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Tashkent State Agrarian University, Uzbekistan

*CORRESPONDENCE

Anand Choudhary
✉ anandparoda84@gmail.com

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Sustainable management of *Alternaria* leaf blight in isabgol (*Plantago ovata*) using chitosan, multi-walled carbon nanotubes, and salicylic acid

Anand Choudhary^{1*}, Arjun Lal Yadav¹, Shipra Sharma¹ and Dama Ram²

¹Department of Plant Pathology, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India, ²Department of Plant Pathology, College of Agriculture, Agriculture University, Kota, Rajasthan, India

Introduction: *Alternaria* leaf blight, caused by *Alternaria alternata* (Fr.) Keissler, is one of the most destructive diseases of isabgol (*Plantago ovata* Forsk.). Conventional fungicide-based control raises environmental concerns and threatens long-term sustainability. Therefore, eco-friendly plant defense activators offer potential alternatives for sustainable disease management and food security.

Methods: This study assessed the efficacy of chitosan, multi-walled carbon nanotubes (MWCNTs), and salicylic acid (SA) under both laboratory and field conditions. *In vitro* assays were carried out to evaluate mycelial inhibition, while field trials were performed during two consecutive *Rabi* seasons (2022–2023 and 2023–2024) under a randomized block design (RBD) at Swami Keshwanand Rajasthan Agricultural University, Bikaner, India. Treatments involved seed priming and foliar application at various concentrations.

Results: *In vitro*, salicylic acid (200 ppm) and chitosan (150 ppm) exhibited the highest pathogen inhibition (67.14 and 62.60%, respectively), followed by MWCNTs (45.45% at 150 ppm). Field evaluations revealed that chitosan (100 ppm, seed treatment + foliar spray) significantly reduced disease severity (51.30%) and improved yield (805.29 kg/ha). Salicylic acid at 200 ppm provided the greatest overall benefit, with 55.60% disease control and the highest yield (837.06 kg/ha). The least effective treatment reduced disease by only 10.87% with a yield of 665.69 kg/ha.

Conclusion: This study supports sustainable agriculture by integrating eco-friendly defense activators that reduce chemical fungicide dependence. Considering the Asia-Pacific context, such low-input, resource-efficient approaches can enhance smallholder resilience in arid and semi-arid ecosystems.

KEYWORDS

Alternaria leaf blight, chitosan, isabgol, MWCNTs, plant defense activators, salicylic acid

1 Introduction

“*Plantago ovata*,” commonly known as psyllium or isabgol, belongs to the *Plantaginaceae* family. Traditionally used in Indian and Chinese herbal medicine, psyllium treats conditions such as skin irritations, high blood pressure, constipation, diarrhea, chronic dysentery, and intestinal ulcers (Fernandez-Banares, 2006). Its water-soluble, gelatinous properties make it suitable for drug delivery systems and absorption. Additionally, psyllium has cholesterol-lowering and wound-healing properties (Taneja et al., 1989; Tomar et al., 2010).

Alternaria leaf blight has become a serious problem in recent years. It has been found that downy mildew-affected crops are more prone to be attacked by *Alternaria alternata*. This disease causes considerable damage every year and sometimes becomes very severe, resulting in total loss of yield. Moreover, *Alternaria* can produce several mycotoxins such as tenuazonic acid, alternariol, alternariol monomethyl ether, altenuene, and tentoxin (Pedras and Park, 2015; Siciliano et al., 2017).

The widespread use of chemicals has caused pest resistance and a decline in natural pest enemies, threatening biodiversity. Researchers are currently exploring eco-friendly disease control methods using chitosan, salicylic acid, MWCNTs, and plant extracts (Soleimani and Kirk, 2012; Choudhary et al., 2021; Dhaka et al., 2022; Lidi and Uge, 2024). Salicylic acid application enhances plant processes, activating antioxidative enzymes such as peroxidase, polyphenol oxidase, superoxide dismutase, and phenylalanine ammonia lyase. These enzymes improve plant defense against stresses, triggering an immediate oxidative burst in response to salicylic acid treatment (Hayat et al., 2010; Noreen and Ashraf, 2009; Idrees et al., 2011). Similarly, chitosan has been identified as a promising biological control agent for numerous plant diseases (Hadrami et al., 2010). Numerous studies highlight the potential of chitosan and its mechanisms for controlling plant diseases across various crops (Sharif et al., 2018; Malerba and Cerana, 2018; Mishra et al., 2024). Multi-walled carbon nanotubes (MWCNTs) have recently gained attention for their antifungal and plant-protective potential. They can suppress pathogen growth by disrupting fungal cell walls, inducing oxidative stress, and inhibiting spore germination. MWCNTs may also enhance plant defense by activating antioxidant enzymes and modulating reactive oxygen species (ROS) signaling, thereby strengthening host resistance. These properties make MWCNTs promising nanomaterials for sustainable and eco-friendly plant disease management (Rai et al., 2022; Li et al., 2023; Riseh et al., 2022).

This study aimed to evaluate the antifungal efficacy of salicylic acid, chitosan, and multi-walled carbon nanotubes (MWCNTs) against *A. alternata*, the causal agent of leaf blight in isabgol (*Plantago ovata*). The investigation included both laboratory and field experiments to assess their potential in reducing disease severity and improving seed yield under eco-friendly and sustainable management conditions.

2 Materials and methods

2.1 Experiment

A two-year field experiment was conducted at the Department of Plant Pathology, College of Agriculture, Bikaner, Swami Keshwanand

Rajasthan Agricultural University, Bikaner, Rajasthan (India) (28.10° N, 73.18° E) in Rabi 2022–2023 and 2023–2024. Each treatment was replicated three times under a randomized block design. The altitude of the field location is 223.88 m above sea level. The area is characterized by stormy southwest winds with frequent dust storms. Soils of the experimental field are sandy in texture and very low in fertility with respect to almost all nutrients. The isabgol plants were sown in the first week of November with 30 × 5 cm spacing. All agronomic practices were followed according to the package of practice (Figure 1).

2.2 Fungal cultures and inoculation

The culture of *A. alternata* was isolated from an infected plant of isabgol, and its pathogenicity was confirmed according to Koch's postulates. The fungus was cultured on potato dextrose agar (PDA) for 14 days at ambient temperature (28 ± 2 °C). A volume of 15 mL of sterile water was poured into a Petri dish and gently scraped with a sterile glass rod to obtain spore suspension. The spore suspension was filtered through three layers of sterile cheesecloth and adjusted to 1 × 10⁶ spores/mL using a hemocytometer (Figure 2). The conidial suspension of *A. alternata* was applied to the experimental field in sufficient quantity at 45 days after sowing (DAS) at a volume of 15 mL m⁻² of crop canopy to ensure uniform inoculation. The percent disease intensity (PDI) was assessed for each plot on a disease rating scale of 1–9 (Gugino et al., 2007) based on the percentage of leaf area symptomatic (1 = 0% tissue symptomatic, 2 = up to 1%, 3 = 2–5%, 4 = 6–10%, 5 = 11–20%, 6 = 21–30%, 7 = 31–40%, 8 = 41–50%, and 9 = over 50%). The intensity was calculated using the formula of Wheeler (1969).

2.3 Effect of the defensive activator against *Alternaria alternata* in vitro

In the completely randomized design (CRD) with three replications, an experiment was conducted to evaluate the inhibition effect of antifungal compounds (Table 1) against the *A. alternata* through the poisoned food technique (Nene and Thapliyal, 1993). Each treatment solution was prepared separately before application. Chitosan was dissolved in 1% (v/v) glacial acetic acid, stirred continuously overnight, and adjusted to the desired concentrations (0.05, 0.10, and 0.15%) using sterile distilled water. Multi-walled carbon nanotubes (MWCNTs) were dispersed in distilled water with 0.05% Tween-20 as a surfactant and subjected to sonication for 30 min to achieve a uniform suspension at concentrations of 50, 100, and 150 ppm. All solutions were freshly prepared prior to each experiment and applied as foliar sprays under field conditions or incorporated into the growth medium for *in vitro* assays. The efficacy of the antifungal compounds was expressed as the percentage inhibition of mycelial growth compared to the control, which was calculated using the formula given by Vincent (1947).

$$I = \frac{C - T}{C} \times 100$$

Where, I = inhibition percent.

C = colony diameter (mm) in the control Figure.

T = colony diameter (mm) in the treated Figure.



FIGURE 1
Overall view of field experiment.



FIGURE 2
Symptoms of Alternaria leaf blight of isabgol.

2.4 Effect of the salicylic acid against *Alternaria alternata* in vitro

In the completely randomized design (CRD) with four replications, an experiment was conducted to evaluate the inhibition effect of salicylic acid (Table 2) against *A. alternata* through the poisoned food technique (Nene and Thapliyal, 1993). Each treatment

solution was prepared separately before application. The salicylic acid (SA) solutions were prepared by dissolving analytical-grade SA in a small volume of ethanol and then diluting with sterile distilled water to obtain final concentrations of 50, 100, and 150 ppm. The efficacy of the salicylic acid was expressed as the percentage inhibition of mycelial growth compared to the control, which was calculated using the formula given by Vincent (1947).

TABLE 1 Salicylic acid (SA) treatments used as defense activators against *Alternaria* leaf blight of isabgol under *in vivo* conditions.

Treatment No.	Name of antifungal compounds	Concentrations (ppm)
T ₁	Chitosan	50
T ₂	Chitosan	100
T ₃	Chitosan	150
T ₄	Multi-walled carbon nanotubes	50
T ₅	Multi-walled carbon nanotubes	100
T ₆	Multi-walled carbon nanotubes	150
T ₇	Control	–

TABLE 2 List of salicylic acid evaluated against *A. alternata* *in vitro*.

Treatment No.	Name of antifungal compounds	Concentrations (ppm)
T ₁	Salicylic acid	50
T ₂	Salicylic acid	100
T ₃	Salicylic acid	150
T ₄	Salicylic acid	200
T ₅	Control	–

TABLE 3 List of antifungal compounds against *Alternaria* leaf blight of isabgol *in vivo*.

Treatment No.	Name of antifungal compounds
T ₁	Seed treatment with chitosan solution (100 ppm)
T ₂	Seed treatment with MWCNTs in a 75 ppm solution
T ₃	Foliar spray with chitosan solution (100 ppm) at 40 DAS
T ₄	Foliar spray with MWCNTs (50 ppm) solution at 40 DAS
T ₅	T ₁ + T ₃
T ₆	T ₁ + T ₄
T ₇	T ₂ + T ₃
T ₈	T ₂ + T ₄
T ₉	Control

2.5 To test the efficacy of the antimicrobial compound against *Alternaria* leaf blight of isabgol *in vivo*

The study was undertaken to evaluate the efficacy of antifungal compounds (chitosan and multi-walled carbon nanotubes [MWCNTs]) (Table 3) against the *Alternaria* leaf blight disease through seed treatment and foliar application under field conditions. For seed treatment, isabgol seeds were lightly dried and then mixed with the respective treatment solutions (chitosan, salicylic acid, or MWCNTs) at a ratio of 1:1 (w/v) in a sterile tray. The seeds were gently stirred with a glass rod for 3–5 min to allow uniform surface contact, ensuring that excessive wetting was avoided to prevent clumping due to mucilage. The coated seeds were air-dried under shade for 20–25 min until free-flowing and

then used for sowing. This method ensured uniform coating despite the sticky nature of isabgol seeds. MWCNTs were dispersed in a 0.05% Tween-20 solution using ultrasonication for 15 min to ensure uniform dispersion. No visible phytotoxic effects (leaf burn, chlorosis, or growth inhibition) were observed, indicating biosafety at the applied concentrations. The middle two rows of each plot were rated for disease intensity (the presence or absence of one or more lesions) at 60 DAS by examining five leaves from five adjacent plants at five random sites within each plot for a total of 25 leaves per plot (Figure 1). The intensity was calculated using the formula of Wheeler (1969). The details of the experimentation are shown in Table 3.

2.6 To test the efficacy of salicylic acid against *Alternaria* leaf blight of isabgol *in vivo* and *in vitro*

Seed treatment and foliar spray of salicylic acid (Table 4) at the initiation of disease were applied based on the following details under field conditions. The details of the experimentation are shown in Table 4.

2.7 Calculation and statistical analysis

Percent disease intensity (PDI) was calculated 10 days after spraying. Percent disease control was calculated using the following formula:

$$\text{Percent disease intensity} = \frac{\text{Sum of all individual disease rating}}{\text{Total number of plants assessment} \times \text{max. rating}} \times 100$$

$$\text{Percent disease control} = \frac{\text{PDI in control} - \text{PDI in treatment}}{\text{PDI in control}} \times 100$$

The data of percent disease intensity in all the experiments were transformed to their arcsin values (Fisher and Yates, 1963). The statistical analysis of the data of all the laboratory experiments was performed following a completely randomized design. The data of the field experiment were analyzed using the randomized block design (Cochran and Cox, 1957).

3 Results and discussion

3.1 Efficacy of antimicrobial compound against *Alternaria alternata* *in vitro*

The effect of antifungal compounds (chitosan and multi-walled carbon nano-tubes) was tested at 50, 100, and 150 ppm concentrations using the poisoned food technique on the growth of *A. alternata* under *in vitro* conditions. Observations on average colony diameter and percent inhibition of linear growth compared to the control are presented in Table 5 and Figure 3. The results revealed that all of the antifungal compounds evaluated significantly reduced the mycelial

TABLE 4 List of antifungal compounds against *Alternaria* leaf blight of isabgol *in vivo*.

Treatment No.	Seed treatment (ppm)	Foliar spray (ppm)
T ₁	50	50
T ₂	100	100
T ₃	150	150
T ₄	200	200
T ₅	Control	Control

growth of *A. alternata* compared to the control, but their effectiveness varied at various concentrations.

The antifungal activity obtained by the radial growth inhibition assay on PDA with different concentrations of chitosan and multi-walled carbon nanotubes is reported in Table 4. The results indicate that *A. alternata* used in this study was progressively inhibited with increasing concentrations of chitosan and MWCNTs from 50 to 150 ppm. The fungal growth was significantly inhibited by all tested doses of chitosan and MWCNTs ($p < 0.05$) after 7 days of incubation. Chitosan showed a better inhibitory effect on *A. alternata*. Among the tested plant defense activators, chitosan at 150 ppm inhibited mycelial growth of *A. alternata* by 62.60%, while the 50 ppm concentration showed 31.16% inhibition. In comparison, multi-walled carbon nanotubes inhibited mycelial growth by 45.45% at 150 ppm and were the least effective at lower concentrations, with inhibition rates of 14.95 and 30.18% at 50 and 100 ppm concentrations, respectively.

Chitosan's inherent antifungal properties play a pivotal role in disease reduction by disrupting fungal cell walls, altering membrane permeability, and inhibiting mycelial growth. This direct inhibitory effect was evident from the significant reduction in disease severity and intensity observed across concentrations in the present study. Although previous studies have reported that chitosan can induce plant defense responses and activate systemic acquired resistance (SAR) mechanisms (Orzali et al., 2017; De Barros-Alexandrino et al., 2022; Riseh et al., 2022), this aspect was not evaluated in the present study. Therefore, the disease suppression observed in this study can be primarily attributed to chitosan's direct antifungal action rather than its role as a defense inducer.

3.2 Efficacy of salicylic acid against *Alternaria alternata* *in vitro*

Salicylic acid was evaluated against *A. alternata* *in vitro* at concentrations of 50, 100, 150, and 200 ppm. The data are summarized in Table 6 and Figure 4. The results showed that the efficacy increased with increased salicylic acid concentrations, and all four concentrations of salicylic acid significantly inhibited the mycelial growth of *A. alternata*.

Of the four concentrations of salicylic acid, the 200 ppm concentration revealed the 67.14% efficacy in terms of mycelial growth inhibition, followed by 150 ppm (47.91%) and 100 ppm (31.52%). Minimum mycelial growth inhibition (21.10%) was found at a 50 ppm concentration of salicylic acid.

The treatments of chitosan, salicylic acid (SA), and MWCNTs significantly inhibited the mycelial growth of *A. alternata* both *in vitro*

and *in vivo*. Although previous reports indicate that chitosan and SA are known to act as plant defense activators, the present study primarily evaluated their direct antifungal activities rather than their roles in defense induction. Therefore, the observed reduction in disease incidence and severity can be attributed to their fungistatic and fungicidal properties rather than systemic resistance mechanisms. The present findings are also in agreement with the results of Allahverdi Beyk et al. (2021), who reported a negative correlation between salicylic acid concentration and colony diameter formation of *A. alternata*. As expected, the highest colony diameter was recorded in the control medium (without SA), whereas the smallest colony diameter was observed in the medium supplemented with 16 mM salicylic acid. Increasing SA concentration led to a significant dose-dependent reduction in the colony diameter of *A. alternata*, indicating that SA effectively inhibited mycelial growth. Similarly, Meena et al. (2022) demonstrated that salicylic acid suppressed mycelial growth and sporulation of *Alternaria solani*, with the highest inhibition (68.45%) observed at 200 ppm.

The inhibitory impact of salicylic acid on *A. alternata* mycelial growth aligns with its known role as a signaling molecule involved in plant defense responses. The ability of salicylic acid to induce defense mechanisms in plants and consequently inhibit the growth of pathogens, which makes it a potential candidate for integrated disease management strategies (Bellés et al., 1999; Dempsey et al., 1999; An and Mou, 2011).

3.3 Efficacy of antimicrobial compound against *Alternaria* leaf blight disease of isabgol under field conditions

The effects of different concentrations of chitosan and multi-walled carbon nanotubes against *Alternaria* leaf blight of isabgol under field conditions are shown in Table 7 and Figure 5. No phytotoxic symptoms such as leaf necrosis, discoloration, or growth inhibition were observed in any treatment, confirming the safety of the tested concentrations. The application of T₅ (ST chitosan solution [100 ppm] + FA chitosan solution [100 ppm]) showed the greatest fungicidal activity in the suppression of disease severity, causing 51.30% disease reduction, which revealed 25.71 and 24.81% disease intensity in Rabi 2022–2023 and 2023–2024, respectively. This was followed by T₇ (ST MWCNTs in 75 ppm + FA chitosan solution 100 ppm), whereas the least effective treatment was T₂ (ST MWCNTs in 75 ppm), which revealed 46.62 and 45.51% disease intensity in Rabi 2022–2023 and 2023–2024, respectively.

The pooled data from consecutive years also revealed that T₅ was the most effective, exhibiting the maximum yield (805.29 kg/ha) and disease control (51.30%), while T₂ was the least effective among all 12 treatments, exhibiting the lowest yield (665.69 kg/ha) and disease control (10.87%). Seed treatment of isabgol with liquid media is challenging due to the sticky nature of the seeds. Therefore, foliar application is the most practical approach for controlling plant diseases in the field.

Despite numerous reports highlighting the potential efficacy of chitosan against various plant diseases, its performance exhibited only moderate fungicidal activity in combating this particular disease, resulting in a 30% reduction in disease severity. In contrast, research by Sathiyabama et al. (2014) reported that the application of chitosan at 1 mg/mL could reduce the disease severity of early blight disease of

TABLE 5 Efficacy of antimicrobial compounds against *A. alternata* in vitro.

Treatments	Antimicrobial compounds	Dose (ppm)	Mycelial growth (mm)*	Percent mycelial growth inhibition
T ₁	Chitosan	50	61.95 (51.89)	31.16
T ₂	Chitosan	100	51.83 (46.02)	42.41
T ₃	Chitosan	150	33.66 (35.44)	62.60
T ₄	MWCNTs	50	76.54 (61.01)	14.95
T ₅	MWCNTs	100	62.83 (52.41)	30.18
T ₆	MWCNTs	150	49.09 (44.46)	45.45
T ₇	Control	–	90.00 (71.53)	0.00
S. Em±			0.29	
CD ($p = 0.05$)			0.89	

* Mean of three replications. Figures in parentheses are angular-transformed means.

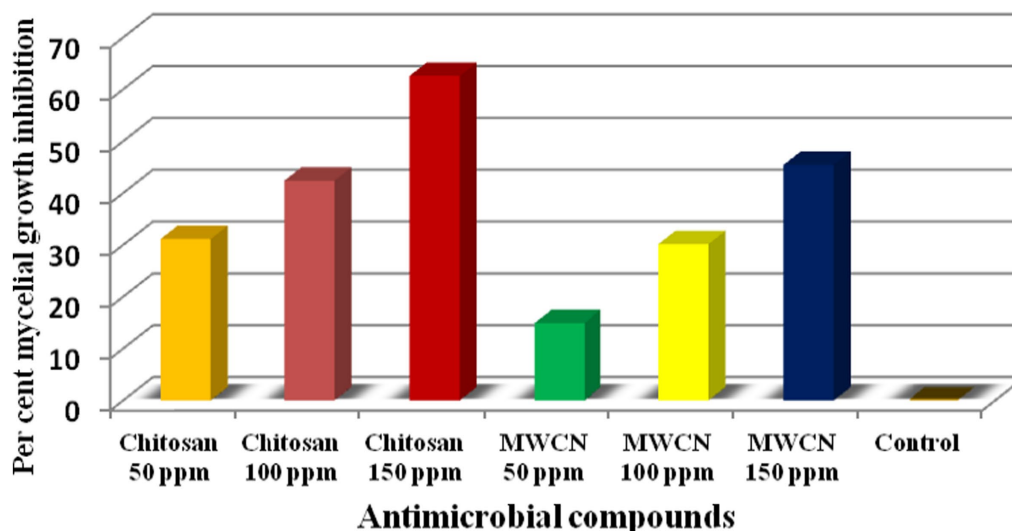


FIGURE 3
Efficacy of antimicrobial compound against *A. alternata* in vitro.

TABLE 6 Efficacy of salicylic acid against *A. alternata* in vitro.

Treatments	Salicylic acid (ppm)	Mycelial growth (mm)*	Percent mycelial growth inhibition
T ₁	50	71.06 (57.44)	21.10
T ₂	100	61.63 (51.70)	31.52
T ₃	150	46.88 (43.19)	47.91
T ₄	200	29.57 (32.92)	67.14
T ₅	Control	90 (71.53)	0.00
S. Em±		0.28	
CD ($p = 0.05$)		0.87	

* Mean of four replications. Figures in parentheses are angular-transformed means.

tomato caused by *A. solani* by 75%. Similarly, Abd-El-Kareem and Haggag (2014) reported substantial success with chitosan application at 2 g/L, resulting in a reduction of more than 76.6% in the intensity of early blight in potatoes caused by *A. solani*. Additionally, this

application led to an impressive increase in tuber yield by more than 80% compared to the untreated control.

In a study conducted by Wan Ahmad Sofian et al. (2022), the evaluation of chitosan involved concentrations of 0, 25, 50, 75, 100, and 125 ppm. The chitosan application was carried out once a week, starting 30 days after sowing. Concentrations ranging from 75 to 100 ppm exhibited the most effective performance in disease control, affecting both fruits and leaves. The results suggested that increasing chitosan concentration positively correlates with enhanced plant growth and effective control of cucumber diseases. Although MWCNTs were applied at low, non-toxic levels, future studies should assess long-term soil and ecological safety before large-scale application.

3.4 Efficacy of salicylic acid against *Alternaria* leaf blight disease of isabgol under field conditions

Data regarding percent disease intensity and yield for the 2 years Rabi 2022–2023 and 2023–2024 are presented in Table 8

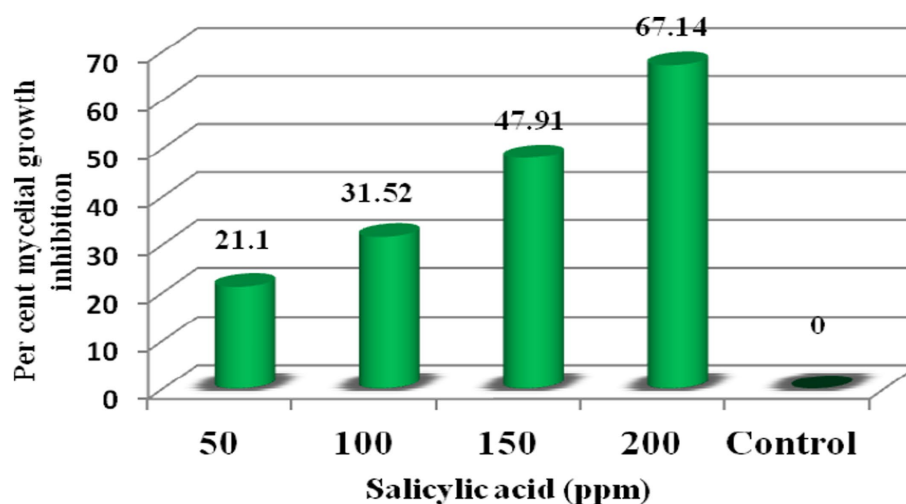


FIGURE 4
Efficacy of salicylic acid against *A. alternata* in vitro.

TABLE 7 Efficacy of antimicrobial compound against Alternaria leaf blight disease of isabgol under field conditions.

Treatments	Antimicrobial compounds	Percent disease intensity*			Disease control (%)	Yield (kg/ha)*		
		2022–23	2023–24	Pooled		2022–23	2023–24	Pooled
T ₁	ST* chitosan solution (100 ppm)	45.46 (42.37)	42.64 (40.73)	44.05 (41.55)	15.17	675.33	678.72	677.02
T ₂	ST MWCNTs in 75 ppm	46.62 (43.03)	45.51 (42.39)	46.07 (42.71)	10.87	660.43	670.95	665.69
T ₃	FA* chitosan solution (100 ppm)	31.42 (34.00)	28.81 (32.35)	30.12 (33.18)	41.93	747.89	757.32	752.60
T ₄	FA MWCNTs (50 ppm) solution	37.01 (37.44)	36.81 (37.33)	36.91 (37.39)	28.84	684.68	686.01	685.34
T ₅	T ₁ + T ₃	25.71 (30.39)	24.81 (29.82)	25.26 (30.14)	51.30	803.30	807.27	805.29
T ₆	T ₁ + T ₄	33.84 (35.51)	30.87 (33.70)	32.36 (34.64)	37.61	742.96	761.13	752.05
T ₇	T ₂ + T ₃	30.51 (33.45)	28.71 (32.27)	29.61 (32.95)	42.91	756.10	757.23	756.67
T ₈	T ₂ + T ₄	36.23 (36.99)	34.00 (35.64)	35.11 (36.32)	32.31	728.37	749.45	738.91
T ₉	Control	53.74 (47.13)	50.01 (44.98)	51.87 (46.06)	0	649.00	653.54	651.27
S. Em±		1.67	1.67	1.21		27.23	29.58	21.09
CD ($p = 0.05$)		5.05	5.07	3.68		82.35	89.46	63.79
CV (%)		7.66	7.94	5.67		6.58	7.06	5.06

ST, seed treatment; FA, Foliar application. * Mean of three replications. Figures in parentheses are angular-transformed means.

and Figure 6, revealing that all concentrations of salicylic acid were significantly superior to the control in controlling the disease and increasing the yield. The minimum percent disease intensity was recorded with 200 ppm salicylic acid, showing 23.30 and 21.10% during Rabi 2022–2023 and 2023–2024, respectively. This was followed by 150 ppm (29.50 and 25.54%) and 100 ppm (35.07 and 32.55%), whereas 50 ppm concentration showed the highest disease intensity (43.86 and 42.05%) in Rabi 2022–2023 and 2023–2024, respectively.

Two-year pooled data on seed yield and percent disease control indicated that the maximum yield (837.04 kg ha⁻¹) and disease control (55.60%) were recorded with 200 ppm salicylic acid, followed

by 150 ppm (779.59 kg ha⁻¹ and 44.97%) and 100 ppm (761.94 kg ha⁻¹ and 32.39%), respectively. The minimum yield (694.37 kg ha⁻¹) and disease control (14.11%) were observed at 50 ppm salicylic acid. Mettraux et al. (2002) reported that, at lower concentrations, salicylic acid lacks direct antifungal activity, whereas at higher concentrations, it can exert toxic effects on the fungal pathogen by disrupting membrane integrity and metabolic processes. In the present study, no visible phytotoxic effects on plants were observed at the tested concentrations, suggesting that the inhibitory action of salicylic acid was directed primarily toward the pathogen rather than the host. The results suggested that the inhibitory effect of salicylic acid at higher concentrations is primarily associated with

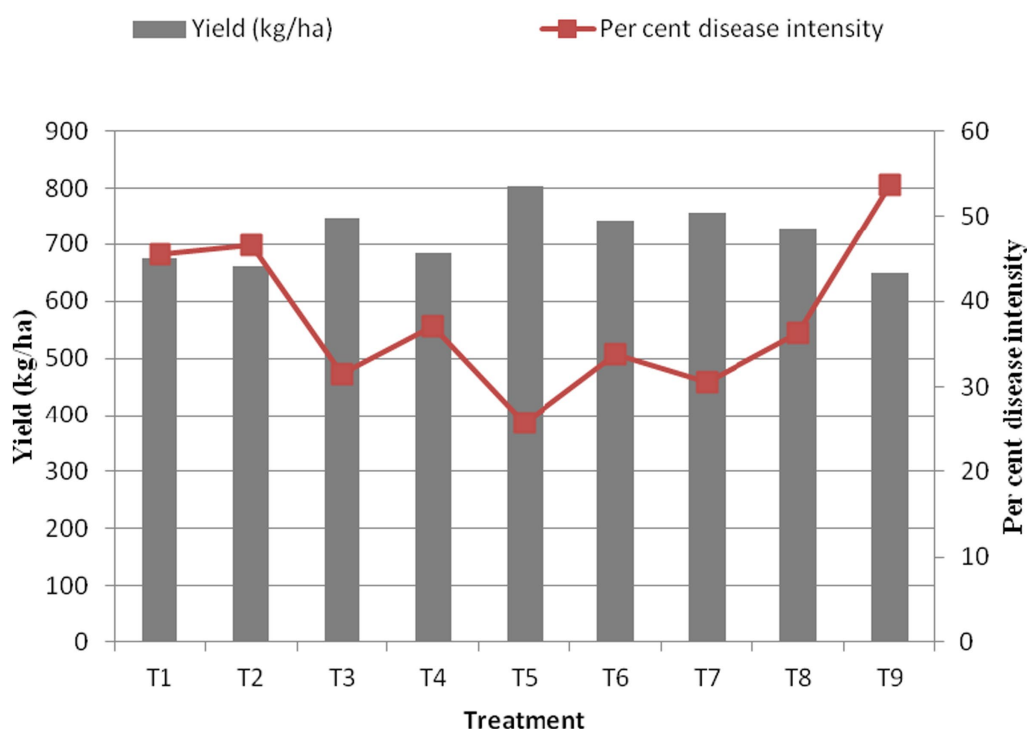


FIGURE 5

Efficacy of antimicrobial compound against *Alternaria* leaf blight disease of blond psyllium under field condition pooled basis, 2022–23 and 2023–24.TABLE 8 Efficacy of salicylic acid against *Alternaria* leaf blight of isabgol under field conditions.

Treatments	Salicylic acid (ppm)		Percent disease intensity*			Percent disease control	Yield (kg/ha)*		
	Seed treatment	Foliar treatment	2022–2023	2023–2024	Pooled		2022–2023	2023–2024	Pooled
T ₁	50	50	43.86 (41.42)	42.05 (40.40)	42.95 (40.91)	14.11	689.46	699.29	694.37
T ₂	100	100	35.07 (37.05)	32.55 (37.48)	33.81 (37.26)	32.39	747.43	776.46	761.94
T ₃	150	150	29.50 (35.22)	25.54 (32.54)	27.52 (33.91)	44.97	773.25	785.93	779.59
T ₄	200	200	23.30 (33.72)	21.10 (30.24)	22.20 (32.01)	55.60	826.86	852.57	837.06
T ₅	Control		53.73 (28.77)	53.73 (27.27)	50.01 (28.07)	–	655.46	668.54	662.00
S. Em±			2.33	1.39	1.69		37.23	39.23	30.87
CD (<i>p</i> = 0.05)			7.74	4.62	5.59		115.99	122.22	96.20
CV (%)			11.49	7.19	8.50		10.08	10.37	8.26

* Mean of four replications. Figures in parentheses are angular-transformed means.

its direct fungitoxic activity, such as interference with fungal membrane integrity and enzyme function. Although previous studies have reported that SA can activate plant defense signaling pathways, leading to systemic acquired resistance (SAR), such mechanisms were beyond the scope of the present study and were not experimentally verified here.

According to Loake and Grant (2007), salicylic acid activates resistance by inhibiting certain antioxidant enzymes, such as catalase

and peroxidase, resulting in the increased accumulation of H_2O_2 . Simultaneously, salicylic acid can indirectly contribute to the protection of chlorophyll molecules by enhancing the presence of carotenoid molecules. According to Chitra et al. (2008), the induction of systemic resistance against the leaf blight pathogen of *A. alternata* in groundnut was observed through the foliar application of salicylic acid. Similarly, the application of SA showed resistance against the leaf blight pathogen of *A. alternata*. The present findings are in agreement

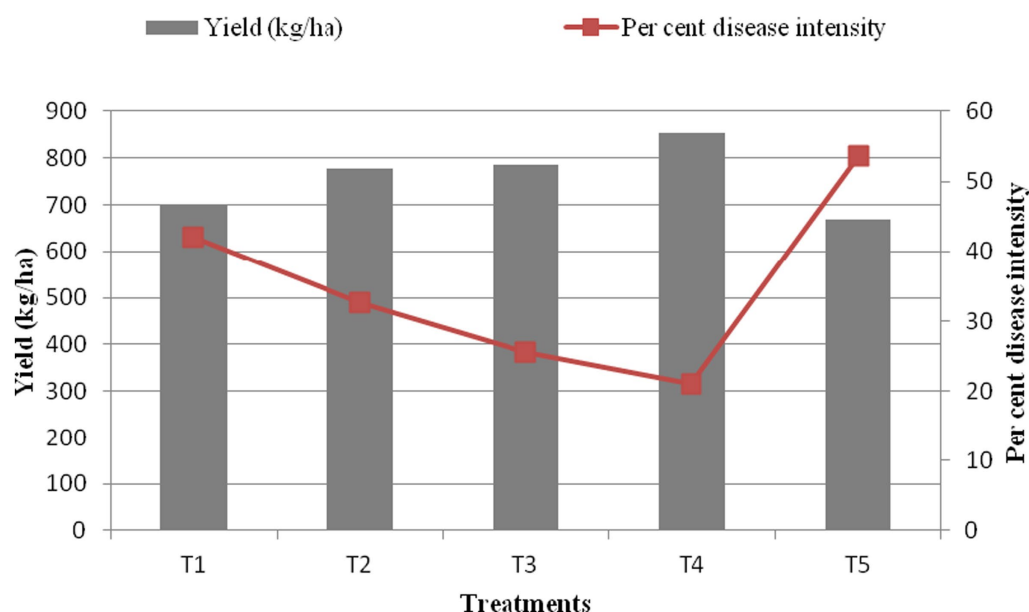


FIGURE 6

Efficacy of salicylic acid against *Alternaria* leaf blight disease of blond psyllium under field condition pooled basis, 2022–23 and 2023–24.

with earlier reports by An and Mou (2011), Allahverdi Beyk et al. (2021), Meena et al. (2022), and Fang et al. (2025), which demonstrated that salicylic acid (SA) significantly inhibited the spore formation and radial growth of *Alternaria* spp., although the degree of inhibition varied with concentration. Chitosan enhances plant defense by activating phenylpropanoid metabolism, leading to increased levels of phenolics, lignin, and pathogenesis-related (PR) proteins. Salicylic acid triggers systemic acquired resistance via the accumulation of hydrogen peroxide and the activation of enzymes such as peroxidase, polyphenol oxidase, and phenylalanine ammonia lyase, reinforcing host defense barriers.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AC: Writing – original draft, Investigation, Writing – review & editing, Conceptualization. AY: Formal analysis, Supervision, Writing – review & editing, Project administration. SS: Data curation, Writing – review & editing, Software. DR: Formal analysis, Writing – review & editing, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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