005 % concentration (45). Cinnamon oil, at concentrations of 0.05 % and 0.1 %, proved most effective at restricting the mycelial development of *Gloeosporium papayi* compared to the control. Additionally, essential oils from cardamom and citronella demonstrated significant ($p < 0.05$) inhibition of the mycelial growth of

Table 3. *In vitro* inhibition of mycelial growth of *Lasiodiplodia theobromae* (LT₁) and *Colletotrichum papayae* (CP₁) by bacterial isolates

Isolates	<i>Lasiodiplodia theobromae</i>			<i>Colletotrichum papayae</i>		
	Mycelial growth (mm)	Percent Inhibition over control (%)	Inhibition zone (mm)	Mycelial growth (mm)	Percent Inhibition over control (%)	Inhibition zone (mm)
PfP1	28.33 ^a	67.68	6.76	21.33 ^a	75.94	11.67
PfP2	31.33 ^c	64.25	6.35	28.66 ^c	67.67	7.86
PfP3	37.00 ^f	57.79	5.68	30.33 ^d	65.79	7.01
PfP4	34.33 ^d	60.83	6.08	33.00 ^e	62.77	7.67
PfP5	38.66 ^g	55.89	5.02	36.66 ^f	58.65	6.23
PfP6	36.66 ^e	58.17	5.81	55.00 ^h	37.96	5.33
PfP7	32.00 ^c	63.49	6.34	28.67 ^c	67.66	8.33
BsP1	29.66 ^b	66.16	6.61	25.33 ^b	71.43	9.67
BsP2	34.12 ^d	61.07	6.46	38.26 ^g	56.84	6.02
Control	87.66 ^h	87.66	-	88.66 ⁱ	-	-

Mean of three replications. Values in each column followed by the same letter are not significantly different according to the DMRT method ($p = 0.05$).

Table 4. *In vitro* inhibition of plant oils against *Lasiodiplodia theobromae* (LT₁)

Sl. No	Plant oils	<i>Lasiodiplodia theobromae</i>		<i>Colletotrichum papayae</i>	
		Minimum inhibitory concentration (MIC)	Minimum lethal concentrations (MLC)	Minimum inhibitory concentration (MIC)	Minimum lethal concentrations (MLC)
1	Lemongrass oil	0.06	0.08	0.06	0.06
2	Citronella oil	0.1	0.1	0.08	0.1
3	Palmarosa oil	0.06	0.06	0.06	0.06
4	<i>Eucalyptus</i> oil	0.05	0.1	0.05	1.0
5	Geranium oil	0.06	0.08	0.06	0.06
6	Pungam oil	No control	No control	No control	No control
7	Gingelly oil	No control	No control	No control	No control
8	Castor oil	No control	No control	No control	No control

Mean of 3 replications; Values in each column followed by the same letter are not significantly different according to the DMRT method ($p = 0.5$).

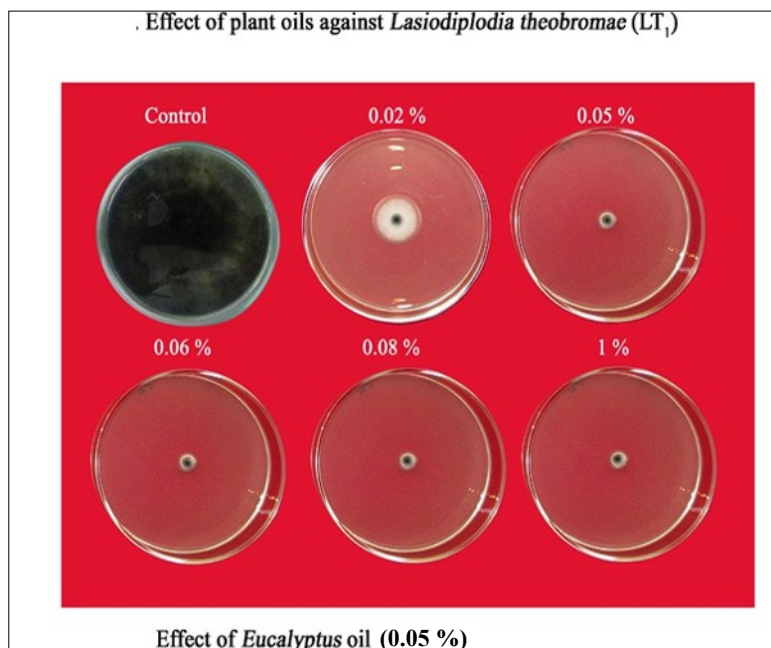


Fig. 7. Effect of plant oil against *Lasiodiplodia theobromae*.

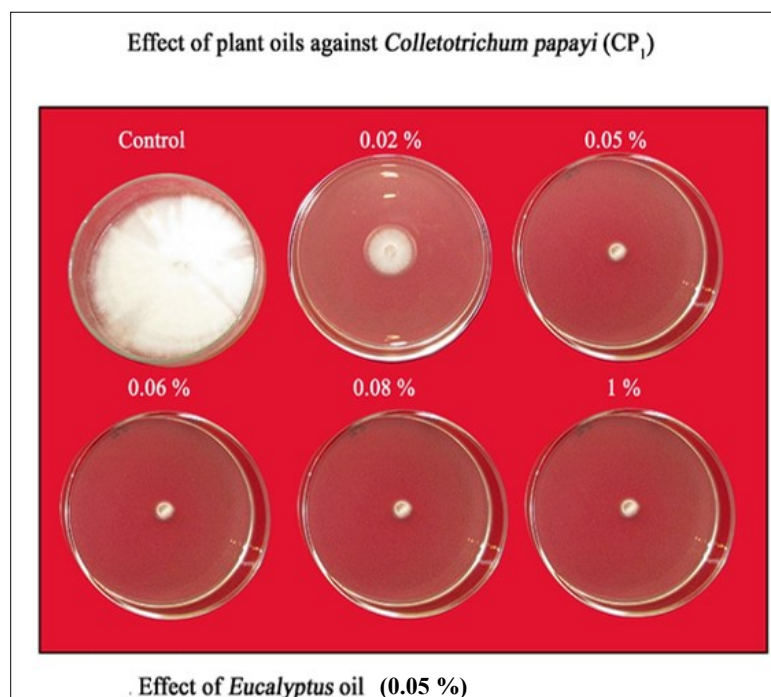


Fig. 8. Effect of plant oil against *Colletotrichum papayae*.

Colletotrichum sp. compared with the other essential oils tested (44). Cinnamon oil at 200, 400, 800 and 1000 ppm concentration showed complete inhibition of *C. gloeosporioides* even after 9 days after incubation. Among different plant oils tested, lemongrass oil at 15 % concentration resulted in complete inhibition of *C. gloeosporioides* which was followed by lemongrass oil at 10 % concentration (98.23 %). Minimum percent inhibition was recorded with Eucalyptus at 5 % concentration (39.81 %) (46).

The antimicrobial activity of the oil was concentration-dependent, with different microorganisms exhibiting varying levels of sensitivity. The primary antifungal constituents identified in Eucalyptus oil included 1,8-cineole (16.2 %), alpha-pinene (15.6 %), alpha-phellandrene (10.0 %) and p-cymene (8.1 %), which are largely responsible for suppressing *L. theobromae* and *C. papayae*. The proposed mechanism of action involves disrupting the fungal cell membrane leading to structural damage, leakage and subsequent cell death as well as obstructing membrane synthesis and inhibiting

spore germination, fungal growth and cellular respiration. Because of high volatility and lipophilicity of the essential oils, they are readily attached to penetrate into the cell membrane to exert their biological effect (33, 46) According to their results, concentrations of plant essential oils are direct effect on fungal growth of pathogens. Higher concentrations of essential oils can inhibit maximum fungal growth. The mechanism of plant essential oils involves, inhibition of hyphal growth, interruption in nutrient uptake, disruption of mitochondrial structure and eventually disorganisation of fungal pathogens (46). The above results lend support to the present investigations.

Effect of post-harvest dipping of plant oils and antagonists against papaya anthracnose

In the present investigation, post-harvest dipping of papaya fruits in a combined treatment consisting of Eucalyptus oil (0.05 %) + *P. fluorescens* (PfP₁) at 0.2 % + *B. subtilis* (BsP₁) at 0.2 % (T₅) completely suppressed disease development up to 8 days after

inoculation (DAI), resulting in a 91.27 % reduction in disease incidence compared to the control. This was followed by T₃, comprising *P. fluorescens* (PfP₁) at 0.2 % + *B. subtilis* (BsP₁) at 0.2 %, which recorded 91.66 % disease reduction over the control at 8 DAI. The inoculated control recorded the maximum disease index of 76.33 % (Table 5; Fig. 9).

However, in contrast, the present study showed that the treatment of banana fruit var. Robusta (Cavendish-AAA) with oils of *Ocimum Sanctum* L., *Cymbopogon citrate* (DC.) Stapf, *Cymbopogon nardus* (L.) Rendle and *Cymbopogon martini* (Roxb.) W. Watson not only reduced the crown rot severity (*C. musae* and *L. theobromae*) significantly, but also increased the shelf life of banana fruits (47). Early researchers stated that ‘Sekaki’ papaya were exposed to lemongrass oil fumigation (0, 7, 14, 28 $\mu\text{L L}^{-1}$) for 18 hr and at room temperature for 9 days (7). Lemongrass oil vapour, applied at a concentration of 28 $\mu\text{L L}^{-1}$, demonstrated the highest efficacy in controlling anthracnose on artificially inoculated papaya fruit. Notably, this treatment suppressed the disease without causing any significant alterations to the fruit's quality parameters. Coatings formed by synergistic chitosan (5 mg/mL) and *C. citrate* oil (0.15, 0.3 or 0.6 $\mu\text{L mL}^{-1}$) combination decreased anthracnose lesion development in guava, mango and papaya inoculated with *Colletotrichum* species during storage (48). Immersion of the fruits in 0.1 % cinnamon oil was found to completely suppress disease development at 8 DAI, achieving a 95.44 % reduction in disease incidence compared to the control in papaya. These earlier reports are in line and lend support to the results observed in the present study (48).

Biological management of papaya anthracnose by post-harvest dipping with plant oils and antagonists

In the present study, among the various treatments, Treatment T₅ (*Eucalyptus* oil 0.05 % + *P. fluorescens* (PfP₁) 0.2 % + *B. subtilis* (BsP₁) 0.2 %) recorded the minimum disease index (2.04 %) and the highest disease reduction (95.75 % over the control) at 12 days after storage.

This was followed by T₃, which recorded a disease index of 4.00 % and 91.66 % disease reduction over the control. In contrast, the control treatment recorded the highest disease incidence and disease index (Table 5; Fig. 9).



Fig. 9. Biological management of papaya anthracnose.

Table 5. Effect of selected plant oils and bacterial antagonist against anthracnose of papaya by post-harvest fruit dipping method

Treatment No.	Treatments	With pathogen inoculation		Without pathogen inoculation				
		Percent disease index (PDI)	Disease reduction over control	Percent disease index (%)				Disease reduction over control (%)
				4	7	9	12	
T ₁	<i>Pseudomonas fluorescens</i> (PfP ₁) at 0.2 %	12.00 ^d (20.26)	84.27	0.00	0.00	0.00	6.00 ^c (14.17)	87.5
T ₂	<i>Bacillus subtilis</i> (BsP ₁) at 0.2 %	14.33 ^e (22.24)	81.22	0.00	0.00	0.00	7.33 ^d (15.70)	84.72
T ₃	<i>Pseudomonas fluorescens</i> (PfP ₁) + <i>Bacillus subtilis</i> (BsP ₁) each at 0.2 %	8.00 ^b (16.42)	89.51	0.00	0.00	0.00	4.00 ^b (11.53)	91.66
T ₄	<i>Eucalyptus</i> oil at 0.05 %	10.66 ^c (19.05)	86.03	0.00	0.00	0.00	7.00 ^d (15.34)	85.41
T ₅	T ₃ + T ₄	2.66 ^a (9.38)	96.51	0.00	0.00	0.00	2.04 ^a (8.21)	95.75
T ₆	Thiabendazole (1000 ppm)	2.50 ^a (9.09)	96.72	0.00	0.00	0.00	1.90 ^a (7.92)	97.5
T ₇	Inoculated control	76.33 ^f (60.88)	-	0.00	0.00	0.00	48.00 ^f (43.85)	-
T ₈	Healthy control	10.66 ^c (19.05)	-	0.00	0.00	0.00	8.23 ^e (16.67)	-

Mean of three replications; Values in each column followed by the same letter are not significantly different according to the DMRT method ($p = 0.05$); DAI: days after incubation.

However, in contrast to the present study reported that absolute fungitoxicity of oil of *Mentha arvensis* L. (at 500 ppm) against *Aspergillus flavus* and *Fusarium moniliforme*, two dominant post-harvest pathogens of papaya (31). The oil exhibited prophylactic activity; protected stored papaya at 800 ppm and increased shelf life up to 2 days more than control and pesticide treated fruits. Oliveira used a fruit coating of mesquite gum impregnated with *Citrus aurantifolia* (Christm.) Swingle and *Thymus vulgaris* L. oil (1–5 %) there was 50 % reduction in papaya fruit decay (48). Dipping the fruits in cinnamon oil (0.1 %) recorded minimum disease incidence in papaya. Synergistic combination of chitosan and *Mentha piperita* L. essential oil to reduce the severity of anthracnose lesions in mango infected with different pathogenic *Colletotrichum* species (4).

The bioagents treated fruits, bacterial bioagents *P. fluorescens* and *B. subtilis* were most effective in reducing the mango anthracnose symptoms on fruits and recorded the minimum PDI (%) of 37.70 % and 33.81 % at 10th day of inoculation in fruit dip method (49). In the fruits treated with biocontrol agents and challenged with the pathogen *C. papayae*, the bacterial antagonists *P. fluorescens* and *B. subtilis* recorded significantly lower PDI values of 38.00 % and 35.15 %, respectively, by the 10th day after inoculation. In comparison, the untreated control fruits reached a PDI of 86.33 % under the same challenge inoculation conditions. The seedling treatment with *Trichoderma viride* plus *P. fluorescens* plus neem oil at 5 % showed the most significant results with maximum growth parameters and minimum onion leaf blotch intensity followed by *T. viride* plus *P. fluorescens* plus neem oil at 5 % (39). The above results lend support to the present findings.

Induction of systemic resistance by selected bacterial antagonist and plant oils

Changes in peroxidase (PO) activity

In the present study, post-harvest fruit dipping with *Eucalyptus* oil at 0.05 % + *P. fluorescens* (PfP₁) at 0.2 % + *B. subtilis* (BsP₁) at 0.2 % and the challenge-inoculated samples exhibited a more pronounced induction of peroxidase (PO) activity compared to those treated solely with antagonistic bioformulations or the pathogen alone. This indicates that the interaction between the biocontrol agents and the pathogen triggered a synergistic or primed defensive response within the plant. T₅ shows the highest absorbance across most time

intervals, indicating the most effective treatment under these conditions (Fig. 10). Accumulation of peroxidase has been correlated with induced systemic resistance in several crops (50, 51).

Peroxidases have been implicated in a number of physiological functions that may contribute to resistance including exudation of hydroxyl cinnamyl alcohol into free radical intermediates, phenol oxidation (52), polysaccharide cross linking (53), cross linking of extension monomers and lignification's and also correlated with deposition of phenolic materials into plant cell walls during resistant interactions (54). The banana fruits treated with three-way antagonist mixture viz., NFP₆ + PF₃ + BS₁ recorded maximum induction of PO activity (47). Peroxidase activity was significantly elevated in inoculated mango fruits treated with a combination of 0.5 % *P. fluorescens* (Pf1) and 2 % hexanal. This was followed by the treatment involving a post-harvest dip of 0.5 % *P. fluorescens* (Pf1) alone. Both treatments showed markedly higher enzyme induction compared to the inoculated control when challenged with *L. theobromae*. The increased activity was observed up to 3 days after treatment and thereafter gradually decreased (51). The maximum increase in peroxidase activity was observed on third days with a change in absorbance value of 2.235 in peel and 1.798 in pulp at 490 nm when papaya fruits treated with pre-harvest spray with sp. (BSP1) (5 %) + *Bacillus* post-harvest dipping with cinnamon oil (0.1 %) (55).

Changes in polyphenol oxidase activity

The results of this study demonstrated that PPO activity was progressively enhanced across all treatments. The most significant induction of enzyme activity was observed in fruits treated with a dip of *Eucalyptus* oil (0.05 %) + *P. fluorescens* (PfP₁) at 0.2 % + *B. subtilis* (BsP₁) at 0.2 % and challenge inoculated with the pathogen. T₅ exhibits the highest absorbance values across all treatments, peaking on day 7. The combination of microbial agents and eucalyptus oil appears to produce a robust synergistic effect, amplifying biochemical activity significantly (Fig. 11). Enhanced PPO activity due to the application of bio-control agents have been reported earlier by several researchers (56).

The activity of PPO increased significantly in both the peel and pulp of papaya fruits subjected to different treatments. Among the treatments, the highest PPO activity in the peel tissue (0.625 change in absorbance min⁻¹ g⁻¹ fresh tissue) was observed on the

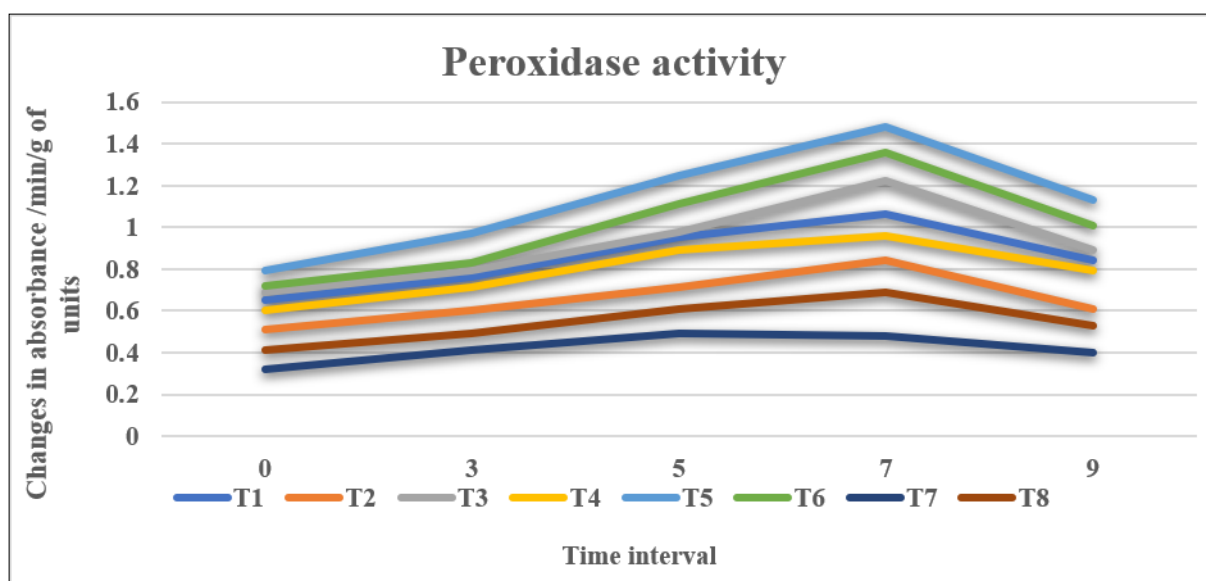


Fig. 10. Changes in peroxidase (PO) activity.

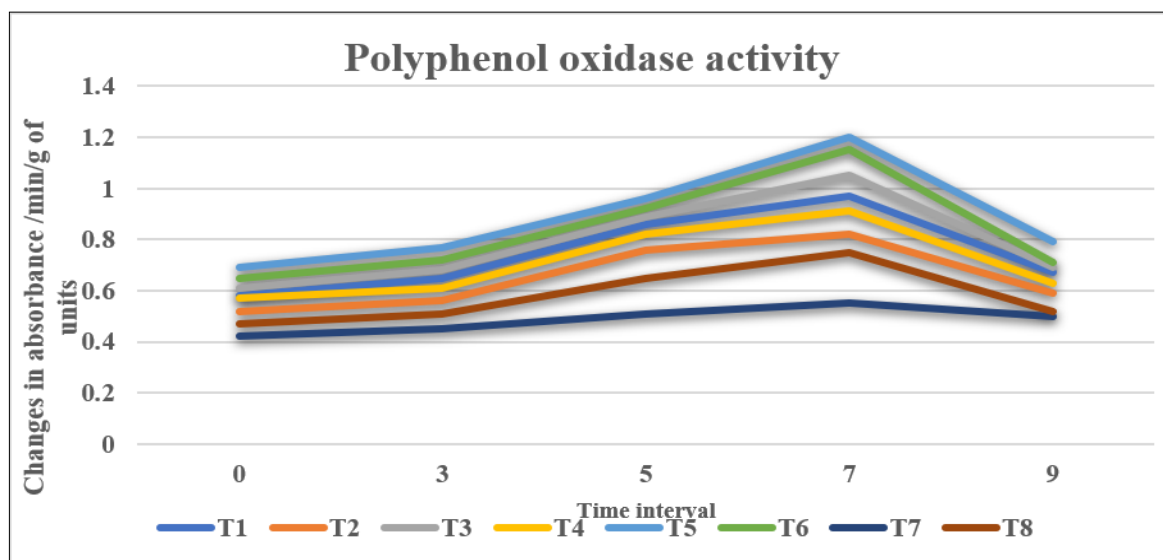


Fig. 11. Changes in polyphenol oxidase (PPO) activity.

third day after inoculation in fruits treated with pre-harvest spray of *Bacillus* sp. (BSP1) (5 %) combined with postharvest dipping in cinnamon oil (0.1 %). This was followed by the treatment comprising pre-harvest spray of *Bacillus* sp. (BSP1) (5 %) along with postharvest dipping in emulsifiable concentrate (EC)-formulated thyme oil (0.1 %), which recorded an absorbance value of 0.590 (57). The induction of defence-related enzymes (PO and PPO) and enhanced disease resistance in maize against *Fusarium verticillioides* by seed treatment with *Jacaranda mimosifolia* D. Don (38). The soil application (SA) of *T. viride* (T.v) at 2.5 kg/ha at 20 DAP plus soil drenching (SD) of carbendazim at 0.1 % at 30 DAP plus SA of *T. viride* at 2.5 kg/ha at 50 DAP plus foliar application (FA) of *P. fluorescens* at 1.0 kg/ha at 70 DAP plus FA of *B. subtilis* at 1.0 kg/ha at 90 DAP was found to be significantly best in induction of PO and PPO in crossandra plants (36). The above results lend support to the present findings.

Changes in phenylalanine ammonia lyase activity

In the present study, higher activity of phenylalanine ammonia lyase (PAL) was observed in fruits dipped in *Eucalyptus* oil (0.05 %) + *P. fluorescens* (PFP₁) at 0.2 % + *B. subtilis* (BsP₁) at 0.2 % and challenge inoculated with the pathogen and pathogen alone inoculated plants. T₅ exhibits the highest absorbance across all intervals, peaking at 120.45 (day 7). The high sustained activity (97.31 on day 9) highlights robust synergistic interactions, making

this the most effective treatment (Fig. 12). A perusal of literature showed that several numbers of publications are available on the increased activity of PAL in bio-control inoculated plants challenge inoculated with the pathogens.

Phenylalanine ammonia-lyase (PAL) is a fundamental enzyme in the biosynthesis of phenols and phytoalexins. An increase in PAL activity signifies the activation of the phenylpropanoid pathway. The primary product of this enzymatic reaction is trans-cinnamic acid, which serves as the immediate precursor for the biosynthesis of salicylic acid, a critical signalling molecule that regulates systemic acquired resistance (SAR). The PAL activity could be induced in plant-pathogen interactions and fungal elicitor treatment (58). Biocontrol treatment against *Colletotrichum* in papaya induced PAL activity, indicating stimulation of host defence metabolism. The increased PAL may have promoted phenolic compound accumulation and strengthened resistance, contributing to lower anthracnose development (59). Induction of PAL by fluorescent *Pseudomonas* was reported in sugarcane against *Colletotrichum falcatum*, in cucumber against *Pythium aphanidermatum* and in tomato against *Fusarium oxysporum* f.sp. *lycopersici* (60). This is accordance with findings of combined application of talc based formulation of bioagents and challenge inoculated with *P. aphanidermatum* showed four to five fold increased activity of PAL when compared to uninoculated control (56).

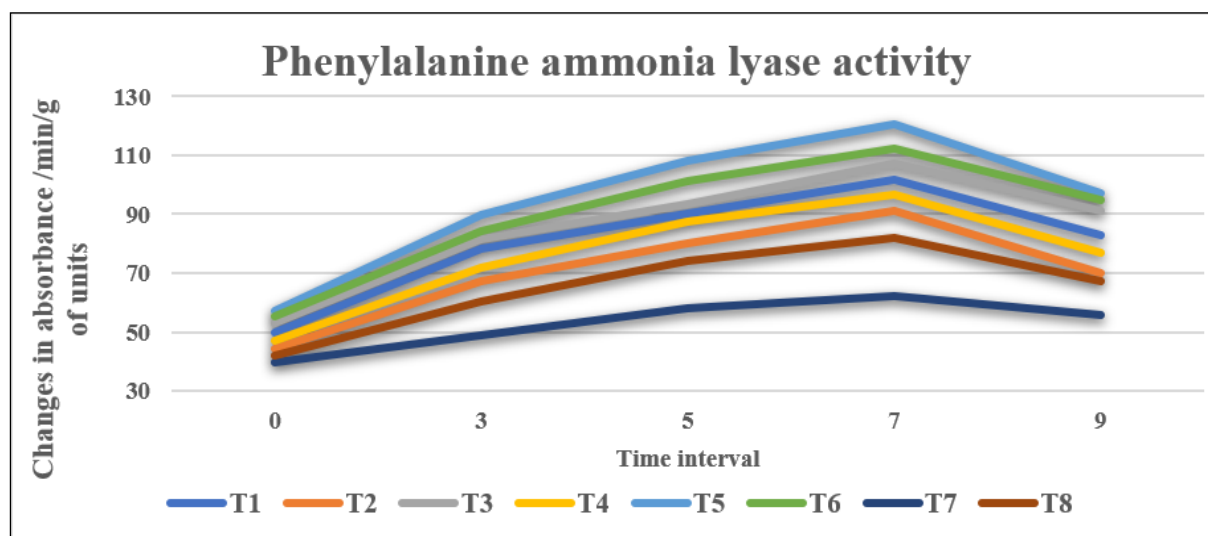


Fig. 12. Changes in phenylalanine ammonia lyase (PAL) activity.

Cowpea plants treated with a combination of seed and soil applications of *P. fluorescens* (at 10 g/kg and 2.5 kg/ha, respectively) along with a soil application of neem oil cake at 0.25 t/ha (T6) demonstrated the highest levels of defence-related enzyme activity when challenged with the pathogen. This treatment significantly induced the production of PO, PPO and PAL, as well as the accumulation of total phenols (57). The SA of *T. viride* at 2.5 kg/ha at 20 DAP plus soil drenching (SD) of carbendazim at 0.1 % at 30 DAP plus SA of *T. viride* at 2.5 kg/ha at 50 DAP plus FA of *P. fluorescens* at 1.0 kg/ha at 70 DAP plus FA of *B. subtilis* at 1.0 kg/ha at 90 DAP was found to be significantly higher in induction of PAL activity (56).

The results indicated that the lowest disease severity index (DSI) of 18.77 was observed in the treatment with *Eucalyptus* oil in Block C, where spraying was conducted 3 times during key fruit developmental stages: flower bud initiation, fruit setting and fruit maturation (Table 6). Similarly, a minimum DSI was reported of 6.67 following the application of *Lantana camara* L. leaf extract at the same three fruit developmental stages (61). Comparable findings were also documented in early results (62). Collectively, the elevated PAL activity observed in treated fruits suggests activation of the phenylpropanoid defence pathway, which may have contributed to enhanced systemic resistance and suppression of anthracnose development following application of antagonistic bacteria and botanical oils, corroborating earlier findings on the protective role of essential oil-mediated host defence responses against *Colletotrichum* infection (63). The anthracnose disease in papaya originates as a pre-harvest quiescent infection, which becomes active under humid conditions. The pathogen remains latent until fruit ripening, at which point symptoms become visible on the peel (60). Given these observations, the pre-harvest application of *Eucalyptus* oil at three critical developmental stages is expected to be highly effective in reducing the incidence of papaya anthracnose.

Conclusion

The present study demonstrated that an integrated approach involving botanical oils and bacterial antagonists' offers an effective and sustainable strategy for the management of postharvest anthracnose disease in papaya. Among the treatments evaluated, the combined application of *Eucalyptus* oil (0.05 %) + *Pseudomonas fluorescens* (PfP₁) at 0.2 % + *Bacillus subtilis* (BsP₁) at 0.2 % (T₅) proved to be the most effective, recording the lowest disease index (2.04 %) and the highest disease reduction (95.75 %) over the control at 12 days after storage. The consortium treatment also effectively suppressed disease development under pathogen-inoculated conditions, indicating strong antagonistic potential against papaya anthracnose pathogens. Furthermore, enhanced activities of defence-related enzymes, including peroxidase (PO), polyphenol oxidase (PPO) and phenylalanine ammonia-lyase (PAL), suggested the induction of host resistance mechanisms following treatment. Overall, the integration of bacterial antagonists with eucalyptus oil represents a promising eco-friendly alternative to chemical fungicides for minimising postharvest losses and improving the shelf life and quality of papaya fruits.

Table 6. Effect of Different essential oil treatments on disease severity index (DSI) in papaya across four blocks

Block	Treatment	DSI
A	Lemongrass oil 3	53.16 ^c
	Citronella oil 5	58.29 ^d
	Palmaria oil 2	50.09 ^b
	<i>Eucalyptus</i> oil 1	45.35 ^a
	Geranium oil 3	54.32 ^c
	Control 6	59.45 ^d
B	Lemongrass oil 3	38.64 ^c
	Citronella oil 5	47.37 ^d
	Palmaria oil 2	34.21 ^b
	<i>Eucalyptus</i> oil 1	22.01 ^a
	Geranium oil 3	39.33 ^c
	Control 6	48.35 ^e
C	Lemongrass oil 3	43.07 ^c
	Citronella oil 5	52.88 ^d
	Palmaria oil 2	32.39 ^b
	<i>Eucalyptus</i> oil 1	18.77 ^a
	Geranium oil 3	43.31 ^c
	Control 6	60.75 ^e
D	Lemongrass oil 3	38.63 ^c
	Citronella oil 5	42.77 ^d
	Palmaria oil 2	34.66 ^b
	<i>Eucalyptus</i> oil 1	26.38 ^a
	Geranium oil 3	37.91 ^c
	Control 6	43.56 ^e

Acknowledgements

The author gratefully acknowledges the Department of Plant Pathology, Faculty of Agriculture, Annamalai University, Chidambaram 608002, Tamil Nadu for providing research facilities, technical support and guidance throughout the research.

Authors' contributions

AM carried out the entire research studies, MSS participated the survey studies, MR drafted the entire manuscript, SRR and VKS carried out the statistical analysis, TSR conducted field trial, PR involved in collecting literatures, LV participated in the design of the study, TB carried out all grammatical checks and NR conceived of the study and coordination. 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

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) as an AI-assisted tool for language editing, grammar correction, sentence restructuring, and improvement of scientific presentation. After using this tool/service, the authors carefully reviewed, revised and edited the content as needed and takes full responsibility for the content of the publication.

References

- Senthilnathan S, Elamathy S, Kiruthika N, Gurunathan S, Prahadeeswaran M, Rameshkumar D. Economic analysis of agricultural growth and crop diversification in Tamil Nadu. *Int J Plant Soil Sci.* 2022;34(19):1–11. <https://doi.org/10.9734/ijpss/2022/v34i1931290>
- AS S. Papaya season in India, its varieties and production [Internet]. 2022 [cited 2026 Jun 1]. <https://abcfruits.com/papaya-varieties-season-production-and-economic-importance/>
- Zahid N, Ali A, Manickam S, Siddiqui Y, Maqbool M. Potential of chitosan-loaded nanoemulsions to control different *Colletotrichum* spp. and maintain quality of tropical fruits during cold storage. *J Appl Microbiol.* 2012;113(4):925–39. <https://doi.org/10.1111/j.1365-2672.2012.05398.x>
- Moraes SRG, Tanaka FAO, Massola Júnior NS. Histopathology of *Colletotrichum gloeosporioides* on guava fruits (*Psidium guajava* L.). *Rev Bras Frutic.* 2013;35(2):657–64. <https://doi.org/10.1590/S0100-29452013000200039>
- Kiranmayee V, Mishra JP, Prasad R, Sekhar JC, Reddy VP, Kumar S. Isolation and *in vitro* evaluation of essential oils against anthracnose of pomegranate caused by *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. *J Pharmacogn Phytochem.* 2020;9(3):37–40.
- Javaid A, Khan IH, Shoaib A. Management of charcoal rot of mungbean by two *Trichoderma* species and dry biomass of *Coronopus didymus*. *Planta Daninha.* 2018;36:e018182795. <https://doi.org/10.1590/S0100-83582018360100104>
- Sharf W, Javaid A, Shoaib A, Khan IH. Induction of resistance in chili against *Sclerotium rolfsii* by plant growth-promoting rhizobacteria and *Anagallis arvensis*. *Egypt J Biol Pest Control.* 2021;31:16. <https://doi.org/10.1186/s41938-021-00374-5>
- Zohaib KA, Bashir U, Khan IH, Javaid A, Anwar W. Synergistic effect of plant growth-promoting rhizobacteria and *Cirsium arvense* against black scurf disease of potato. *Sains Malaysiana.* 2024;53(9):3071–83. <https://doi.org/10.17576/jsm-2024-5309-13>
- Perumal AB, Huang L, Nambiar RB, He Y, Li X, Sellamuthu PS. Application of essential oils in packaging films for the preservation of fruits and vegetables: A review. *Food Chem.* 2022;375:131810. <https://doi.org/10.1016/j.foodchem.2021.131810>
- Ali A, Wee Pheng T, Mustafa MA. Application of lemongrass oil in vapour phase for the effective control of anthracnose of 'Sekaki' papaya. *J Appl Microbiol.* 2015;118(6):1456–64. <https://doi.org/10.1111/jam.12782>
- Liu B, Xue M, Zhou J, Zhang H, Ren L, Fan J. Hot air treatment elicits disease resistance against *Colletotrichum gloeosporioides* and improves the quality of papaya by metabolomic profiling. *Biomed Res Int.* 2022;2022:5162845. <https://doi.org/10.1155/2022/5162845>
- Prabakar K, Raguchander T, Saravanakumar D, Muthulakshmi P, Parthiban VK, Prakasam V. Management of postharvest disease of mango anthracnose incited by *Colletotrichum gloeosporioides*. *Arch Phytopathol Plant Prot.* 2008;41(5):333–9. <https://doi.org/10.1080/03235400600793502>
- Aneja KR. Experiments in Microbiology, Plant Pathology and Biotechnology. New Delhi: New Age International; 2007. 636 p.
- Goos RD, Cox EA, Stotzky G. *Botryodiplodia theobromae* and its association with *Musa* species. *Mycologia.* 1961;53(3):262–77. <https://doi.org/10.1080/00275514.1961.12017959>
- Ekhurutomwen O, Nnamdi C, Shittu O. Botryodiplodin (a mycotoxin) detection in pathogenic *Botryodiplodia theobromae* isolated from diseased coconut fruits. *Proc Niger Acad Sci.* 2023. <https://doi.org/10.57046/HPUP6912>
- Fernandes MB, Mizobutsi EH, De Castro SGV, Matos ADM, Moura MMA, Alemida LBD, et al. Avaliação de extratos vegetais no controle de *Colletotrichum musae*. *Contrib Cienc Soc.* 2023. <https://doi.org/10.55905/revconv.16n.11-203>
- Krishnan P, Bhat R, Kush A, Ravikumar P. Isolation and functional characterization of bacterial endophytes from *Carica papaya* fruits. *J Appl Microbiol.* 2012;113(2):308–17.
- Dennis C, Webster J. Antagonistic properties of species-groups of *Trichoderma*. *Trans Br Mycol Soc.* 1971;57(1):25–39. [https://doi.org/10.1016/S0007-1536\(71\)80050-5](https://doi.org/10.1016/S0007-1536(71)80050-5)
- Vincent JM. Distortion of fungal hyphae in the presence of certain inhibitors. *Nature.* 1947;159(4051):850. <https://doi.org/10.1038/159850b0>
- Bharathi R, Vivekananthan R, Harish S, Ramanathan A, Samiyappan R. Rhizobacteria-based bio-formulations for the management of fruit rot infection in chillies. *Crop Prot.* 2004;23(9):835–43. <https://doi.org/10.1016/j.cropro.2004.01.007>
- Baratta MT, Dorman HJD, Deans SG, Figueiredo AC, Barroso JG, Ruberto G. Antimicrobial and antioxidant properties of some commercial essential oils. *Flavour Fragr J.* 1998;13(4):235–44. [https://doi.org/10.1002/\(SICI\)1099-1026\(199807\)13:4<235::AID-FFJ732>3.0.CO;2-T](https://doi.org/10.1002/(SICI)1099-1026(199807)13:4<235::AID-FFJ732>3.0.CO;2-T) [https://doi.org/10.1002/\(SICI\)1099-1026\(1998070\)13:4<235::AID-FFJ733>3.3.CO;2-K](https://doi.org/10.1002/(SICI)1099-1026(1998070)13:4<235::AID-FFJ733>3.3.CO;2-K)
- Hammerschmidt R, Kuc J, editors. Induced Resistance to Disease in Plants. Dordrecht: Springer; 1995. <https://doi.org/10.1007/978-94-015-8420-3>
- Mayer AM, Harel E, Ben-Shaul R. Assay of catechol oxidase—a critical comparison of methods. *Phytochemistry.* 1966;5(4):783–9. [https://doi.org/10.1016/S0031-9422\(00\)83660-2](https://doi.org/10.1016/S0031-9422(00)83660-2)
- Dickerson DP, Pascholati SF, Hagerman AE, Butler LG, Nicholson RL. Phenylalanine ammonia-lyase and hydroxycinnamate: CoA ligase in maize mesocotyls inoculated with *Helminthosporium maydis* or *Helminthosporium carbonum*. *Physiol Plant Pathol.* 1984;25(2):111–23. [https://doi.org/10.1016/0048-4059\(84\)90050-X](https://doi.org/10.1016/0048-4059(84)90050-X)
- Gomez KA, Gomez AA. Statistical Procedures for Agricultural Research. 2nd ed. New York: John Wiley & Sons; 1984. 698 p.
- Lamare N, Radhakrishnan NV, Thara SS, Simi S, Kumar AS, Rithesh L. Screening of mango varieties against anthracnose disease caused by *Colletotrichum gloeosporioides* and its *in vitro* management through biocontrol agents and fungicides. *J Adv Biol Biotechnol.* 2024;27(11):1063–72. <https://doi.org/10.9734/jabb/2024/v27i111691>
- Kumar RR, Jain AK, Sharma V, Das P, Sahni P. Enhancing precision in papaya crop health management: a CNN-based approach for early disease detection and classification. In: 2024 IEEE International Conference on Information Technology, Electronics and Intelligent Communication Systems (ICITEICS); 2024; Bangalore, India. p. 1–6. <https://doi.org/10.1109/ICITEICS61368.2024.10625272>
- Freeman S, Prusky D. Foliar, floral and soilborne diseases. In: Litz RE, editor. The Mango: Botany, Production and Uses. Wallingford: CAB; 2026. p. 260–303 <https://doi.org/10.1079/9781845934897.0231>
- Sankar TG, Gopi V, Bharathi YH, Gopal K, Lakshmi LM. Growth of *Botryodiplodia theobromae*, an incitant of longitudinal splitting of bark and wood disease in acid lime (*Citrus aurantifolia* Swingle), as influenced by pH levels, temperature and growth media. *Int J Curr Microbiol Appl Sci.* 2016;5(12):756–64. <https://doi.org/10.20546/ijcmas.2016.512.086>
- Aktaruzzaman M, Afroz T, Hong SJ, Kim BS. Identification of *Botrytis cinerea*, the cause of post-harvest gray mold on broccoli in Korea. *Res Plant Dis.* 2017;23(4):372–8. <https://doi.org/10.5423/RPD.2017.23.4.372>
- Du C, Yang D, Jiang S, Zhang J, Ye Y, Pan L, et al. Biocontrol agents inhibit banana fusarium wilt and alter the rooted soil bacterial community in the field. *J Fungi.* 2024;10(11):771. <https://doi.org/10.3390/jof10110771>
- Zaitoun FM, H YK, Fahmy MM, Ziyada SM. Role of certain bioagents against guava decline disease and in enhancement of the growth of guava trees. *J Phytopathol Dis Manag.* 2015:43–54.
- Kumar A, Rabha J, Jha DK. Antagonistic activity of lipopeptide-biosurfactant producing *Bacillus subtilis* AKP against *Colletotrichum capsici*, the causal organism of anthracnose disease of chilli.

- Biocatal Agric Biotechnol. 2021;36:102133. <https://doi.org/10.1016/j.bcab.2021.102133>
34. Kjeldgaard B, Neves AR, Fonseca C, Kovács ÁT, Domínguez-Cuevas P. Quantitative high-throughput screening methods designed for identification of bacterial biocontrol strains with antifungal properties. *Microbiol Spectr.* 2022;10(2):e01433-21. <https://doi.org/10.1128/spectrum.01433-21>
 35. Sahoo U, Tripathi U, Shukla P, Patel AK. *In vitro* potency of chemical fungicides over *Alternaria lini* (Dey) growth inhibition causing black bud disease of linseed. *Int J Environ Clim Change.* 2023;13(10):2784–90. <https://doi.org/10.9734/ijec/2023/v13i102943>
 36. Kamensky M, Ovadis M, Chet I, Chernin L. Soil-borne strain IC14 of *Serratia plymuthica* with multiple mechanisms of antifungal activity provides biocontrol of *Botrytis cinerea* and *Sclerotinia sclerotiorum* diseases. *Soil Biol Biochem.* 2003;35(2):323–31. [https://doi.org/10.1016/S0038-0717\(02\)00283-3](https://doi.org/10.1016/S0038-0717(02)00283-3)
 37. Quecine MC, Araujo WL, Marcon J, Gai CS, Azevedo JL, Pizzirani-Kleiner AA. Chitinolytic activity of endophytic *Streptomyces* and potential for biocontrol. *Lett Appl Microbiol.* 2008;47(6):486–91. <https://doi.org/10.1111/j.1472-765X.2008.02428.x>
 38. Chin-A-Woeng TF, Bloemberg GV, van der Bij AJ, van der Drift KM, Schripsema J, Kroon B, et al. Biocontrol by phenazine-1-carboxamide-producing *Pseudomonas chlororaphis* PCL1391 of tomato root rot caused by *Fusarium oxysporum* f. sp. *radicis-lycopersici*. *Mol Plant Microbe Interact.* 1998;11(11):1069–77. <https://doi.org/10.1094/MPMI.1998.11.11.1069>
 39. Raaijmakers JM, Weller DM. Exploiting genotypic diversity of 2,4-diacetylphloroglucinol-producing *Pseudomonas* spp.: characterization of superior root-colonizing *P. fluorescens* strain Q8r1-96. *Appl Environ Microbiol.* 2001;67(6):2545–54. <https://doi.org/10.1128/AEM.67.6.2545-2554.2001>
 40. Wang S, Zhu X, Xie H, Li H, Li H, Wang W, et al. Structural diversification and biosynthesis of pesticidal pyrroline-derived alkaloid from *Penicillium citrinum* SCSIO DF147. *J Agric Food Chem.* 2026;74(6):5379–90. <https://doi.org/10.1021/acs.jafc.5c15871>
 41. Nielsen TH, Sørensen D, Tobiasen C, Andersen JB, Christophersen C, Givskov M, et al. Antibiotic and biosurfactant properties of cyclic lipopeptides produced by fluorescent *Pseudomonas* spp. from the sugar beet rhizosphere. *Appl Environ Microbiol.* 2002;68(7):3416–23. <https://doi.org/10.1128/AEM.68.7.3416-3423.2002>
 42. Silo-Suh LA, Lethbridge BJ, Raffel SJ, He H, Clardy J, Handelsman J. Biological activities of two fungistatic antibiotics produced by *Bacillus cereus* UW85. *Appl Environ Microbiol.* 1994;60(6):2023–30. <https://doi.org/10.1128/AEM.60.6.2023-2030.1994>
 43. Faltova I, Urbanova K, Kokoska L. *In vitro* growth-inhibitory effect of essential oils against plant pathogenic bacteria and fungi in vapour phase. *Planta Med.* 2022;88(15):P276. <https://doi.org/10.1055/s-0042-1759249>
 44. Zalewska ED, Zawiślak G, Papliński R, Walasek-Janusz M, Gruszecki R. Antifungal effects of some essential oils on selected allergenic fungi *in vitro*. *Acta Sci Pol Hortorum Cultus.* 2022;21(6):115–27. <https://doi.org/10.24326/asphc.2022.6.10>
 45. Muthukumar A, Kumar KS. Chemical composition and antifungal activity of essential oils against die-back of hippeastrum. *Indian J Hort.* 2012;69(3):381–4.
 46. Thejeswini PG, Nidhi Monica KJ, Ganesh A, Shivaraj H, Uma RB. Synergistic effect of *Indigofera cordifolia*-mediated Cu–ZnO nanocomposites for antimicrobial, antioxidant and hemocompatibility activities. *Hybrid Adv.* 2026;13:100667. <https://doi.org/10.1016/j.hybadv.2026.100667>
 47. Sangeetha G, Thangavelu R, Usha Rani S, Muthukumar A, Udayakumar R. Induction of systemic resistance by mixtures of antagonist bacteria for the management of crown rot complex on banana. *Acta Physiol Plant.* 2010;32(6):1177–87. <https://doi.org/10.1007/s11738-010-0513-y>
 48. Lima Oliveira PD, de Oliveira KÁR, Vieira WA dos S, Câmara MPS, de Souza EL. Control of anthracnose caused by *Colletotrichum* species in guava, mango and papaya using synergistic combinations of chitosan and *Cymbopogon citratus* (D.C. ex Nees) Stapf. essential oil. *Int J Food Microbiol.* 2018;266:87–94. <https://doi.org/10.1016/j.jfoodmicro.2017.11.018>
 49. Jeevanantham S, Praveen A, Livitha R, Balamurugan K. Postharvest anthracnose of mango caused by *Colletotrichum gloeosporioides*: a review. *Arch Curr Res Int.* 2024;24(2):106–15. <https://doi.org/10.9734/acri/2024/v24i2637>
 50. Abu-Bakar N, Juri NM, Abu-Bakar RA, Sohaime MZ, Badrun R, Sarip J, et al. Recombinant protein foliar application activates systemic acquired resistance and increases tolerance against papaya dieback disease. *Asian J Agric Rural Dev.* 2021;11(1):1–9.
 51. Muthukumar A, Venkatesh A. Biological inductions of systemic resistance to collar rot of peppermint caused by *Sclerotium rolfsii*. *Acta Physiol Plant.* 2014;36(6):1421–31. <https://doi.org/10.1007/s11738-014-1520-1>
 52. Pp S, W F. Gewebespezifische oxidative Umsetzung von Polyphenolen durch Peroxidase in Kirschtrieben. *Gartenbauwissenschaft.* 1980;45.
 53. Fry SC. Cross-linking of matrix polymers in the growing cell walls of angiosperms. *Annu Rev Plant Physiol.* 1986;37:165–86. <https://doi.org/10.1146/annurev.pp.37.060186.001121>
 54. Graham MY, Graham TL. Rapid accumulation of anionic peroxidases and phenolic polymers in soybean cotyledon tissues following treatment with *Phytophthora megasperma* f. sp. *glycinea* wall glucan 1. *Plant Physiol.* 1991;97(4):1445–55. <https://doi.org/10.1104/pp.97.4.1445>
 55. Bari L, Hassan P, Absar N, Khatun S, Hossain M. Purification and characterization of peroxidase from anthracnose disease infected papaya (*Carica papaya* L.). *Bangladesh J Med Biochem.* 2014;6(2):49–57. <https://doi.org/10.3329/bjmb.v6i2.17643>
 56. Muthukumar A, Eswaran A, Sangeetha G. Induction of systemic resistance by mixtures of fungal and endophytic bacterial isolates against *Pythium aphanidermatum*. *Acta Physiol Plant.* 2011;33(5):1933–44. <https://doi.org/10.1007/s11738-011-0742-8>
 57. Feng L, Sun J, Jiang Y, Duan X. Role of reactive oxygen species against pathogens in relation to postharvest disease of papaya fruit. *Horticulturae.* 2022;8(3):205. <https://doi.org/10.3390/horticulturae8030205>
 58. Klessig DF, Malamy J. The salicylic acid signal in plants. *Plant Mol Biol.* 1994;26(5):1439–58. <https://doi.org/10.1007/BF00016484>
 59. Bai G, Gao J, Zhang S, Meng L, Chu R, Zhang J, et al. *Bacillus cereus* ZW21-derived VOCs, hydroxyacetone and 3-methyl-3-buten-1-ol, control postharvest papaya anthracnose through direct antifungal activity and host transcriptional reprogramming. *Int J Food Microbiol.* 2026;111782. <https://doi.org/10.1016/j.jfoodmicro.2026.111782>
 60. Martin-Rivilla H, Garcia-Villaraco A, Ramos-Solano B, Gutierrez-Mañero FJ, Lucas JA. Extracts from cultures of *Pseudomonas fluorescens* induce defensive patterns of gene expression and enzyme activity while depressing visible injury and reactive oxygen species in *Arabidopsis thaliana* challenged with pathogenic *Pseudomonas syringae*. *AoB Plants.* 2019;11(5):plz049. <https://doi.org/10.1093/aobpla/plz049>
 61. Kahawattage A, Hansini N, Daranagama DA, Ranasinghe C. Effect of pre-treatments with natural compounds for controlling anthracnose in papaya variety Red Lady. *J Hort Postharvest Res.* 2023;6(2):169–80.
 62. Rana VS, Prasad D, Blazquez MA. Chemical composition of the leaf oil of *Lantana camara*. *J Essent Oil Res.* 2005;17(2):198–200. <https://doi.org/10.1080/10412905.2005.9698874>
 63. Kumar A, Kudachikar VB. Antifungal properties of essential oils against anthracnose disease: a critical appraisal. *J Plant Dis Prot.* 2018;125(2):133–44. <https://doi.org/10.1007/s41348-017-0128-2>

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://horizonpublishing.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://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.