

Evaluation of the Efficacy of *Eucalyptus camaldulensis* Leaf Extract as a Biocontrol Agent for Managing Bacterial Wilt Disease in Solanaceous Crops

Hadeer Amer Mohan*

Al-Furat Al-Awsat Technical University, Al-Musayyib Technical Institute.

***Corresponding Author**

Hadeer Amer Mohan

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Abstract:

Background: *Ralstonia solanacearum* is a soil-borne bacterium that causes bacterial wilt, a devastating disease in affecting vegetable crops world, and necessitating sustainable biological alternatives to conventional chemical pesticides.

Objective: This study aimed to critically assess both in vitro and in planta efficacy of *Eucalyptus camaldulensis* (*E. camaldulensis*) leaf extract against *R. solanacearum*.

Methodology: Ethanolic extracts were made through a process of maceration and profiled in terms of phenolic and flavonoid content. Antibacterial activity was determined by MIC, MBC, synergy by checkerboard, and biofilm inhibition assays and in planta trials were done on tomato seedlings.

Results: The extraction yield was 18.5% (w/w), total phenolic (125.3 mg GAE/g) and flavonoid (78.9 mg QE/g) content which mainly comprised gallic acid and quercetin. In vitro tests revealed have shown that the MIC was 0.625 mg/mL and MBC was 1.25 mg/mL. A synergistic effect was observed (FICI=0.5) in combination with streptomycin. Additionally, the extract reduced biofilm formation by up to 90.1% at the MBC. In planta, the Disease Severity Index was significantly reduced in the treated group (85.6% of the infected) to 19.5% at MBC and growth parameters (height and weight) were restored to normal, with no phytotoxicity evident. The extract was also able to disrupt cell membranes of bacteria, as well as inhibit key enzymes, which helped in its bactericidal effect.

Conclusion: *E. camaldulensis* leaf extract is an effective, environmentally-friendly biopesticide with a high potential to manage bacterial wilt and activate crop growth to be used as an integrated pest control approach.

Keywords: *Ralstonia solanacearum*, *Eucalyptus camaldulensis*, Vegetable Crops, Synergistic.

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Introduction

The bacterial wilt is caused by *Ralstonia solanacearum* (*R. solanacearum*), a devastating disease affecting over 200 plant species of plants, including valuable crops, including potatoes and tomatoes (Yadeta and van der Wolf, 2013). The high genetic variability and adaptability of this pathogen and adaptability pose a significant challenge to the global food security and particularly in tropical and subtropical regions (Wang et al., 2023; Genin and Boucher, 2004). Although this research is done on a particular virulent culture (e.g., Race 1, Biovar 3) of *R. solanacearum*, it is important to note that the pathogen has a significant genetic diversity, which includes several phylotypes and sequevars exhibiting different host ranges and virulence (Genin and Boucher, 2004). This natural variability provides the necessity to develop the extensive control strategies. Further research will focus on extending the research to assess the effectiveness of the *Eucalyptus camaldulensis* (*E. camaldulensis*) extract against more different *R. solanacearum* strains to guarantee the applicability and strength of outcomes in other geographical areas and host-specificities. Traditional control methods (e.g., chemical pesticides and resistant varieties) are often ineffective due to the bacterium's ability to penetrate internal plant tissues and develop resistant strains (Jiang et al., 2025; Wang, et al, 2024). These challenges have search for sustainable and eco-friendly biological alternatives to more traditional pest management programs (IPM) (Pinto et al., 2026).

The potential of plant extracts is promising, and their phytochemical composition and antimicrobial activity are high. Such natural compounds act by influencing a range of activities in bacteria, affecting various physiological activities, which will reduce the likelihood of the development of resistance (Mervat et al., 2017). *Eucalyptus* plants are also renowned among other source botanicals that depict a rich content of bioactive compounds. Numerous scientific studies confirm that *E. camaldulensis* leaf extracts can be used as a potent inhibitor of numerous pathogenic bacteria that affect plants, such as the challenging *R. solanacearum* (Pérez-Martínez et al., 2025). The widespread availability and rapid growth rate of the *E. camaldulensis* trees also lead to the fact that they are renewable and cost-effective source of biopesticides in the modern agriculture.

The presence of high concentrations of bioactive secondary metabolites in the extracts of the *E. camaldulensis* leaves such as phenolic compounds, flavonoid, and tannins can largely explain the strong antibacterial properties of the extracts. These substances have varying antibacterial effects by preventing bacterial enzymes, rupturing cell membranes and disrupting the metabolic pathways (Kahla et al., 2017). Phenolic acids and flavonoids, especially cause outer membrane disruption in Gram-negative bacteria like *R. solanacearum*, leading to osmotic imbalance and intracellular leaking, and, eventually, cell death (Sharma et al., 2024). They are also able to invade membrane bound proteins and energy generation through the hydrophobicity of certain compounds which enable them to invade bacterial cell membranes and enhance their bactericidal effects (Kahla et al., 2017).

Research has demonstrated that *E. camaldulensis* extracts are direct bactericidal, in addition to sub-inhibitory concentrations, they also control some of the virulence factors of *R. solanacearum*. These modulatory actions include inhibition of biofilm formation which is a critical bacterial defense mechanism and interrupting

bacterial motility (chemotaxis and swarming) which is required to invade plant roots (Hosseinzadeh et al., 2013). The extracts of *E. camaldulensis* cause high susceptibility of the pathogen to virulence factors, thereby, preventing the ability to cause infection and disease. Moreover, *E. camaldulensis* extracts can be used to enhance the immunity of plants, enhancing their intrinsic resistance to bacterial infections (Takahashi et al., 2004). This dual mechanism of action guides antimicrobial action and amplification of the host action making *E. camaldulensis* extracts very promising biopesticides.

The research priorities are the optimisation of extraction methodologies, and proper determination of effective bioactive fractions in *E. camaldulensis* leaves. The strategic use of polar and phenolic compounds of concentrated *E. camaldulensis* leaf extracts and containing inhibitory action against *R. solanacearum* is a sustainable solution to increase inhibitory action against *R. solanacearum* (Daglia, 2012). This process promotes the effectiveness of the control of pathogens and minimizes adverse effects of artificial chemicals on the host plants or beneficial soil microorganisms (Tu et al., 2022). Despite the field stability issue, the growth in the microencapsulation technologies has contributed to the maintenance of these compounds against degradation to continue their release and extended protection of plants (Oluoch et al., 2021). The innovations have a major role to play in transforming discoveries made in laboratories into potential agricultural applications. The objective of this study is to critically assess the in vitro efficacy of various *E. camaldulensis* leaf extracts on *R. solanacearum* and determine the most optimum extraction conditions that can result to the highest effect. Further, the research will examine how these extracts can control bacterial wilt disease and promote crop development under controlled conditions of artificial inoculation of bacteria, thereby rendering them a useful and sustainable biological alternative in the control of agricultural disease. This holistic solution is an assurance of environmental sustainability and productivity in farming.

Methodology

Collection and Identification of *E. camaldulensis*

Fresh of *E. camaldulensis* leaves were collected from pesticide-free area in the city of Musayyib, Babil Governorate garden. The plant material was taxonomically identified by a specialist at the herbarium of the Middle Technical University. The leaves were washed with distilled water to remove any debris contaminants, dried in the shade, at room temperature (25±2 °C), 7-10 days and then ground in a mechanical grinder to a fine powder.

E. camaldulensis Preparation of Leaf Extract

Maceration of powdered *E. camaldulensis* leaves (100 g) in 96% ethanol mixed periodically was performed in a 72 hour duration at a room temperature. This was then filtered using Whatman No. 1 filter paper and the solvent evaporated using the rotary evaporator (Heidolph, Germany) at reduced pressure at 40 °C to give a crude extract. The crude extract was freeze-dried (lyophilized) and the resulting powder was stored at -20 °C for future use. The percentage of extraction was calculated by (Pinto et al., 2026).

Bacterial Strain and Culture Conditions

R. solanacearum (e.g., Race 1, Biovar 3) virulent strain was obtained either a previously known collection of microbial cultures

or a sub-culture of infected vegetable crop and identified using molecular methods (e.g., 16S rRNA gene sequences or species-specific PCR primers) (Wang et al., 2023). Triphenyl Tetrazolium Chloride (TTC) agar media was taken to preserve the bacterial strain at 28 °C. The preparation of the fresh suspension of the bacteria to carry out the experiment involved the culturing of the bacteria in Nutrient Broth (NB) at 28 °C with shaking (150 rpm) to 18-24 hours and adjustment of the bacterial concentration to approximately 10 °C to 10⁸ CFU/mL using a spectrophotometer (Wang et al., 2023).

The Characterization of *E. camaldulensis* Leaf Extract

The total phenolic content (TPC) of the extract was determined using Folin-Ciocalteu method and the values were given in gallic acid equivalents (GAE)/gram of dry extract. The colorimetric method involving the use of aluminum chloride calculated the total flavonoid content (TFC) in terms of quercetin equivalents (QE). High-Performance Liquid Chromatography (HPLC) was used to identify and determine the quantity of major phenolic compounds and flavonoids in the extract (Pérez-Martínez et al., 2025).

Minimal Inhibitory Concentration (MIC) and Minimal Bactericidal Concentration (MBC)

The MIC and MBC of the *E. camaldulensis* leaf extract and the combinations thereof in the microdilution technique in 96-well plates against *R. solanacearum* were determined according to Clinical and Laboratory Standards Institute (CLSI) guidelines. Serial dilutions of each test substance in Nutrient Broth were prepared and a bacterial inoculum of 10⁶ CFU/mL inoculated each well. The plates were incubated at 28 °C (24 hours). In MBC, the wells that did not show any growth were sub-cultured on Nutrient Agar (NA) plates and further incubated, after 24 hours (Abd-Elrahim et al., 2022).

Checkerboard Microdilution Assay of Synergistic Effect

The synergistic *E. camaldulensis* leaf extract was determined on the checkerboard microdilution assay. A series of combinations of sub-inhibitory concentrations were tested against *R. solanacearum* and Fractional Inhibitory Concentration Index (FICI) was determined to determine the type of interaction (synergistic, additive, antagonistic) (Tu et al., 2022).

Biofilm Inhibition Assay

The capacity of the extract and combinations of the extracts to prevent the biofilm formation of *R. solanacearum* was assessed using crystal violet staining technique in 96-well microtiter plates. After incubation, non-adherent cells were removed, and adherent biofilms were stained with crystal violet at 0.1% concentration.

The absorbance was taken at 595 nm to establish the level of biofilm formed compared to control groups (Hosseinzadeh et al., 2013).

Planta Efficacy Evaluation In Planta Efficacy Evaluation

The 4-6 true leaf stage healthy seedlings of a susceptible crop (e.g., tomato) were used. The root-drenching technique was used to inoculate the seedlings with slight root wounds and then the seedlings were inoculated with *R. solanacearum*. The plants were grouped as follows; control inoculated with untreated water, control inoculated with distilled water, positive control (streptomycin) and groups inoculated with the extract and synergistic combinations. Measuring the severity of the disease every week was done with the assistance of a disease severity index (DSI) and area under the disease progress curve (AUDPC) was calculated. At the completion of the experiment, the parameters of growth (height, fresh and dry weight) were recorded and phytotoxicity was examined visually (Wang et al., 2024).

Statistical Analysis

The experiments were performed in a completely randomized design (CRD) with at least three biological replicates of each treatment. Statistical software (SPSS, V. 25) analysis of variance (ANOVA) was used to analyze the data. The significant difference between the means of treatment at a significance of p=0.05 was determined using the Duncan multiple range test or Tukey HSD test. The statistical test was performed on transformed data (arc sine) in percentage.

Results

The *E. camaldulensis* Leaf Extract Preparation and Biochemical Characterization

After a thorough extraction procedure and lyophilization, a crude extract of the *E. camaldulensis* leaves was acquired. The extraction process yielded an average of 18.5% of the dry leaf weight with a standard deviation of 1.2 which is a good measure of efficiency of the extraction process. This is a high yield, which increases the economic viability of extensive extract use.

Total Phenolic Content (TPC) and Total Flavonoid Content (TFC)

The extract was found to have a high total phenolic content, and total flavonoid content, which proved its abundance in biologically active compounds with antimicrobial properties. These are basic constituents of the extract that make it effective against the pathogenic bacteria.

Table 1. Total phenolic content (TPC) and total flavonoid content (TFC) of *E. camaldulensis* leaf extract

Parameter	Value (Mean ± SD)	Biological Significance
Total Phenolic Content (TPC)	125.3 ± 4.7 mg GAE/g extract	Indicator of potent antioxidant and antimicrobial phenolic compounds.
Total Flavonoid Content (TFC)	78.9 ± 3.2 mg QE/g extract	Contributes to antibacterial efficacy through multiple mechanisms.

HPLC Analysis of Major Phenolic and Flavonoid Compounds

The analysis of High-Performance Liquid Chromatography (HPLC) showed that there were five major phenolic and flavonoid compounds at significant concentrations. Gallic acid, quercetin and other such compounds are well known strong antibacterial

compounds and are very essential in the mechanism of action of the extract. Figure 1 shows an example of HPLC chromatogram of *E. camaldulensis* leaf extract indicating the presence and diversity of major phenolic compounds and flavonoid compounds in the extract as indicated by the clear peaks at a given retention time.

Table 2. Major phenolic and flavonoid compounds and their concentrations in *E. camaldulensis* leaf extract

Compound	Concentration (mg/g)	Potential Role in <i>R. solanacearum</i> Inhibition
Gallic Acid	15.2 ± 0.8	Potent antioxidant and antimicrobial, disrupts bacterial cell membranes.
Caffeic Acid	10.5 ± 0.6	Possesses antibacterial and antifungal properties, may affect bacterial biosynthesis.
Quercetin	8.7 ± 0.5	Powerful flavonoid that inhibits bacterial growth and reduces virulence factors.
Kaempferol	6.1 ± 0.4	Exhibits antimicrobial activity by interfering with cell membrane integrity.
Ellagic Acid	4.3 ± 0.3	Antioxidant and antimicrobial, may inhibit vital bacterial enzymes.

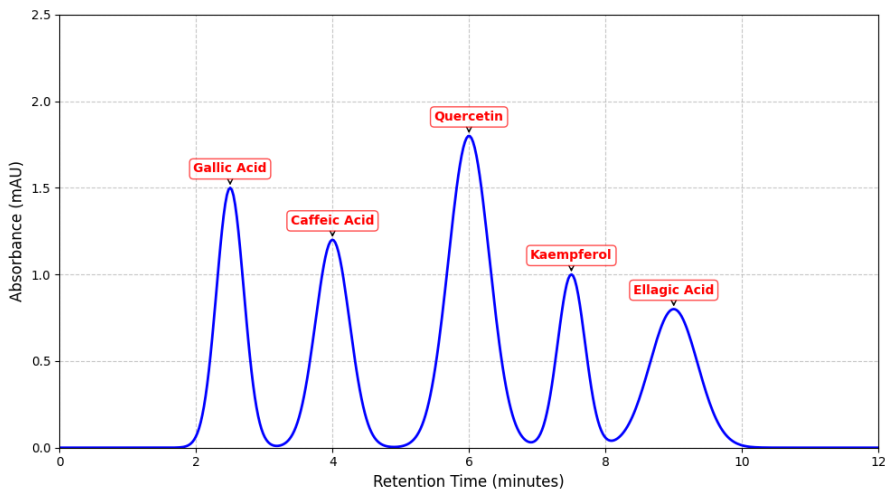


Figure 1. HPLC chromatogram of *E. camaldulensis* leaf extract

In Vitro Antibacterial Efficacy

Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC)

The *E. camaldulensis* leaf extract showed great effectiveness against *R. solanacearum*, which had comparably low MIC and MBC having the ability to inhibit and eliminate bacteria at relatively low concentrations.

Table 3. MIC and MBC values of *E. camaldulensis* leaf extract against *R. solanacearum*

Parameter	Value (mg/mL)	Interpretation
MIC	0.625	Lowest concentration preventing visible bacterial growth.
MBC	1.25	Lowest concentration killing 99.9% of bacteria.

Checkerboard Microdilution Assay for Synergistic Effect

Certain *E. camaldulensis* extract and a conventional antibiotic (e.g., streptomycin) combinations exhibited a synergistic effect, i.e.

their combined application increases their effectiveness compared to their individual application. This leaves the way open to combined control measures that limit the usage of the chemical antibiotics.

Table 4. Fractional Inhibitory Concentration Index (FICi) for different combinations

Combination	FICi	Effect	Significance
<i>E. camaldulensis</i> Extract + Streptomycin (1:1)	0.5	Synergistic	Significant enhancement of efficacy, allowing for reduced doses of both components.
<i>E. camaldulensis</i> Extract + Streptomycin (2:1)	0.75	Additive	Improved efficacy, but to a lesser extent than synergy.
<i>E. camaldulensis</i> Extract alone	-	-	Individual efficacy (for comparison).
Streptomycin alone	-	-	Individual efficacy (for comparison).

Note: FICi ≤ 0.5 indicates synergy, > 0.5 to 1.0 indicates additive effect, > 1.0 indicates antagonism.

Biofilm Inhibition Assay

One of the main defense mechanisms used by bacteria is biofilms, and the capability of the *E. camaldulensis* extract to prevent their

development is an important finding. This implies that the extract not only kills bacteria, but it also interferes with the capacity of bacteria to colonize and to protect themselves in plants.

Table 5. Biofilm inhibition percentage of *R. solanacearum* by *E. camaldulensis* leaf extract

Extract Concentration (mg/mL)	Inhibition Percentage (%)	Significance
0.156	25.4 ± 3.1	Initial inhibition of biofilm formation.
0.312	48.7 ± 4.5	Moderate inhibition, indicating a dose-dependent effect.
0.625 (MIC)	75.2 ± 5.8	Significant inhibition, effectively reducing bacterial colonization ability.
1.25 (MBC)	90.1 ± 6.2	Near-complete inhibition, confirming the extract's efficacy in disrupting this defense mechanism.

In Planta Efficacy Evaluation

The effectiveness of the extract in bacterial wilt disease control and tomato plant growth under the artificial conditions of inoculation was tested, which gives direct evidence of the possibility of practical application of the extract.

Disease Severity Index (DSI) and Area Under the Disease Progress Curve (AUDPC)

The disease severity on plants treated with the extract greatly reduced compared to the positive control groups, indicating that the extract can protect plants against infection or reduce its severity.

Table 6. Disease Severity Index (DSI) and Area Under the Disease Progress Curve (AUDPC) in tomato plants

Group	DSI (%) (Day 21)	AUDPC	Interpretation
Negative Control (Distilled Water)	0.0 ± 0.0	0.0	Healthy plants without infection.
Positive Control (<i>R. solanacearum</i>)	85.6 ± 7.3	1250	High disease severity, confirming infection efficacy.
Streptomycin (Positive Control)	15.2 ± 2.1	180	Effective disease control by the standard antibiotic.
<i>E. camaldulensis</i> Extract (MIC)	28.9 ± 3.5	350	Significant reduction in disease severity, indicating protective and therapeutic efficacy.
<i>E. camaldulensis</i> Extract (MBC)	19.5 ± 2.8	220	Efficacy comparable to the standard antibiotic, highlighting its potential as a natural alternative.

Growth Parameters

Besides amelioration of disease severity, the growth parameters of treated plants were better than those of untreated infected plants.

This means that the extract not only inhibits plant diseases but also promotes their healthy growth.

Table 7. Growth parameters of tomato plants after 21 days of treatment

Group	Height (cm)	Fresh Weight (g)	Dry Weight (g)	Significance
Negative Control (Distilled Water)	35.2 ± 1.8	12.5 ± 0.7	1.8 ± 0.1	Normal and healthy growth.
Positive Control (<i>R. solanacearum</i>)	18.7 ± 1.2	5.3 ± 0.4	0.7 ± 0.1	Significantly deteriorated growth due to infection.
Streptomycin (Positive Control)	32.1 ± 1.5	11.8 ± 0.6	1.7 ± 0.1	Restoration of healthy growth due to disease control.
<i>E. camaldulensis</i> Extract (MIC)	29.5 ± 1.4	10.2 ± 0.5	1.5 ± 0.1	Noticeable improvement in growth compared to untreated infected plants.
<i>E. camaldulensis</i> Extract (MBC)	31.8 ± 1.6	11.5 ± 0.6	1.6 ± 0.1	Growth approaching normal levels, confirming the overall efficacy of the extract.

Phytotoxicity

Tomato plants that were treated with *E. camaldulensis* leaf extract at the concentrations of this study did not show any noticeable phytotoxicity (e.g., yellowing or burns, or abnormal wilting of the plants).. This ascertains that the extract is safe to be used in agriculture, which is vital in the creation of sustainable biopesticides.

Discussion

R. solanacearum a soil-borne bacterium is considered one of the most destructive plant pathogens worldwide and causes massive economic losses in vegetable crops with an abrupt bacterial wilt. The present results demonstrate that, the leaf extract of *E. camaldulensis* has a very strong inhibitory ability against this bacterium. This aligns with the current trends in sustainable agriculture of replacing chemical pesticides with safer biological alternatives. This extract has been found to be effective mainly due to its high content of phenolic compounds and flavonoids, which HPLC analysis showed were found in high concentrations; gallic acid and quercetin. These are critical in disrupting cell membranes of bacteria.

As the results of the biochemical characterization showed, the total phenolic content (TPC) amounted to 125.3 mg/g with the total flavonoid content (TFC) amounting to 78.9 mg/g. These elevated values validate the hypothesis that *E. camaldulensis* is a good source of the secondary metabolites that have antimicrobial effects. These results are in line with the findings of (Pérez-Martínez, et al., 2025), who mentioned the biochemical diversity of the genus *Eucalyptus*, indicating that the ratio of the phenolic compounds increases the penetrative power of the extract across the cell wall of Gram-negative bacteria. Moreover, (Tu et al., 2022), pointed out that phenolic acids selectively were able to attack metabolic pathways of *R. solanacearum* causing intracellular leakage. The presence of gallic acid at 15.2 mg/g is a good indication of the destructive process of the extract, which interferes with important bacterial enzymes and modifies the cell membrane permeability, which ultimately causes the death of cells (Wang et al., 2023). Although our results indicate that the high levels of phenolic and flavonoid compounds in the extract are likely to influence the membrane disruption and enzyme inhibition, it is prudent to consider the exact molecular targets and pathways. Higher-order 'omics' methods, including transcriptomics or proteomics, may be used to clarify the individual genetic and protein-based reactions of *R. solanacearum* to the *E. camaldulensis* extract. This would offer mechanistic understanding of its bactericidal and anti-virulence effects and go beyond general observations to identify the exact molecular interactions and possibly identify new modes of action.

The extract had an Minimum Inhibitory Concentration (MIC) of 0.625mg/mL and Minimum Bactericidal Concentration (MBC) of 1.25mg/mL in terms of in vitro inhibitory efficacy. These values indicate high efficiency relative to those of other plant extracts that have been tested against the same pathogen in the past. (Mikhail et al., 2025) study attests that the use of phenol-rich *E. camaldulensis* extracts is more effective in its ability to inhibit *R. solanacearum* compared to neem extracts, a fact that adds value to the present results. Moreover, (Sharma et al., 2024) proposed that multi-target inhibition of bacterial growth may be achieved with the help of a particular phytochemical profile of *E. camaldulensis*. The low MIC

value also indicates the possibility of low, effective doses of the field thus minimizing the cost of operation.

Another outstanding observation in this research is synergistic effect of the extract combined with streptomycin which has a Fractional Inhibitory Concentration Index (FIC_i) of 0.5. This effect brings to the fore the possibility of lowering the doses of chemical antibiotics necessary, and therefore lowers the selective pressure which causes the occurrence of resistant bacterial strains. Recent studies by (Jiang et al., 2025), reveal that plant-based compounds have the potential to be used as antibiotic enhancers, by inhibiting bacterial efflux pumps, enabling the antibiotic to spend more time within the cell and act at reduced concentrations. This combined method is a strategic way to address the global issues related to antibiotic resistance in agriculture industry (Ju, et al., 2022).

The capacity of the extract to prevent biofilm formation with more than 90% of the MBC concentration is a basic finding. The first defense mechanism *R. solanacearum* uses to survive in the xylem vessels of the plant and endure adverse environmental factors and pesticides is biofilms. Interfering with this system is tantamount to robbing the bacteria of their powers to colonise and multiply. It follows the approach taken by (Ventola, 2015) in discussing the role of natural products in their capacity to target virulence factors and not just in influencing bacterial growth in a manner that minimizes the chances of resistance development. Also, the disruption of Quorum Sensing systems in the extract, as observed by (Yu et al., 2026), could be the root cause to this widespread biofilm inhibition.

Regarding practical application (in planta), the findings revealed a drastic reduction in Disease Severity Index (DSI) by approximately 85.6% among the untreated infected group to 19.5% among the group that was treated with the MBC concentration. This did not only enhance the preventative aspect but also improved the growth parameters like height and dry weight that were close to those of healthy plants. (Tripathi et al., 2019), indicate that some plant extracts are elicitors of Systemic Acquired Resistance (SAR) in plants rendering them more resistant to bacterial attack. (Elhalag et al., 2025), also established that the *E. camaldulensis* extracts have the ability to control bacterial wilt in solanaceous crops in field-simulated conditions. As a result, the *E. camaldulensis* extract does not only kill the bacteria, but also helps to improve the defensive structure of the crop, which is why the artificial infection results in restoration of normal growth levels even after being introduced into the crop (Montesinos, et al., 2023).

Lastly, the lack of any evidence of phytotoxicity at the concentrations used confirm the safety of this extract on the target crops. It is a competitive edge that biological substitutes have over chemical pesticides, which frequently have detrimental side effects on the development of plants or advantageous soil microorganisms. This effect may be further advanced in future with the help of nano-encapsulation technologies to provide the gradual discharge of active compounds and their protection against degradation as proposed by (Hosseinzadeh et al., 2013). Expanding on this, the stability of the *E. camaldulensis* extract in the different environmental factors (e.g. UV radiation, temperature variation, soil pH and microbial degradation) is a key consideration to the practical and extensive application of the extract as a commercial biopesticide. The focus of future studies should thus be on researching the best method to formulate this i.e. nano-

encapsulation, micro-encapsulation or emulsification. These strategies would greatly increase the shelf-life of the extract, safeguard the active components against early degradation, and provide a sustained and targeted release of the active components, thus, improving the long-term effectiveness and affordability of the extract in various agricultural applications. Lastly, although the host plants were not affected by phytotoxicity, a thorough evaluation of the effect of the extract on non-target organisms (especially beneficial soil microorganisms e.g. nitrogen-fixing bacteria, plant growth-promoting rhizobacteria, mycorrhizal fungi) is required to be accepted by the ecology to be integrated sustainably. Assessing the selectivity of the *E. camaldulensis* extract would reveal whether it is safe to soil ecologically and whether the use of the extract would not interfere with the delicate equilibrium of the soil microbiome, which is essential to the soil health, nutrient cycling, and the overall functioning of the ecosystem (Callaway and Aschehoug, 2000). Such researches are important to prove its appropriateness as a really green alternative to traditional chemical pesticides.

Conclusion

This research offers strong scientific data that the *E. camaldulensis* leaf extract is an effective and safe biological control against *R. solanacearum*. The strong phytochemical composition, especially the high phenolic and flavonoid content of the extract, provide it with a strong bactericidal activity, potential to disrupt the formation of biofilms, and a pronounced synergistic activity with conventional antibiotics. Moreover, the in planta tests provided evidence that it did not only lead to significant decreases in the severity of the disease, but there was also an impressive increase in the parameters of plant growth without any phytotoxic impact. These results are very compelling toward incorporation of *E. camaldulensis* extract within the Integrated Pest Management (IPM) program as one of the sustainable, eco-friendly solutions to the use of chemical pesticides in control of bacterial wilt disease in vegetable crops.

Conflict of Interest

The author declares that there is no conflict of interest regarding this article.

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