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Management of bacterial leaf blight of rice caused by *Xanthomonas oryzae* pv. *oryzae* using plant products and essential oils

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Abstract

A significant challenge to rice cultivation globally is that leaf blight caused by bacteria (BLB) severely impacts quality of the crop and yield. Increasing dependence on synthetic agrochemicals has raised serious concerns related to environmental contamination, pathogen resistance and human health hazards, thereby necessitating the development of sustainable and eco-friendly alternatives. The current study aimed to assess the efficacy of several plant extracts and essential oils in the combat toward BLB. Among tested botanicals, *Zingiber officinale* exhibited the highest antibacterial activity, recording inhibition zones of 0.30 cm and 0.50 cm at 5% and 10% concentrations, respectively. Among essential oils, lemongrass oil (500 ppm) showed superior efficacy with an inhibition zone of 0.40 cm under *in vitro* conditions. The most promising treatment, *Z. officinale* (10%), was further validated under pot culture conditions, where it recorded the lowest disease severity (PDI: 8.69). Field evaluation during the Pishanam season (2021-2022) confirmed its effectiveness, with seed treatment combined with foliar application resulting in the lowest PDI (5.40) and the maximum grain yield (6467 kg ha^{-1}) then *Phyllanthus niruri* (PDI: 7.32; yield: 5734 kg ha^{-1}). The efficacy of these treatments was further supported by GC-MS analysis which identified key bioactive compounds associated with antibacterial activity against Xoo. In order to promote the promise of identified plant-derived antimicrobial metabolites in sustainable BLB management, future research will concentrate upon *in silico* evaluation.

1. Introduction

One of the most significant staple grains produced worldwide, rice (*Oryza sativa* L.) provides the majority of people around the world to their main source of food. Asia accounts for around 90% of the world's rice consumption and production, highlighting the region's critical role in sustaining general nutrition (Bandumula, 2018). Due to its significance, rice production is significantly impacted by several of pathogenic organisms. Among the most severe is bacterial leaf blight (BLB), which is caused by *Xanthomonas oryzae* pv. o*ryzae* (Xoo). In accordance with reports, BLB can cause yield decline ranging up to 50 per cent globally (Shekhar and Kumar, 2020) along with as elevated to be 81.3% (Prasad *et al*., 2018; Swati *et al*., 2015). In early stages of plant growth, BLB appears as a vascular wilt. During the reproductive period, it develops into the typical signs of leaf blight (Naqvi, 2019). The rod-shaped, motile Gram-negative organism that initiates the infection penetrates the host organism primarily by wounds and then colonizes the xylem tissue (Yadeta *et al*., 2013). Before being classified as *X. oryzae,* the pathogen had many taxonomic alterations, evolving from *Bacillus oryzae* to *Pseudomonas oryzae* to *Bacterium oryzae* (Saxena *et al*., 2020).

The management of BLB is based on a multifaceted strategy that includes genetic, chemical, and cultural tactics; each of which comes with limits of their own. Cultural measures that reduce inoculum concentrations and disease incidence include removing contaminated debris, field sanitation, appropriate drainage, timely weeding, and balanced nutrient management; however, their effectiveness is frequently impacted by external factors (Niwas *et al*., 2021). Chemical that includes the utilization of antibacterial and bactericide products composed of copper provide rapid disease suppression but are associated with several drawbacks such as the emergence of resistant pathogen strains, environmental contamination, disruption of beneficial microbiota, increased production costs and regulatory restrictions (Orta-Rivera *et al*., 2023). Despite the widespread adoption of genetic resistance through traditional breeding and marker-assisted selection, resistance breakdown due to pathogen diversity and linkage drag altering desirable agronomic traits remains to be major concerns (Collins *et al*., 2018). Although, precise mutation of resistance and susceptibility genes is possible using cutting-edge genome modification like CRISPR-Cas9, challenges with off-target impacts, resistance durability, possible effects on plant physiological functions, as well as public and regulatory acceptance still exist (Zafar *et al*., 2020). Because of these constraints, there is a rising demand to implement ecologically sound and sustainable BLB

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management method. Biological control using beneficial micro-organisms has gained attention in recent years; however, concerns regarding ecological stability and long-term safety remain, as certain biocontrol agents may exhibit opportunistic behaviour under specific environmental conditions (Ram and Singh, 2018). Because of an abundance of bioactive secondary metabolites with antimicrobial properties, plant-derived extracts and essential oils have become promising substitutes in this aspect. These natural products have plenty of benefits especially biodegradability, low environmental effect, broad-spectrum efficacy against phytopathogens, and decreased chance of resistance development (Wani *et al*., 2022). Additionally, their targeted activity and unique mechanisms of action indicate that they are effective options for long-term disease management (Patel *et al*., 2025). The most recent studies has revealed that plant extracts such as the phenolic-rich extracts of *L. petiolata*, exhibit antibacterial properties against Xoo (Rattanaanan *et al*., 2025) and chloroform leaf extracts of *C. hirsutus* (Shivalingaiah and Sateesh, 2013). In order to effectively manage bacterial leaf blight in rice and promote sustainable agriculture and long-term crop yield, the current research reintroduction and systematic evaluation of plant extracts and essential oils offers a viable and ecologically sound approach.

2. Materials and Methods

2.1 Collection and preparation of plant extract

Twenty diverse botanicals were collected and properly washed with normal water flow. The samples had been used for the preparation of an extract after being shade-dried. For aqueous extraction, 5 g and 10 g of plant tissues were separately homogenized in equal volumes (1:1 w/v) of distilled water to obtain 5% and 10% concentrations, respectively. The blends were filtered through two layers of sterile muslin cloth and then centrifuged for 10 min at 10,000 rpm. The supernatants were subsequently collected and utilized as crude extracts.

2.2 Screening of botanicals and essential oils against BLB

The bacterial leaf blight pathogen was isolated from infected rice leaf samples collected from V.O.C AC and RI, Killikulam and the pure culture was maintained for subsequent studies. The bactericidal properties of plant extracts and essential oils were tested using the paper disc diffusion method. A sterile cotton swab was used to distribute uniformly a 24 h old bacterial culture onto sterile nutrient agar. The corresponding plant extracts (5% and 10%) and essential oil solutions (500 ppm, made using 0.1% Tween 20 as an emulsifier) were impregnated into sterile filter paper discs (6 mm diameter). The discs were air-dried under sterile conditions to remove excess moisture and then aseptically placed onto the inoculated agar. Discs treated with sterile distilled water (with emulsifier for oils) served as control. For 48 h, the plates were left to incubate at 28 ± 2°C. The diameter of the inhibitory zone was recorded. A total of three replication of each treatment were performed.

2.3 Evaluation of botanicals extracts and essential oils against BLB under pot culture conditions

The efficacy of selected plant extracts, *viz*., *Phyllanthus niruri*, *Anisomeles malabarica*, *Zingiber officinale*, *Ricinus communis*, *Parthenium hysterophorus*, *Justicia adhatoda*, *Ocimum sanctum*, *Emblica officinalis* and essential oil (lemongrass oil) were evaluated against BLB under glasshouse conditions. The ten treated rice variety ASD 16 seedlings were planted in mud pots filled with clay loam soil. A virulent culture of BLB was grown at room temperature, centrifuged, and the bacterial pellet was once more prepared in sterile distilled water to achieve a concentration of 1×10^8 CFU ml^{-1}. Using an appropriate emulsifier, plant extracts were made at a concentration of 10% and lemongrass oil at 500 ppm. Rice seedlings that were seven days old were evenly treated with the treatments. The pin-prick approach was used to inoculate plants with the bacterial suspension two days following spraying. Three replications of each treatment were carried out. Seven days after inoculation, disease symptoms were noticed. Ten randomly chosen leaves from each replication were used to score the disease severity using the IRRI Standard Evaluation System 2013 (SES) scale (Raina *et al*., 2019).

Grade	Disease intensity
0	No infection
1	1-5% leaf area infected
2	6-12% leaf area infected
3	13-25% leaf area infected
4	25-50% leaf area infected
5	51-100% leaf area infected

The per cent disease index (PDI) was worked out by using McKinney (1923) formula *viz.:*

$$\text{PDI} = \frac{\text{Sum of individual ratings}}{\text{Total number of leaves observed}} \times \frac{100}{\text{Maximum grade}}$$

2.4 Field evaluation of plant extracts against BLB

Field tests were conducted in 2021 and 2022 during the Pishanam seasons to evaluate the efficacy of several plant extracts against rice BLB. The experiments were conducted at the Rice Research Station in Ambasamudram (2022) and the Agricultural College and Research Institute in Killikulam (2021). The experiment was set up using a design with random blocks with three replications and seven treatments. In addition to an untreated control, the treatments included foliar spraying, seed treatment and a combination of 10% concentrations of *P. niruri* and *Z. officinale*. Seed treatment was performed prior to sowing, and foliar applications were carried out at the recommended crop stage. Symptoms expression was observed 15 days after spraying. McKinney's method was applied to find the per cent disease index (PDI). Grain yield was recorded at harvest and expressed as kg ha^{-1}. The formula below was applied to determine the cost-benefit ratio (CBR):

$$\text{CBR} = \text{Cost of cultivation (₹ ha}^{-1}\text{)} \,/\, \text{Gross return (₹ ha}^{-1}\text{)}$$

where,

$$\text{Gross return} = \text{Yield} \times \text{Market price of grain}$$

2.5 GC-MS analysis of effective botanicals

Z. officinale and *P. niruri* were chosen for phytochemical characterisation based on economic analysis and efficacy. A Shimadzu GC-MS (QP 2020) equipped with an Elite-1 (100% dimethyl polysiloxane)

stationary phase and a Rxi-5MS column (30 m × 0.25 mm ID) was used to examine 10% ethanolic extracts. The carrier gas utilized was 1 ml min^{-1} of helium. The internal temperature of the oven was set up to rise from 110°C for 2 min to 280°C with a 9 min break. The injector temperature was maintained at 250°C for the duration of the 45 min run. A 1 µl sample was injected for analysis. By comparing mass spectra with the NIST library (Version 2.0, 2005) using spectrum similarity and retention duration, substances were identified using Turbo Mass software (v5.1).

2.6 Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA), following the procedure described by Gomez and Gomez (1984). Treatment differences were found to be significant at the 5% probability level (p>0.05). Mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at p>0.05.

3. Results

3.1 Efficacy of plant extracts and essential oil against BLB pathogen

Table 1 and Figures 1a, b represent the *in vitro* antibacterial activity of different plant extracts against bacterial leaf blight, in which *Z. officinale* rhizome extract recorded the highest inhibition zone of 0.30 cm and 0.50 cm at 5 and 10 per cent concentrations, respectively, followed by *P. niruri* and *A. malabarica* leaf extracts with inhibition zones of 0.25 cm and 0.40 cm, and 0.20 cm and 0.33 cm, respectively. Table 2 and Figure 2 represent the *in vitro* evaluation of different essential oils against *X. oryzae* pv. *oryzae*, in which lemongrass oil at 500 ppm recorded the highest inhibition zone (0.40 cm, followed by citronella oil and cinnamon oil with inhibition zones of 0.30 cm each, whereas eucalyptus oil exhibited the lowest inhibition zone (0.10 cm).

Table 1: The effect of extracts from plants against rice bacterial leaf blight

S.No	Botanical name	Place of collection	Common name	Inhibition zone (cm)	
				5%*	10%*
1.	*Withania somnifera*	V.O.C AC and RI,	Aswagandha	0.10^{e}	0.10^{e}
2.	*Ocimum sanctum*	Killikulam	Tulsi	0.15^{d}	0.20^{d}
3.	*Aegle marmelos*		Vilvam	0.00^{f}	0.00^{f}
4.	*Bougainvillea spectabilis*		Bougainvillea	0.00^{f}	0.20^{d}
5.	*Azardirachta indica*		Neem	0.10^{e}	0.10^{e}
6.	*Justicia adhatoda*		Adathoda	0.15^{d}	0.20^{d}
7.	*Calotropis gigantean*		Eruku	0.00^{f}	0.20^{d}
8.	*Cilitoria ternatea*		Sangupushpam	0.10^{e}	0.20^{e}
9.	*Acalypha indica*		Kuppaimaeni	0.10^{e}	0.00^{f}
10.	*Coleus amboinicus*		Coleus	0.10^{e}	0.20^{d}
11.	*Phyllanthus niruri*		Keezhanelli	0.25^{b}	0.40^{b}
12.	*Tribulus terrestris*		Nerunji	0.10^{e}	0.10^{e}
13.	*Allium sativum*		Garlic	0.10^{e}	0.20^{d}
14.	*Parthenium hysterophorus*		Parthenium	0.15^{d}	0.20^{d}
15.	*Senna alexandrina*		Senna	0.10^{e}	0.20^{d}
16.	*Anisomeles malabarica*		Perunthumbai	0.20^{c}	0.33^{c}
17.	*Zingiber officinale*		Ginger	0.30^{a}	0.50^{a}
18.	*Ricinus communis*		Castor	0.15^{d}	0.25^{d}
19.	*Murraya koenigi*		Curry Leaf	0.10^{e}	0.20^{e}
20.	*Emblica officinalis*		Amla	0.15^{d}	0.25^{d}
21.	Control			0.00^{f}	0.00^{f}
		CD (0.05)		0.045	0.074

* Values represent the mean of three replications. Means sharing the same letter under DMRT (p=0.05) are not significantly different.

Figure 1a: ***In vitro*** **evaluation of botanicals against BLB.**

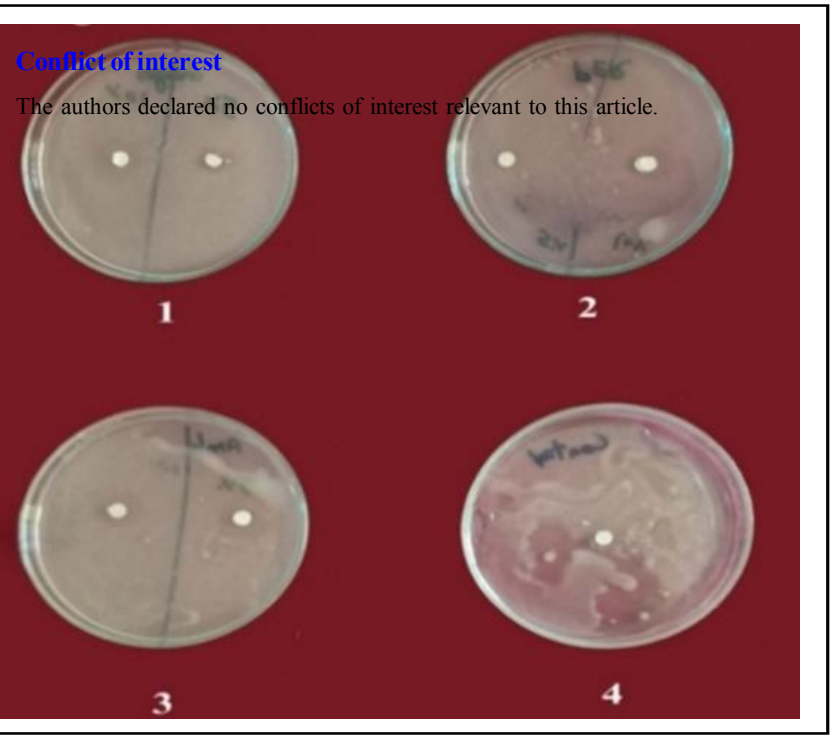


Figure 1b: Effective plant extract treatments against bacterial leaf blight (BLB): (1) ***Zingiber officinale*****, (2)** ***Anisomeles malabarica*****, (3)** ***Phyllanthus niruri,*** **and (4) untreated control.**

Conflict of interest

The authors declared no conflicts of interest relevant to this article.

3.2 Efficacy of identified effective plant products against BLB under glass house condition

Table 3 represents the effect of different plant extracts against bacterial leaf blight under pot culture conditions, in which T3 (*Z. officinale* @ 10%) recorded the lowest per cent disease index (8.69) compared to the inoculated control (67.66), followed by T1 (*P. niruri* @ 10%) and T2 (*A. malabarica* @ 10%) with PDI values of 10.66 and 12.70, respectively.

Table 2: Effect of essential oils against bacterial leaf blight of rice

S. No.	Common name	Inhibition zone (cm)*
1.	Eucalyptus oil @ 500 ppm	0.10[d]
2.	Wintergreen oil @ 500 ppm	0.20[c]
3.	Lemongrass oil @ 500 ppm	0.40[a]
4.	Citronella oil @ 500 ppm	0.30[b]
5.	Cinnamon oil@ 500 ppm	0.30[b]
6.	Control	0.00[e]
	CD (0.05)	0.081

Means are based on three replications. Treatments with identical letters are not significantly different at $p>0.05$ (DMRT).

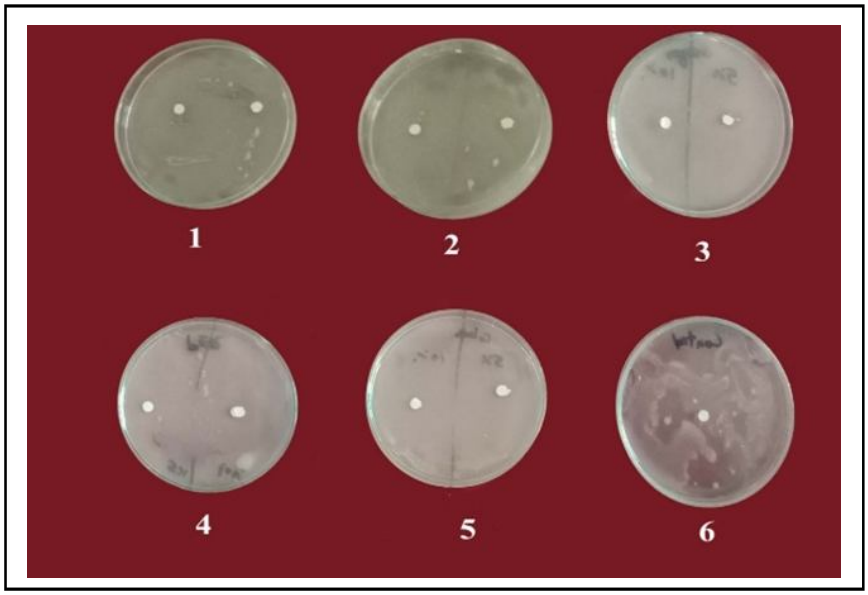


Figure 2: *In vitro* evaluation of different essential oils against bacterial leaf blight (BLB): (1) Eucalyptus oil, (2) Wintergreen oil, (3) Lemongrass oil, (4) Citronella oil, (5) Cin namon oil, and (6) untreated control.

Table 3: Effect of plant products against BLB under glass house condition

Treatment number	Treatments	Per cent disease index*
T 1	*Phyllanthus niruri* @10%	10.66[ab]
T 2	*Anisomeles malabarica* @ 10%	12.70[bc]
T 3	*Zingiber officinale* @ 10%	8.69[a]
T 4	*Ricinus communis* @ 10%	14.55[cd]
T 5	*Parthenium hysterophorus*	19.47[f]
T 6	*Justicia adhatoda*	20.00[g]
T 7	*Ocimum sanctum*	20.18[g]
T 8	*Emblica officinalis* @ 10%	20.88[g]
T 9	Lemongrass oil @ 500 ppm	15.02[e]
T 10	Inoculated control	67.66[h]
	CD (p=0.05)	2.12

Means are based on three replications. Treatments with identical letters are not significantly different at $p>0.05$ (DMRT).

3.3 Effect of plant extract against BLB of rice under field condition

Tables 4 and 5 together with Figures 3 and 4 represent the effect of different plant product treatments against bacterial leaf blight under field conditions during Pishanam 2021 and 2022, respectively. During Pishanam 2021, field trial was conducted with seven treatments were followed with three replications. Observation of disease intensity was recorded on 15 days after spraying. Among the different treatments imposed against BLB under field condition, T6 (Seed treatment and spraying of *Z. officinale* @ 10%) showed a minimum per cent disease index (5.12) and optimum yield of 6560 kg/ha against untreated control (25.80 and 4250 kg/ha, respectively). During Pishanam 2022, field trial was conducted at Rice Research Station, Ambasamudram with effective plant products against bacterial leaf blight. For this trial, seven treatments were followed with three replications. Observation of disease intensity was recorded on 15 days after spraying. Among the different treatments imposed against BLB under field condition, T6 (Seed treatment and spraying of *Z. officinale* @ 10%) found that most significant yield of 6342 kg/ha and a minimal PDI of 5.61.

Table 4: Effect of plant products against bacterial leaf blight of rice under field trail I

Treatment number	Treatments	Percent disease index*	Yield kg/ha	CBR
T 1	Seed treatment of *Phyllanthus niruri* @10%	8.39^{f}	5220^{c}	1:2.20
T 2	Spraying of *Phyllanthus niruri* @10%	7.92^{e}	5600^{bc}	1:2.23
T 3	Seed treatment and spraying of *Phyllanthus niruri* @10%	7.00^{d}	5852^{bc}	1:2.30
T 4	Seed treatment of *Zingiber officinale* @10%	6.53^{c}	5925^{ab}	1:2.09
T 5	Spraying of *Zingiber officinale* @10%	6.00^{b}	6230^{ab}	1:2.14
T 6	Seed treatment and spraying of *Zingiber officinale* @10%	5.12^{a}	6560^{a}	1:2.20
T 7	Untreated control	25.80^{g}	4250^{d}	
	CD (0.05)	2.15	642.13	

*Means are based on three replications. Treatments with identical letters are not significantly different at $p<0.05$ (DMRT).

Figure 3: Evaluation of plant extract against BLB in field trail I.

Table 5: Effect of plant products against bacterial leaf blight of rice under field trail II

Treatment number	Treatments	Percent disease index*	Yield kg/ha	CBR
T 1	Seed treatment of *Phyllanthus niruri* @10 %	8.67[f]	5000[f]	1:2.18
T 2	Spraying of *Phyllanthus niruri* @10%	8.10[e]	5416[e]	1:2.20
T 3	Seed treatment and spraying of *Phyllanthus niruri* @10%	7.53[d]	5650[d]	1:2.25
T 4	Seed treatment of *Zingiber officinale* @ 10%	6.78[c]	5694[c]	1:2.05
T 5	Spraying of *Zingiber officinale* @ 10%	6.10[b]	6025[b]	1:2.11
T 6	Seed treatment and spraying of *Zingiber officinale* @ 10%	5.61[a]	6342[a]	1:2.16
T 7	Untreated control	28.63[g]	4100g	
	CD (0.05)	26.36	690.59	

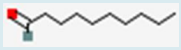
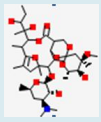
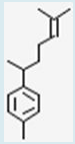
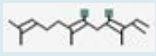
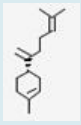
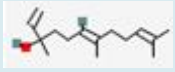
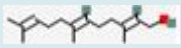
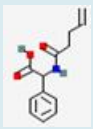
*Means are based on three replications. Treatments with identical letters are not significantly different at $p<0.05$ (DMRT).

Figure 4: Evaluation of plant extract against BLB in field trail II.

3.4 Identification of metabolites from effective plant extracts

GC-MS analysis of *Z. officinale* and *P. niruri* extracts revealed a diverse array of bioactive compounds, highlighting their strong antimicrobial potential against phytopathogens. Tables 6 and 7 represent the GC-MS profiling and identified bioactive compounds of *Z. officinale* and *P. niruri*, respectively, in which 29 and 40 compounds were detected, predominantly belonging to terpenoids, phenolics, fatty acids, esters and aromatic derivatives, indicating a complex and synergistic chemical composition. In *Z. officinale*, the major constituent was a furan derivative (26.05%), followed by methoxy phenol derivative (6.89%), dihydrocapsaicin (6.16%), benzene derivative (5.49%) and 9,12-octadecadienoic acid (4.97%), suggesting their key role in antimicrobial activity. Its biological function is further supported by the presence of distinctive chemicals including gingerol, capsaicin, nerolidol, α-farnesene and β-bisabolene, which are known for their antimicrobial properties. Similarly, *P. niruri* extract exhibited major constituents including 3,4-dimethoxy-N,N-dimethylbenzylamine (22.02%), 9,12-octadecadienoic acid (9.90%), n-hexadecanoic acid (9.06%) and fumaric acid derivatives (9.49%), along with other important compounds such as 9,12,15-octadecatrienoic acid (4.92%), phytol and tetradecanoic acid which are known for their antimicrobial and antioxidant activities.

Table 6: List of metabolites identified from *Z. officinale* through GC-MS analysis

Peak	Retention time	Area %	Volatile compound	Biological activity	Chemical structure
1	6.431	0.62	endo-Borneol	Antifungal	
2	6.687	0.52	Decanal	Antimicrobial	
3	8.997	0.36	Tricyclo undecene derivative	Antibacterial	
4	9.064	2.03	β-Curcumene	Antioxidant	
5	9.220	5.49	Benzene derivative	Antioxidant	
6	9.331	2.43	Cyclohexadiene derivative	Antifungal	
7	9.364	1.46	α-Farnesene	Antimicrobial	
8	9.442	2.39	β-Bisabolene	Antifungal	
9	9.842	1.19	Nerolidol	Antimicrobial	
10	10.542	3.66	Butanone derivative	Antibacterial	
11	10.875	0.36	Sesquisabinene hydrate	Antioxidant	
12	10.953	0.77	Dodecatrienol derivative	Antimicrobial	
13	12.708	2.33	n-Hexadecanoic acid	Antifungal	
14	13.275	0.43	Aminobenzeneacetic acid derivative	Antimicrobial	
15	13.586	0.42	Methoxyphenyl derivative	Antifungal	

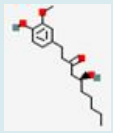
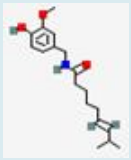
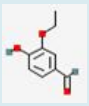
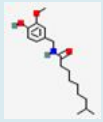
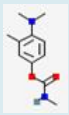
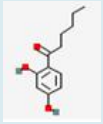
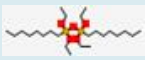
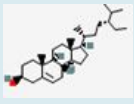
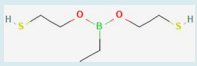
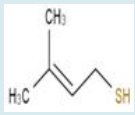
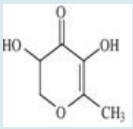
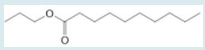
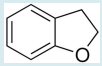
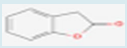
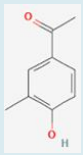
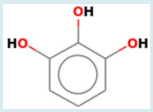
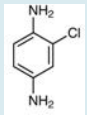
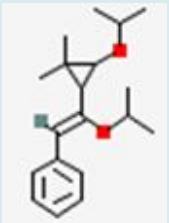
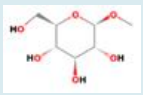
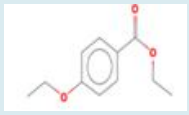
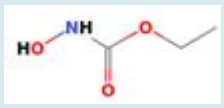
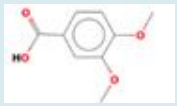
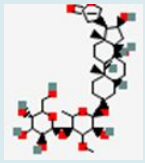
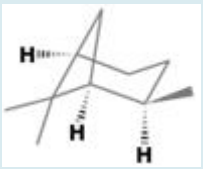
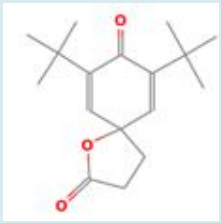
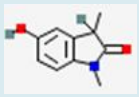
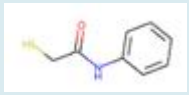
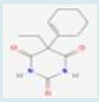
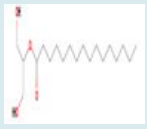
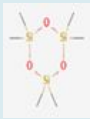
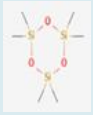
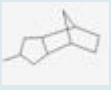
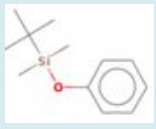
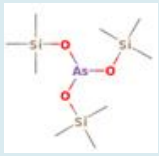
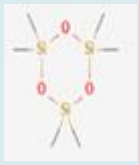
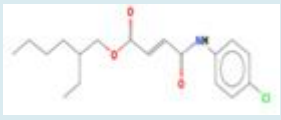
16	13.730	1.47	Phenylacetic acid derivative	Antifungal	
17	13.852	4.97	9,12-Octadecadienoic acid (Linoleic acid)	Antioxidant	
18	14.841	26.05	Furan derivative	Antioxidant	
19	15.063	1.24	Gingerol	Antifungal	
20	15.130	0.48	Capsaicin	Antimicrobial	
21	15.863	1.16	Ethyl vanillin	Antifungal	
22	15.974	6.16	Dihydrocapsaicin	Antimicrobial	
23	16.052	1.01	Aminocarb	Antimicrobial	
24	16.196	0.47	Hexanoylresorcinol	Antioxidant	
25	17.263	1.71	Dihydroxyacetophenone derivative	Antimicrobial	
26	17.863	0.35	Cyclotrisiloxane	Antibacterial	
27	17.996	0.33	Silane derivative	Antimicrobial	
28	21.274	0.37	Siloxane derivative	Antifungal	
29	21.474	1.51	γ-Sitosterol	Antimicrobial	

Table 7: List of metabolites identified from *P. niruri* through GC-MS analysis

Peak	Retention time	Area %	Volatile compound	Biological activity	Chemical structure
1	4.420	0.40	Boronic acid, ethyl-, bis(2-mercaptoethyl ester)	Antimicrobial	
2	5.987	0.12	3-Methyl-3-butene-1-thiol	Antimicrobial	
3	6.109	0.40	4H-Pyran-4-one, 2,3-dihydro-3,5-di hydroxy-6-methyl-	Antimicrobial	
4	6.687	0.20	Decanoic acid, propyl ester	Antioxidant and antibacterial	
5	6.853	0.40	Benzofuran, 2,3-dihydro-	Antibacterial and antiviral	
6	7.075	0.30	2-Coumaranone	Antibacterial	
7	7.753	0.42	4-Hydroxy-3-methylacetophenone	Antioxidant	
8	8.375	0.39	1,2,3-Benzenetriol	Antimicrobial	
9	8.509	0.21	1,4-Benzenediamine, 2-chloro-	Antibacterial	
10	8.820	1.61	2-Isopropoxyethyl propionate	Antiviral	
11	9.175	0.48	Cyclopropane, 1,1-dimethyl-2-(1-me thylethoxy)-3-(3-methyl-1-pentynyl)-	Antimicrobial	
12	9.331	0.19	beta.-D-Glucopyranoside, methyl	Antibacterial	

13	9.586	0.55	Benzoic acid, 4-ethoxy-, ethyl ester	Antimicrobial and antibacterial	
14	10.097	0.16	Carbamic acid, hydroxy-, ethyl ester	Antibacterial	
15	10.319	0.19	2-(3,4-Dimethyl-.alpha.-thiosemica rbazonobenzyl)benzoic acid	Antimicrobial	
16	10.686	0.78	Card-20(22)-enolide, 3-[(2,6-dideoxy -4-O-.beta.-D-glucopyranosyl-3-O -methyl-.beta.-D-ribo-hexopyranosy l)oxy]-5,14-dihydroxy-19-oxo-, (3. beta.,5.beta.)-	Antimicrobial	
17	11.330	0.94	Tetradecanoic acid	Antioxidant	
18	11.875	0.42	Bicyclo[3.1.1]heptane, 2,6,6-trime th yl-, (1.alpha.,2.beta.,5.alpha.)	Antioxidant and antimicrofouling	
19	11.191	0.16	2-Pentadecanone, 6,10,14-trimethyl	Antioxidant	
20	12.042	0.17	Tetradecanal	Antibacterial	
21	12.175	0.19	17-Pentatriacontene	Antibacterial	
22	12.408	0.15	7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione	Antifungal and antibacterial	
23	12.708	9.06	n-Hexadecanoic acid	Antioxidant	

24	13.619	0.12	2,3-dihy droxypropyl ester	Antibacterial	
25	13.675	0.62	Phytol	Antimicrobial and antioxidant	
26	13.852	9.90	9,12-Octadecadienoic acid (Z,Z)-	Antimicrobial	
27	14.286	1.04	Indole-2-one	Antimicrobial	
28	15.108	0.11	Acetamide,	Antibacterial	
29	15.885	0.21	Cyclobarbital	Antimicrobial	
30	15.974	0.98	Hexadecanoic acid	Antioxidant	
31	16.885	0.26	1,2-Bis(trimethylsilyl)benzene	Antioxidant and antimicrobial	
32	17.019	0.28	1,4-Bis(trimethylsilyl)benzene	Antioxidant and antimicrobial	
33	17.474	0.23	Cyclotrisiloxane, hexamethyl-	Antimicrobial	
34	17.919	0.15	Cyclotrisiloxane, hexamethyl-	Antimicrobial	
35	17.996	22.02	3,4-Dimethoxy-N,N-dimethyl-benzylamine	Antibacterial	
36	18.063	2.65	Phenol tbdms	Antimicrobial	

37	18.141	0.70	Arsenous acid, tris(trimethylsily) ester	Antimicrobial	
38	18.230	0.24	Cyclotrisiloxane, hexamethyl-	Antimicrobial	
39	18.463	9.49	Fumaric acid	Antimicrobial	

4. Discussion

Bacterial leaf blight drastically decreases the outcome of rice, an essential cereal in the world. Developing integrated disease management methods that are environmentally sound is crucial due to the need for ecological sustainability and the rising need for food. Because of their affordability, safety and biodegradability, plant extracts and essential oils have become effective substitutes in this case. Thus, the current study was carried out to evaluate the antibacterial efficacy of several botanicals and identify the bioactive elements of these plants that prevent the disease. Consistent with earlier reports (John and James, 1999), the present investigation demonstrated that plant extracts can effectively suppress pathogen activity. Among the twenty botanicals screened under *in vitro* conditions, *Z. officinale* exhibited the highest antibacterial activity, recording inhibition zones of 0.30 cm and 0.50 cm at 5% and 10% concentrations, respectively, followed by *P. niruri*. The addition of bioactive secondary metabolites including phenolics, flavonoids and terpenoids, which damage bacterial cell membranes and obstruct metabolic pathways may be the reason for extract higher efficiency. These results are consistent with those of Mukeshambala *et al*. (2024), who emphasized the antibacterial potential of *P. niruri* because of its lignan and flavonoid content and Adamu *et al*. (2021), who observed a concentration-dependent increase in inhibition. The current findings are corroborated by Srinivas *et al*. (2024), who reported the antagonistic activity of *A. sativum*, *A. indica* and *Z. officinale* against BLB. The antibacterial properties of essential oils, which are volatile byproducts of secondary metabolism in plants are well known (Šovljanski *et al*., 2023). Lemongrass oil at 500 ppm showed the greatest inhibition in the present analysis (0.40 cm), followed by citronella and cinnamon oils (0.30 cm each). These findings support previous research (Singh *et al*., 2018) that found essential oils have potent antibacterial action. Citral (geranial and neral), which damages membrane integrity and allows cellular contents to leak out, may be responsible for lemongrass oil greater effectiveness. The moderate activity of citronella and cinnamon oils may be due to compounds such as citronellal, geraniol and cinnamaldehyde, which inhibit enzymatic systems and metabolic functions. Supporting this, Kolozsváriné Nagy *et al*. (2023) reported that essential oils exhibit significant *in vitro* inhibition and low MIC values against *Xanthomonas* spp., while Singh *et al*. (2017) demonstrated their ability to suppress virulence and biofilm formation through quorum sensing inhibition.

Under glasshouse conditions, *Z. officinale* at 10% recorded the lowest percent disease index (8.69), followed by *P. niruri*, indicating their strong efficacy in reducing disease severity. The effectiveness of these botanicals under pot culture suggests their ability to function beyond *in vitro* conditions possibly through combined host immunity promotion and antibacterial effect. Gangwar *et al*. (2021) and Labu *et al*. (2026), who showed significant decreases in BLB severity utilizing botanical extracts under controlled conditions corroborate our findings. In comparison to the untreated control the combination of seed treatment and 10% foliar spray of *Z. officinale* produced the best grain yield (6560 kg ha^{-1}) and the lowest disease incidence (PDI 5.12) at the field level. Improved plant health, long-term disease suppression and early-stage protection may all contribute to this improved performance. The reduction in disease severity likely contributed to better photosynthetic efficiency and grain filling thereby increasing yield.

GC-MS analysis further substantiated the antimicrobial potential of the selected botanicals. *Z. officinale* extract revealed a complex mixture of 29 compounds including terpenoids, phenolics and fatty acids with major constituents such as furan derivatives, methoxy phenols and dihydrocapsaicin. Similarly, *P. niruri* extract contained 39 compounds, dominated by 3,4-dimethoxy-N, N-dimethylbenzyla-mine, octadecadienoic acid, and hexadecanoic acid. The presence of phenolic chemicals and fatty acids in both extracts indicates to the identical mechanism of metabolic inhibition and membrane disruption. These results align with previous research (Zhang *et al*., 2021; Yousfi *et al*., 2021) that found fatty acids, phenolics, and terpenoids have a major role in antibacterial action. Compounds with antibacterial and antioxidant qualities in *P. niruri* include phytol and octadecadienoic acid (Fatema *et al*., 2019; Hasan *et al*., 2024).

5. Conclusion

The study concludes that plant-derived extracts and essential oils provide an effective and sustainable approach for managing bacterial leaf blight in rice. Among the treatments evaluated, *Z. officinale* and *P. niruri* exhibited strong antibacterial activity under *in vitro* conditions which was further validated under pot and field conditions. Notably, integrated application of *Z. officinale* (seed treatment + foliar spray at 10%) significantly reduced disease severity and enhanced grain yield. Essential oils, particularly lemongrass oil also showed promising inhibitory effects against the pathogen. Numerous bioactive substances, including as phenolics, terpenoids and fatty acids, were found by GC-MS analysis. These substances most likely contribute to antimicrobial activity by disrupting membranes and interfering with metabolism.

Acknowledgements

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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