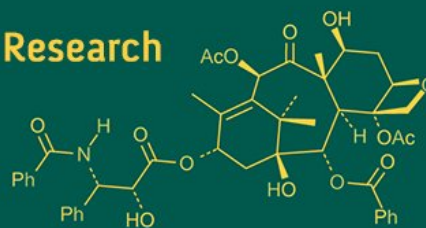


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Guddu Rajput
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Ramji Singh
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Ankit Kumar Singh
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Prashant Mishra
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Uday Pratap Shahi
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Gaje Singh
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Mukesh Kumar
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Corresponding Author:
Ankit Kumar Singh
Sardar Vallabhbhai Patel
University of Agriculture and
Technology, Meerut, Uttar
Pradesh, India

Eco-friendly management of bacterial leaf blight of rice using botanicals and antibiotic combinations

Guddu Rajput, Ramji Singh, Ankit Kumar Singh, Prashant Mishra, Uday Pratap Shahi, Gaje Singh and Mukesh Kumar

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Abstract

Bacterial leaf blight (BLB), caused by *Xanthomonas oryzae* pv. *oryzae*, is an economically important disease of rice that can substantially reduce crop productivity under favourable environmental conditions. Increasing concerns regarding the intensive use of chemical bactericides and the development of reduced sensitivity to antibiotics have created a need for effective and comparatively eco-friendly disease-management options. The present investigation evaluated the antibacterial and disease-suppressing efficacy of selected plant products, natural products, antibiotics and antibiotic-fungitoxicant combinations against BLB of Basmati rice cv. PB-1121 under laboratory and field conditions. The pathogen was isolated from naturally infected rice leaves collected from the Crop Research Centre, SVPUAT, Meerut, and maintained on nutrient agar medium. *in vitro* efficacy was evaluated using an agar diffusion assay at different concentrations, while field efficacy was assessed in a randomized block design with three replications and ten treatments. Among the natural and plant products evaluated *in vitro*, cow urine produced the greatest inhibition zone, increasing from 8.50 mm at 5% to 12.33 mm at 10% and 15.66 mm at 15%. Among antibiotic and fungitoxicant combinations, streptomycin + oxytetracycline produced the highest inhibition at 1% (12.50 mm) and 2% (12.33 mm), whereas neem oil + copper oxychloride produced the greatest inhibition at 4% (16.00 mm). Under field conditions, streptomycin + oxytetracycline recorded the lowest disease intensity (49.76%) and maximum disease control (36.52%). However, the highest grain yield (43.61 q ha⁻¹) was obtained with streptomycin + copper oxychloride, followed by oxytetracycline + copper oxychloride (43.33 q ha⁻¹) and streptomycin + oxytetracycline (41.11 q ha⁻¹). The untreated control recorded the highest disease intensity (78.39%) and lowest grain yield (28.61 q ha⁻¹). The findings demonstrate that treatment performance under laboratory conditions did not necessarily correspond to field performance, emphasizing the importance of integrated laboratory and field evaluation. Antibiotic combinations showed the most consistent disease suppression, whereas selected plant and natural products demonstrated potential as supplementary components of an eco-friendly BLB management programme.

Keywords: Bacterial leaf blight, *Xanthomonas oryzae* pv. *oryzae*, basmati rice, botanicals, cow urine, neem oil, streptomycin, oxytetracycline, eco-friendly disease management

1. Introduction

Rice (*Oryza sativa* L.) belongs to the family Poaceae as it is an important food crop with two important species such as *Oryza sativa* (Asian rice) and *Oryza glaberrima* (African rice) (Mohapatra *et al.*, 2025) ^[10]. Genus *Oryza* has another species, namely, *Oryza glaberrima* i.e. wild species. In Asia, *O. sativa* is differentiated into three sub-species based on geographical distribution, namely *indica*, *japonica*, and *javanica*. The plant is native to semi-aquatic conditions, where the presence of inter-organ aerenchyma facilitates the exchange of respiratory gases in submerged plant parts. Rice is a bisexual, self-pollinated crop having a growth period of 3-6 months (Mohapatra *et al.*, 2021) ^[9], which is consumed by more than 50 percent of world population. It contributes 23 percent and 50 percent of total calories consumed by global and Indian population respectively. Rice is an essential component of the diets and livelihoods of over 3.5 billion people. It is consumed as staple food, fulfilling daily energy demands and part of the protein requirement. Brown rice is comparatively more nutritious, containing more lipids, minerals, vitamins, dietary fiber, micronutrients, and bioactive compounds (Zhao *et al.*, 2020) ^[20]. Rice provides 2/3 of the calories for most Asian countries with rice-based diets.

Although rice is grown in more than 100 countries, 90 percent of the total global production comes from few Asian countries viz. China, India (Valavanidis *et al.*, 2025) [19]. The worldwide area under rice cultivation in 2025-26 was about 172.72 million hectares with production of 542.82 million metric tons and productivity 4.70 metric tons/hectares⁻¹ whereas in India the area under cultivation was about 52 million hectares with production of about 152 million metric tons and productivity about 4.39 metric tons/hectares⁻¹. In India Telangana shares a high percent of production of about 22 percent followed by Uttar Pradesh with 11 percent and west Bengal with 11 percent.

"Basmati" is long grain aromatic rice grown for many centuries in a specific geographical area, in the Himalayan foothills of the Indian sub-continent, blessed with characteristics of extra-long slender grains that elongate at least twice their original size with a characteristic soft and fluffy texture upon cooking, delicious taste, superior aroma and distinct flavor, Basmati rice is unique among other aromatic long-grain rice varieties (APEDA). The areas of Basmati Rice production in India as per Basmati Export Development Foundation (BEDF) survey report 2024-25 are Punjab, Haryana, Himachal Pradesh, Jammu & Kashmir, Uttar Pradesh and Uttarakhand. Rice is prone to many diseases among them bacterial diseases are most destructive which cause significant yield loss. Bacterial diseases such as bacterial leaf blight (BLB) (*Xanthomonas oryzae* pv. *oryzae*), bacterial leaf streak (BLS) (*Xanthomonas oryzae* pv. *oryzicola*) and bacterial panicle blight (BPB) (*Burkholderia glume*) have regular occurrence (Kumar *et al.*, 2017) [6]. The bacterial leaf blight disease is caused by *Xanthomonas oryzae* pv. *oryzae* is one of the most serious diseases in irrigated and rainfed ecosystem in Asia and cause considerable loss. It is considered as a major threat to rice production because of its wide spread, distribution and its destructiveness under favourable conditions (Behera *et al.*, 2024) [1]. It is one of the major diseases of rice which can cause overall 10-95 percent yield losses (Kurniawati *et al.*, 2021) [7]. It is a destructive disease of rice causes 20-50 percent yield losses in conducive conditions. Bacterial leaf blight (BLB) usually attacks rice in the flowering stage and can cause yield losses of up to 50 percent in severely infected fields (Logavito *et al.*, 2025) [8]. The *Xanthomonas oryzae* pathogen is distributed from infected leaves to roots and then from roots to the soil and nearby water. Grasses in the fields contribute to the perpetuation of the infection cycle serving as potential reservoirs that maintain the pathogen's presence in the environment (Ritbamrung *et al.*, 2025) [14]. The symptom of bacterial blight can be categorized into leaf blight wilting (Kressek) and whitish-yellow leaf. The leaf blight symptoms described by longitudinal lesions developed along the leaf edge. The lesion starts as small water-soaked streaks a few centimeters from the tip, where water pores are distributed. It rapidly enlarges in length and width, forming a yellow to greyish white in a colour lesion with a wavy margin along the leaf edge until the entire leaf dries up.

Generally, the Gram-negative bacteria *Xanthomonas oryzae* pv. *oryzae* are the causative agent of bacterial leaf blight (BLB), received attention for being an economically damaging pathogen of rice worldwide (Sanya *et al.*, 2022) [15]. In the recent past, the disease is mainly managed by various chemicals like copper fungicide and antibiotics which are deleterious to the environment and human health

and are becoming less effective due to development of antibiotic resistance in BLB pathogen (Javeedvali *et al.*, 2024) [5]. Because they offer a sustainable, safe, and environmentally friendly substitute for chemical pesticides, the use of botanicals and plant extracts to control bacterial leaf blight (BLB) in rice. These natural products, which are rich in antimicrobial compounds like phenolics, flavonoids, alkaloids, tannins, and terpenoids, effectively suppress the BLB pathogen *Xanthomonas oryzae* pv. *oryzae*. They are also biodegradable, leave no toxic residues, and present few health risks, making them appropriate for both farmers and consumers. In addition to being affordable, readily accessible, and consistent with integrated disease management strategies, botanicals bolster the plant's natural defensive systems, guaranteeing long-term and sustainable BLB control.

2. Materials and Methods

2.1 Experimental site

The investigation was conducted at the Crop Research Centre and Biocontrol Laboratory of the Department of Plant Pathology, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India. The experimental site is located at approximately 29°01' N latitude and 77°45' E longitude at an elevation of about 237 m above mean sea level. The region has a semi-arid subtropical climate, with hot summers and cool winters.

2.2 Rice cultivar

Basmati rice cultivar PB-1121, described in the source document as highly susceptible to bacterial leaf blight, was used for field evaluation. Seed material was obtained through the APEDA-associated source near SVPUAT, Meerut.

2.3 Isolation and maintenance of the pathogen

Rice leaves showing typical BLB symptoms were collected from the Crop Research Centre. Infected leaf tissues were washed thoroughly and cut into approximately 5-mm pieces containing both healthy and diseased tissue. The pieces were surface sterilized with 0.1% sodium hypochlorite for 30-60 s and rinsed three times with sterile distilled water. The sterilized tissues were aseptically transferred onto nutrient agar medium and incubated at 25±2 °C. Bacterial colonies developing after approximately 48 h were transferred individually to nutrient agar slants to obtain pure cultures. The nutrient agar medium consisted of beef extract (3 g), peptone (5 g), agar (20 g) and distilled water (1000 mL), adjusted to pH 6.8 and sterilized before use.

2.4 Pathogenicity assessment

Pathogenicity was evaluated under field conditions using 25-day-old PB-1121 seedlings. Seedlings were transplanted at 20 × 10 cm spacing and maintained under adequate moisture. Bacterial inoculation was performed at the maximum tillering stage using a bacterial suspension of approximately 10⁷-10⁸ cells mL⁻¹. Uninoculated plants were maintained as controls. Disease development was recorded, and the pathogen was re-isolated from symptomatic tissues to confirm association with the observed disease.

2.5 In vitro evaluation of treatments

The antibacterial activity of plant products, natural products, antibiotics and combinations was assessed using a diffusion-

based assay. The laboratory experiment was conducted in a completely randomized design with three replications. Observations were recorded 72 h after inoculation and inhibition zones were expressed in millimetres. For the plant/natural products, BLB-A, BLB-B, BLB-C, Solution A Extracts of-Adhathoda Vasica Extract-20ml Azadiracta indica-20ml Equisetum hyemale-20ml Allium sativa-20ml Hydrastis canadensis-20ml Solvent-Alcohol/water 50:50 Solution B-Extracts 100ml Aconite nap-20ml Plantago-20ml Aloe vera-20ml Ocimum sant-20ml Eucalyptus globulus-20ml Solvent Alcohol/Water-90:10 Solution C-Mix of A + B. Cow dung extract and cow urine were evaluated at 5, 10 and 15% concentrations. The antibiotic/fungitoxicant treatments included streptomycin + oxytetracycline + copper oxychloride, streptomycin + oxytetracycline, neem oil + copper oxychloride and neem oil at 1, 2 and 4% concentrations. The inhibition zone was calculated as the diameter of the growth-inhibited area after accounting for the diameter of the well.

2.6 Field evaluation

The field experiment was conducted using a randomized block design with three replications and ten treatments. Individual plots measured 3 × 4 m, and rice seedlings were transplanted at 20 × 10 cm spacing. Twenty-one-day-old seedlings were transplanted at three seedlings per hill.

The treatments were

Treatment	Treatment description
T ₁	BLB-A plant product @ 2 mL L ⁻¹
T ₂	BLB-B plant product @ 2 mL L ⁻¹
T ₃	BLB-C plant product @ 2 mL L ⁻¹
T ₄	Streptomycin @ 15 g ha ⁻¹ + copper oxychloride @ 500 g ha ⁻¹
T ₅	Oxytetracycline @ 75 g ha ⁻¹ + copper oxychloride @ 500 g ha ⁻¹
T ₆	Streptomycin @ 15 g ha ⁻¹ + oxytetracycline @ 75 g ha ⁻¹
T ₇	Cow dung extract 10%
T ₈	Cow urine 10%
T ₉	Neem oil @ 0.03%
T ₁₀	Untreated control

All field treatments were applied as foliar sprays at 45 and 60 days after transplanting.

2.7 Disease assessment

Disease scoring was done after 90 days of transplanting with the help of scale. Disease intensity was assessed using the 0-9 IRRI scale based on the proportion of leaf area affected. The grades were 0, 1, 3, 5, 7 and 9 corresponding to 0, 1-5, 6-12, 13-25, 26-50 and 51-100% affected leaf area, respectively. Percent disease intensity was calculated from the observed disease scores.

2.8 Plant growth and yield observations

Plant height was recorded at 60 and 90 days after sowing. Panicle length was recorded at maturity. The crop was harvested during 25-26 October 2025. Grain yield from each plot was recorded separately and adjusted to 14% moisture before conversion to q ha⁻¹.

2.9 Statistical analysis

The experimental data were subjected to analysis of variance. Treatment means were compared using the critical difference at the 5% probability level. Standard error of the

mean was also calculated as reported in the experimental document.

3. Results

3.1 In vitro efficacy of plant products and natural products

The tested treatments differed substantially in their antibacterial activity. A clear concentration-dependent response was observed for most plant and natural products. Cow urine was the most effective treatment at all three concentrations. Its inhibition zone increased from 8.50 mm at 5% to 12.33 mm at 10% and 15.66 mm at 15%. BLB-C produced inhibition zones of 5.83, 7.83 and 8.50 mm at 5, 10 and 15%, respectively. BLB-B produced 5.16, 6.50 and 7.50 mm, whereas BLB-A produced 4.93, 6.50 and 6.50 mm. Cow dung extract recorded the lowest inhibition among the evaluated natural products, with 4.33, 5.66 and 5.83 mm at 5, 10 and 15%, respectively. No inhibition was recorded in the untreated control.

Table 1: Inhibition zone of plant and natural products against *X. oryzae* pv. *oryzae*

Treatment	5% (mm)	10% (mm)	15% (mm)
BLB-A	4.93	6.50	6.50
BLB-B	5.16	6.50	7.50
BLB-C	5.83	7.83	8.50
Cow dung extract	4.33	5.66	5.83
Cow urine	8.50	12.33	15.66
Control	0.00	0.00	0.00

The maximum inhibition observed with cow urine at 15% demonstrates its comparatively strong direct antibacterial activity under the laboratory conditions of the experiment.

3.2 in vitro efficacy of antibiotic and fungi toxicant combinations

The response of antibiotic and fungitoxicant combinations varied with concentration. At 1%, streptomycin + oxytetracycline produced the greatest inhibition zone (12.50 mm), followed by neem oil + copper oxychloride (9.17 mm) and streptomycin + oxytetracycline + copper oxychloride (8.17 mm). Neem oil alone produced the lowest inhibition zone (5.17 mm). At 2%, streptomycin + oxytetracycline again produced the highest inhibition (12.33 mm), closely followed by neem oil + copper oxychloride (11.33 mm). At 4%, neem oil + copper oxychloride became the most effective combination, producing a 16.00-mm inhibition zone, followed by streptomycin + oxytetracycline (13.67 mm).

Table 2: Inhibition zone of antibiotic and fungi toxicant combinations

Treatment	1% (mm)	2% (mm)	4% (mm)
Streptomycin + oxytetracycline + copper oxychloride	8.17	10.50	11.17
Streptomycin + oxytetracycline	12.50	12.33	13.67
Neem oil + copper oxychloride	9.17	11.33	16.00
Neem oil	5.17	5.67	6.83
Control	0.00	0.00	0.00

These results indicate that the most effective treatment under laboratory conditions depended on concentration, with streptomycin + oxytetracycline being particularly

effective at lower concentrations and neem oil + copper oxychloride showing the greatest inhibition at 4%.

3.3 Effect of treatments on plant height

Treatments produced significant differences in plant height at both assessment dates. At 60 days, BLB-A produced the greatest plant height (61.00 cm), followed by streptomycin + oxytetracycline (43.33 cm) and oxytetracycline + copper oxychloride (43.61 cm). At 90 days, neem oil recorded the greatest plant height (87.66 cm), followed by streptomycin + oxytetracycline (82.00 cm) and cow urine (80.66 cm). The untreated control recorded 65.33 cm at 90 days.

Table 3: Effect of treatments on plant height

Treatment	60 days (cm)	90 days (cm)
BLB-A	61.00	71.00
BLB-B	35.56	67.83
BLB-C	36.11	73.33
Streptomycin + copper oxychloride	36.39	75.33
Oxytetracycline + copper oxychloride	43.61	79.00
Streptomycin + oxytetracycline	43.33	82.00
Cow dung extract	41.11	69.33
Cow urine	36.38	80.66
Neem oil	38.61	87.66
Control	38.61	65.33

3.4 Effect on panicle length and grain yield

Significant treatment differences were also observed in panicle length. Cow dung extract recorded the longest panicles (26.66 cm), followed by cow urine (25.83 cm) and BLB-A (25.66 cm). The untreated control produced the shortest panicles (19.00 cm).

Grain yield showed a different treatment ranking. Streptomycin + copper oxychloride produced the highest grain yield of 43.61 q ha⁻¹, followed by oxytetracycline + copper oxychloride (43.33 q ha⁻¹) and streptomycin + oxytetracycline (41.11 q ha⁻¹). The untreated control produced only 28.61 q ha⁻¹.

Table 4: Effect of treatments on panicle length and grain yield

Treatment	Panicle length (cm)	Grain yield (q ha ⁻¹)
BLB-A	25.66	35.55
BLB-B	21.33	36.11
BLB-C	24.00	36.39
Streptomycin + copper oxychloride	23.83	43.61
Oxytetracycline + copper oxychloride	22.33	43.33
Streptomycin + oxytetracycline	24.66	41.11
Cow dung extract	26.66	36.38
Cow urine	25.83	38.61
Neem oil	22.66	38.61
Control	19.00	28.61

The superiority of the antibiotic-copper combinations in grain yield indicates that disease suppression was associated with improved productivity, although the treatment producing the highest yield was not the same as the treatment producing the lowest disease intensity.

3.5 Disease intensity and disease control under field conditions

Marked differences were observed in BLB intensity among treatments. Streptomycin + oxytetracycline recorded the lowest disease intensity (49.76%) and consequently the highest disease control (36.52%). BLB-B recorded 55.72%

disease intensity and 28.92% disease control, while BLB-C recorded 56.00% disease intensity and 28.56% disease control.

Streptomycin + copper oxychloride and oxytetracycline + copper oxychloride recorded disease intensities of 59.65 and 57.03%, corresponding to disease control values of 23.91 and 27.25%, respectively. Cow urine recorded 63.06% disease intensity and 19.56% disease control. The untreated control recorded the highest disease intensity of 78.39%.

Table 5: Field efficacy of treatments against bacterial leaf blight

Treatment	Disease intensity (%)	Disease control (%)
BLB-A	62.61	20.13
BLB-B	55.72	28.92
BLB-C	56.00	28.56
Streptomycin + copper oxychloride	59.65	23.91
Oxytetracycline + copper oxychloride	57.03	27.25
Streptomycin + oxytetracycline	49.76	36.52
Cow dung extract	59.03	24.70
Cow urine	63.06	19.56
Neem oil	61.62	21.39
Control	78.39	—

The untreated control had 28.63 percentage points greater disease intensity than the best treatment, streptomycin + oxytetracycline.

4. Discussion

4.1 *In vitro* response of botanicals and natural products against BLB

The tested botanicals and natural products showed concentration-dependent antibacterial activity, with cow urine recording the highest inhibition zone (8.50, 12.33 and 15.66 mm at 5, 10 and 15%, respectively). Among the plant products, BLB-C showed the greatest activity at 15% (8.50 mm). Patil *et al.* (2017) ^[11] reported maximum inhibition of 15.00 mm with marigold leaf extract and 14.00 mm with neem leaf extract, while Jabeen *et al.* (2013) recorded 18.5 mm with neem leaf extract. The lower or comparable inhibition observed here may reflect differences in plant material, extraction method, concentration and pathogen isolate. Bulbule and Kadam (2020) ^[2] and Ibanda *et al.* (2024) ^[4] likewise demonstrated substantial variation in antibacterial activity among plant extracts. Overall, the results indicate that selected natural products, particularly cow urine, have *in vitro* antibacterial potential, but their field efficacy requires independent evaluation.

4.2 *In vitro* evaluation of antibiotics, fungitoxicants and their combinations

Antibiotic and fungitoxicant combinations showed concentration-dependent differences in antibacterial activity. Streptomycin + oxytetracycline produced the highest inhibition at 1% (12.50 mm) and 2% (12.33 mm), whereas neem oil + copper oxychloride was most effective at 4% (16.00 mm). Prasad *et al.* (2018) ^[12] reported larger inhibition zones with streptomycin and antibiotic-fungitoxicant combinations, but direct comparison is limited because the compounds, concentrations and experimental conditions differed. The change in treatment ranking with concentration suggests that efficacy depended on both treatment composition and concentration. These findings support the need to evaluate promising combinations under

field conditions rather than relying solely on laboratory inhibition.

4.3 Influence of treatments on plant height

Treatment effects on plant height varied with crop stage. BLB-A recorded the greatest height at 60 days (61.00 cm), whereas neem oil produced the greatest height at 90 days (87.66 cm), followed by streptomycin + oxytetracycline (82.00 cm); the untreated control was 65.33 cm. The change in treatment ranking between observations indicates that treatment effects were not consistent throughout crop development. However, the treatment producing the greatest plant height did not produce the highest grain yield, indicating that plant height alone is insufficient for assessing treatment performance.

4.4 Effect of treatments on panicle development

Cow dung extract produced the longest panicles (26.66 cm), followed by cow urine (25.83 cm) and BLB-A (25.66 cm), compared with 19.00 cm in the untreated control. Despite this response, cow dung extract produced only 36.38 q ha⁻¹ grain yield, whereas streptomycin + copper oxychloride produced 43.61 q ha⁻¹. Thus, panicle length alone did not explain treatment differences in productivity, and other yield components also contributed to final grain yield.

4.5 Effect of treatments on grain yield

Streptomycin + copper oxychloride produced the highest grain yield (43.61 q ha⁻¹), followed by oxytetracycline + copper oxychloride (43.33 q ha⁻¹) and streptomycin + oxytetracycline (41.11 q ha⁻¹), compared with 28.61 q ha⁻¹ in the untreated control. The highest-yielding treatment therefore increased yield by 15.00 q ha⁻¹ (52.4%) over the control. This result agrees with Patel *et al.* (2009), who reported superior performance of streptomycin sulphate + copper oxychloride. Prasad *et al.* (2018)^[12] and Behera *et al.* (2024)^[1] also reported improved yield with antibiotic-copper or integrated management treatments. The present results further show that maximum yield did not necessarily coincide with minimum disease intensity, indicating that yield response is influenced by disease suppression as well as other components of plant growth and productivity.

4.6 Disease intensity and disease control under field conditions

Field evaluation showed clear differences among treatments. Streptomycin + oxytetracycline recorded the lowest disease intensity (49.76%) and highest disease control (36.52%), reducing disease intensity by 28.63 percentage points compared with the untreated control (78.39%). BLB-B and BLB-C provided 28.92 and 28.56% disease control, respectively, while oxytetracycline + copper oxychloride, streptomycin + copper oxychloride, neem oil and cow urine provided 27.25, 23.91, 21.39 and 19.56% control, respectively. Prasad *et al.* (2018)^[12] reported 57.45% disease severity with streptomycin sulphate + copper hydroxide, whereas Behera *et al.* (2024)^[1] achieved substantially lower disease intensity under an integrated management programme. Such differences may arise from variation in cultivar, pathogen pressure, environmental conditions, treatment schedules and disease-assessment methods. Nevertheless, the present results identify streptomycin + oxytetracycline as the most effective

treatment for disease suppression under the conditions tested.

4.7 Relationship between *in vitro* and field performance

A clear difference was observed between laboratory and field performance. Cow urine showed the greatest *in vitro* inhibition among the natural products, but provided only 19.56% disease control in the field. In contrast, streptomycin + oxytetracycline, which showed strong *in vitro* activity, also recorded the lowest field disease intensity and highest disease control. This indicates that *in vitro* inhibition alone is not sufficient for predicting field efficacy. Environmental conditions, treatment persistence, crop growth stage, disease pressure and interactions with the plant surface can influence field performance. Therefore, laboratory screening should be followed by field validation before practical disease-management recommendations are made.

5. Conclusion

The present investigation demonstrated substantial variation in the efficacy of botanicals, natural products, antibiotics and antibiotic-fungi toxicant combinations against bacterial leaf blight of Basmati rice cv. PB-1121. The results obtained under laboratory and field conditions clearly showed that treatment performance was context dependent.

Under *in vitro* conditions, cow urine exhibited the greatest antibacterial activity among the tested natural products, with an inhibition zone of 15.66 mm at 15%. Among antibiotic and fungi toxicant combinations, streptomycin + oxytetracycline was highly effective at 1 and 2%, whereas neem oil + copper oxychloride produced the greatest inhibition at 4%.

Field performance, however, showed a different ranking. Streptomycin + oxytetracycline was the most effective treatment for disease suppression, recording the lowest disease intensity (49.76%) and maximum disease control (36.52%). In contrast, streptomycin + copper oxychloride produced the highest grain yield (43.61 q ha⁻¹), followed closely by oxytetracycline + copper oxychloride (43.33 q ha⁻¹). The untreated control recorded substantially greater disease intensity (78.39%) and the lowest grain yield (28.61 q ha⁻¹).

An important outcome of the study was that the treatment with the greatest antibacterial activity *in vitro* was not necessarily the treatment providing the greatest disease control or yield in the field. Cow urine, for example, showed the strongest laboratory inhibition but did not provide the greatest field disease suppression. This emphasizes that laboratory screening should be complemented by field evaluation before a treatment is considered for practical disease management.

The present findings indicate that antibiotic combinations, particularly streptomycin + oxytetracycline, can provide effective suppression of BLB under the conditions evaluated. At the same time, selected plant products and natural products demonstrated useful activity and may have potential as supplementary components of an integrated and comparatively eco-friendly disease-management programme. Future investigations should focus on identifying the active constituents of the most promising plant products, optimizing their formulations and concentrations, evaluating their compatibility with

biological control agents, and validating their efficacy across rice cultivars, locations and seasons.

Overall, the study provides experimental evidence that integrating effective antimicrobial treatments with promising botanical and natural-product-based approaches may offer a more sustainable strategy for managing bacterial leaf blight of Basmati rice than relying exclusively on conventional chemical/antibiotic treatments.

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