



# Plant Archives

Journal homepage: <http://www.plantarchives.org>  
DOI Url : <https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.1.109>

## MANAGEMENT OF DOWNY MILDEW (*PLASMOPARA VITICOLA*) IN GRAPEVINE USING NON-SYSTEMIC FUNGICIDES: LABORATORY AND FIELD STUDIES

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(Date of Receiving : 19-12-2025; Date of Revision : 23-02-2026; Date of Acceptance : 07-03-2026)

### ABSTRACT

Downy mildew, caused by *Plasmopara viticola*, is one of the most destructive diseases of grapevine, causing severe yield and quality losses under Indian conditions. The present investigation was carried out to evaluate the efficacy of selected Non-systemic fungicides against *P. viticola* under *in vitro* and field conditions during 2022–23 at the Main Horticulture Research and Extension Centre, Bagalkot, Karnataka, 587 104. Eleven non-systemic fungicides were tested under *in vitro* condition at three concentrations, viz., C<sub>1</sub> (1/5 of the field dose), C<sub>2</sub> (1/10 of the field dose), and C<sub>3</sub> (1/15 of the field dose), using the sporangial germination inhibition technique. Field evaluation was conducted on eight-year-old 'Thompson Seedless' grapevines following three foliar sprays at seven day intervals in a randomized complete block design. *In vitro* studies revealed a significant concentration dependent reduction in sporangial germination, with Cyazofamid 34.5% SC recording the highest inhibition (90.20%) at C<sub>3</sub>, followed by Mancozeb 75% WP and Zineb 75% WP. Field evaluation corroborated laboratory findings, as Cyazofamid 34.5% SC resulted in the lowest disease severity on leaves (8.90 PDI) and bunches (8.07 PDI), achieving maximum disease reduction (>88%) and the highest yield (15.20 tons/ha). Mancozeb 75% WP and Zineb 75% WP provided moderate to high disease suppression with appreciable yield improvement over the untreated control. Economic analysis indicated the highest benefit cost ratio with Cyazofamid 34.5% SC, followed by Mancozeb 75% WP and Zineb 75% WP. The study highlights the effectiveness of selected Non-systemic fungicides for sustainable management of grapevine downy mildew under Indian conditions.

**Keywords** : Downy mildew; *P. viticola*; Non-systemic fungicides; Sporangial germination; Field efficacy.

### Introduction

Grapes (*Vitis vinifera* L.), belonging to the family Vitaceae, are among the most important fruit crops cultivated worldwide due to their versatility, high economic value, and wide adaptability to diverse agro-climatic conditions. Grapes are primarily consumed as fresh table fruits and are also extensively utilized for the production of raisins, juice, wine and other processed products. Owing to their commercial significance, grapes play a vital role in enhancing farmers income and promoting export-oriented horticulture (NHB, 2023).

Globally, grapes rank among the top fruit crops in terms of area and production. In India, grape cultivation occupies a prominent position in the horticultural sector, with an area of about 1.75 lakh hectares and production exceeding 30 lakh tones in recent years (APEDA, 2024). The productivity of grapes in India is comparatively high due to the adoption of improved varieties, advanced training systems and intensive crop management practices. Maharashtra is the leading grape producing state, contributing more than 65–70 per cent of total national production, followed by Karnataka and Tamil Nadu. Major grapes growing districts include Nashik and

Sangli in Maharashtra, Vijayapura and Bagalkot in Karnataka and Theni and Krishnagiri in Tamil Nadu (NHB, 2023).

Grapes were introduced to India around the thirteenth century by Persian and Afghan settlers and gradually spread to different regions of the country. Over time, several seedless and seeded varieties such as Thompson Seedless, Anab-e-Shahi, Sonaka, Sharad Seedless and Bangalore Blue have been developed and widely adopted for commercial cultivation (Chadha, 2018). Grapes are nutritionally rich, containing high levels of natural sugars (glucose and fructose), vitamins A, C and B complex, minerals such as potassium and calcium and bioactive compounds including resveratrol and flavonoids, which possess antioxidant, anti-inflammatory, and cardioprotective properties (Kaur *et al.*, 2021).

Despite high productivity, grapes cultivation is severely constrained by several diseases that significantly affect yield and quality. Major fungal diseases such as Downy mildew (*P. viticola*), Powdery mildew (*Erysiphe necator*) and Anthracnose (*Elsinoe ampelina*) are widespread in Indian vineyards and may cause yield losses ranging from 20 to 50 per cent under favorable conditions (Gadoury *et al.*, 2012). Recent reports indicate that erratic weather conditions further aggravate disease incidence, posing a serious threat to sustainable grape production. Therefore, understanding disease dynamics and evaluating effective management strategies are crucial for improving grape yield, quality and profitability.

### Material and Methods

The laboratory and field experiments were conducted during 2022–23 at the Main Horticulture Research and Extension Centre, Bagalkot, University of Horticultural Sciences, Bagalkot, Karnataka, India (16.1775° N, 75.7139° E). Combination fungicides recommended for grape downy mildew management by the National Research Centre for Grapes (NRCG) were selected for evaluation (FRAC, 2024). *In vitro* studies were conducted to assess the efficacy of eleven fungicides at three concentrations: C<sub>1</sub> (1/10 of the recommended field dose), C<sub>2</sub> (1/7.5 of the recommended field dose), and C<sub>3</sub> (1/5 of the recommended field dose) (Table 1; Table 2).

Downy mildew of grapevine, caused by *P. viticola*, is identified by characteristic host symptoms and pathogen features. Infected leaves show yellowish “oil-spot” lesions on the upper surface (Fig.1) and white downy sporulation on the lower surface (Fig. 2) under high humidity (Gessler *et al.*, 2011). Microscopically, *P. viticola* produces lemon-shaped

sporangia borne on dichotomously branched sporangiophores (Fig. 3) release motile zoospores in free water for infection, facilitating rapid epidemic development under favorable environmental conditions (Mugnai *et al.*, 1999; Gadoury *et al.*, 2012). These morphological and symptom-based characters are used for the identification and confirmation of the pathogen in both laboratory and field studies.

Sporangial suspensions of *P. viticola* were prepared by washing sporangia from naturally infected leaves in sterile distilled water, filtering through muslin cloth, and adjusting to  $1 \times 10^5$  sporangia/ml using a hemocytometer (Chavan *et al.*, 2021). Fungicide solutions were freshly prepared in sterile distilled water, and equal volumes (1 ml each) of spore suspension and fungicide solution were mixed in sterile cavity slides, which were then incubated in a moist chamber at 95–100% relative humidity for 24 h at room temperature (Rahman *et al.*, 2020). Spore germination was observed under a compound microscope at 40× magnification, with a minimum of 100 sporangia counted per replicate. Per cent spore germination and inhibition were calculated using standard formulas, and all treatments were replicated thrice. Data were analyzed statistically using SPSS version 2.0

$$\text{Per cent spore germination} = \frac{\text{Number of germinated sporangia}}{\text{Total sporangia observed}} \times 100$$

$$\text{Per cent inhibition over control} = \frac{\text{Germination in control} - \text{Germination in treatment}}{\text{Germination in control}} \times 100$$

Field evaluation was conducted on eight year old Thompson Seedless grapevines, planted at a spacing of 10 × 5 feet on red soil. Treatments were imposed after fruit pruning. A Randomized Complete Block Design (RCBD) with three replications was followed, with each replication comprising 12 vines per treatment. Effective fungicides identified from *in vitro* studies were sprayed three times at 7 day intervals using a knapsack sprayer, and observations were recorded one day before each spray and prior to treatment initiation. Anthracnose disease severity was assessed using the 0–4 scale described by Chatta (1992), where 0 indicated healthy foliage or trace leaf spots, 1 represented up to 10% leaf area covered with anthracnose lesions, 2 indicated 10.1–25% leaf area covered with slight twig infection (1–3 cankers per twig), 3 represented 25.1–50% leaf area covered with heavy twig infection (4–10 cankers per twig), and 4 indicated above 50% leaf area covered with very heavy twig infection (more than 10 cankers per twig) along with severe berry infection.

The disease severity data were converted into Per cent Disease Index (PDI) using the formula by Wheeler (1969):

$$\text{PDI} = \frac{\sum \text{of all numerical ratings}}{\text{Total number of observations}} \times 100$$

× Maximum disease rating

At harvest, yield per vine was recorded in kilograms (Kg) and converted to tons per hectare. Economic analysis was performed to calculate gross return, total cost of cultivation and benefit-cost (B:C) ratio.

$$\text{B : C ratio} = \frac{\text{Gross return}}{\text{Total cost of cultivation}}$$



**Fig. 1. Typical oil-spot symptoms of downy mildew on the upper surface of grapevine leaves**



**Fig. 2. White downy sporulation on the abaxial surface of infected grapevine leaves**



**Fig. 3. Lemon-shaped sporangia of *Plasmopara viticola* borne on dichotomously branched sporangiophores (40×).**

**Table 1 :** Non-Systemic fungicides evaluated for management of downy mildew in Grapes (*Plasmopara viticola*)

Sl. No.	Non-systemic fungicides	Dosage (per ha.)	Dosage (g or ml/lit)	FRAC Code	Mode of Action	Reference
1	Amisulbrom 17.7% SC w/w	375 ml	0.375	21	QiI fungicide, inhibits mitochondrial respiration at Qi site	FRAC, 2025
2	Captan 50 % WP	2500 g	2.50	M04	Multi-site protectant, disrupts enzymes and multiple metabolic pathways	FRAC, 2025
3	COC 50 WP	2500 g	2.5 0	M01	Multi-site contact protectant, denatures proteins and enzymes	FRAC, 2025
4	Cyazofamid 34.5% SC	200 ml	0.20	21	QiI fungicide, blocks electron transport in mitochondria	FRAC, 2025
5	Copper hydroxide 53.8 DF	1500 g	1.50	M01	Multi-site contact protectant, disrupts protein/enzyme function	FRAC, 2025
6	Copper hydroxide 61.41% WG	1250 g	1.25	M01	Multi-site contact protectant, denatures proteins and enzymes	FRAC, 2025
7	Mancozeb 75 WP	2000 g	2.00	M03	Multi-site protectant, inactivates sulfhydryl enzymes	FRAC, 2025
8	Mandipropamid 23.4% SC	800 ml	0.80	40	Carboxylic acid amide, inhibits cell wall cellulose synthesis in oomycetes	FRAC, 2025
9	Metiram 70% WG	2000 g	2 .00	M03	Multi-site protectant, disrupts multiple metabolic processes via sulfhydryl groups	FRAC, 2025
10	Propineb 70 WP	3000 g	3.00	M03	Multi-site protectant, inactivates fungal enzymes, preventing growth	FRAC, 2025
11	Zineb 75% WP	2000g	2.00	M03	Multi-site protectant, disrupts multiple enzyme systems	FRAC, 2025

**Table 2 :** *In vitro* concentrations of Non-systemic fungicides used for evaluation against *Plasmopara viticol*

Sl. No.	Fungicide (Formulation)	Field dosage (g or ml/lit)	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>
1	Amisulbrom 17.7% SC (w/w)	0.375	0.0375	0.050	0.075
2	Captan 50% WP	2.50	0.25	0.333	0.50
3	Copper oxychloride 50% WP	2.5 0	0.25	0.333	0.50
4	Cyazofamid 34.5% SC	0.20	0.020	0.030	0.040
5	Copper hydroxide 53.8% DF	1.50	0.15	0.20	0.30
6	Copper hydroxide 61.41% WG	1.25	0.125	0.167	0.25
7	Mancozeb 75% WP	2.00	0.20	0.30	0.40
8	Mandipropamid 23.4% SC	0.80	0.08	0.107	0.16
9	Metiram 70% WG	2 .00	0.20	0.30	0.40
10	Propineb 70% WP	3.00	0.30	0.40	0.60
11	Zineb 75% WP	2.00	0.20	0.30	0.40

Where: C<sub>1</sub> = 1/10 field dose (recommended concentration); C<sub>2</sub> = 1/7.5 field dose (higher concentration); C<sub>3</sub> = 1/5 field dose (higher concentration)

## Results

The *in vitro* evaluation of Non-systemic fungicides revealed significant variation in sporangial germination of *P. viticola* across different concentrations (C<sub>1</sub>–C<sub>3</sub>) (Table 3 and Fig. 4). A clear concentration dependent reduction in sporangial germination was observed for all fungicidal treatments when compared with the untreated control, which recorded cent per cent germination at all concentrations.

Among the fungicides tested, Cyazofamid 34.5% SC was the most effective, exhibiting the lowest

sporangial germination of 38.50 per cent, 21.30 per cent and 9.80 per cent at C<sub>1</sub>, C<sub>2</sub> and C<sub>3</sub> tested concentration, respectively, corresponding to the highest inhibition levels of 61.50 per cent, 78.70 per cent and 90.20 per cent. This treatment was statistically superior to all other fungicides at each concentration. Mancozeb 75% WP and Zineb 75% WP also showed strong inhibitory activity, recording sporangial germination ranging from 40.88–41.63 per cent at concentration of C<sub>1</sub> to 15.12–16.88 per cent at C<sub>3</sub>, with inhibition levels reaching 84.88 per cent and 83.12 per cent, respectively, at the higher concentration.

Moderate efficacy was observed with Amisulbrom 17.7% SC, Mandipropamid 23.4% SC, Propineb 70% WP and Metiram 70% WG, which reduced sporangial germination to below 18.54 per cent at C<sub>3</sub> concentration, resulting in inhibition values between 81.46 per cent and 83.79 per cent. In contrast, copper based fungicides, namely Copper oxychloride 50% WP and Copper hydroxide 53.8% DF, were comparatively less effective, exhibiting higher sporangial germination (22.46–24.63%) and lower inhibition (75.37–77.54%) even at the highest concentration.

Based on the superior performance of selected Non-systemic fungicides under laboratory conditions, field experiments were conducted to evaluate their efficacy against downy mildew of grape after the third

spray (Table 4). All fungicidal treatments significantly reduced disease severity on both leaves and bunches compared to the untreated control.

Among the treatments, Cyazofamid 34.5% SC recorded the lowest disease severity on leaves (8.90 PDI) and bunches (8.07 PDI), corresponding to the highest reduction over untreated control of 88.50 per cent and 88.12 per cent, respectively. This treatment was statistically superior to all other fungicides and resulted in the maximum yield, recording 20.08 kg/vine and 15.20 tons/ ha. Amisulbrom 17.7% SC ranked second in effectiveness, with leaf and bunch PDI of 11.41 per cent and 10.10 per cent, respectively, and per cent disease reduction exceeding 85 per cent on both plant parts, yielding 19.02 kg/vine and 14.44 tons/ ha.

**Table 3 :** Efficacy of non-systemic fungicides on sporangial germination of *P. viticola* under *in vitro* conditions

Sl. No.	Fungicide (Formulation)	Sporangial germination (%)			Inhibition (%)		
		C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>
1	Amisulbrom 17.7% SC (w/w)	42.63 <sup>b</sup>	28.43 <sup>c</sup>	16.21 <sup>b</sup>	57.37	71.57	83.79
2	Captan 50% WP	45.84 <sup>c</sup>	30.54 <sup>d</sup>	18.92 <sup>c</sup>	54.16	69.46	81.08
3	Copper oxychloride 50% WP	48.21 <sup>d</sup>	33.69 <sup>e</sup>	22.46 <sup>d</sup>	51.79	66.31	77.54
4	Cyazofamid 34.5% SC	38.50 <sup>a</sup>	21.30 <sup>a</sup>	9.80 <sup>a</sup>	61.50	78.70	90.20
5	Copper hydroxide 53.8% DF	50.63 <sup>e</sup>	35.25 <sup>f</sup>	24.63 <sup>e</sup>	49.37	64.75	75.37
6	Mancozeb 75% WP	40.88 <sup>a</sup>	26.54 <sup>b</sup>	15.12 <sup>b</sup>	59.12	73.46	84.88
7	Mandipropamid 23.4% SC	43.50 <sup>b</sup>	28.10 <sup>c</sup>	17.05 <sup>b</sup>	56.50	71.90	82.95
8	Metiram 70% WG	44.02 <sup>c</sup>	29.56 <sup>d</sup>	18.54 <sup>c</sup>	55.98	70.44	81.46
9	Propineb 70% WP	43.24 <sup>b</sup>	27.82 <sup>c</sup>	17.33 <sup>b</sup>	56.76	72.18	82.67
10	Zineb 75% WP	41.63 <sup>a</sup>	25.90 <sup>b</sup>	16.88 <sup>b</sup>	58.37	74.10	83.12
11	Untreated control	100.00 <sup>f</sup>	100.00 <sup>f</sup>	100.00 <sup>f</sup>	0.00	0.00	0.00

Where: C<sub>1</sub> = 1/10 field dose (recommended concentration); C<sub>2</sub> = 1/7.5 field dose (higher concentration); C<sub>3</sub> = 1/5 field dose (higher concentration)

**Table 4:** Field efficacy of Non-systemic fungicides against downy mildew (*Plasmopara viticola*) in Grapes

Tr. No.	Treatments detail	Dose (g or ml/lit)	Disease severity on leaves (PDI) after 3 <sup>rd</sup> spray	% Reduction over control (leaves)	Disease severity on bunch (PDI) after 3 <sup>rd</sup> spray	% Reduction over control (bunch)	Yield per vine (Kg)	Yield (Tons/ha)
T <sub>1</sub>	Cyazofamid 34.5% SC	0.30 ml	8.90 <sup>a</sup> (17.3)	88.5	8.07 <sup>a</sup> (17.04)	88.12	20.08	15.20
T <sub>2</sub>	Amisulbrom 17.7% SC	0.56 ml	11.41 <sup>ab</sup> (19.70)	85.3	10.10 <sup>ab</sup> (18.06)	85.25	19.02	14.44
T <sub>3</sub>	Mancozeb 75% WP	3.0 g	14.63 <sup>b</sup> (22.42)	81.2	12.62 <sup>b</sup> (19.31)	81.33	17.51	13.30
T <sub>4</sub>	Zineb 75% WP	3.0 g	17.88 <sup>bc</sup> (24.90)	77.1	15.15 <sup>bc</sup> (21.02)	77.61	16.23	12.30
T <sub>5</sub>	Propineb 70% WP	4.5 g	18.90 <sup>c</sup> (25.83)	75.6	15.92 <sup>c</sup> (22.00)	75.60	15.51	11.77
T <sub>6</sub>	Copper oxychloride 50% WP	3.75 g	20.32 <sup>cd</sup> (26.85)	71.5	17.71 <sup>cd</sup> (23.07)	71.54	14.52	11.00
T <sub>7</sub>	Untreated Control	—	77.61 <sup>e</sup> (61.82)	—	67.52 <sup>e</sup> (53.53)	—	5.02	4.36

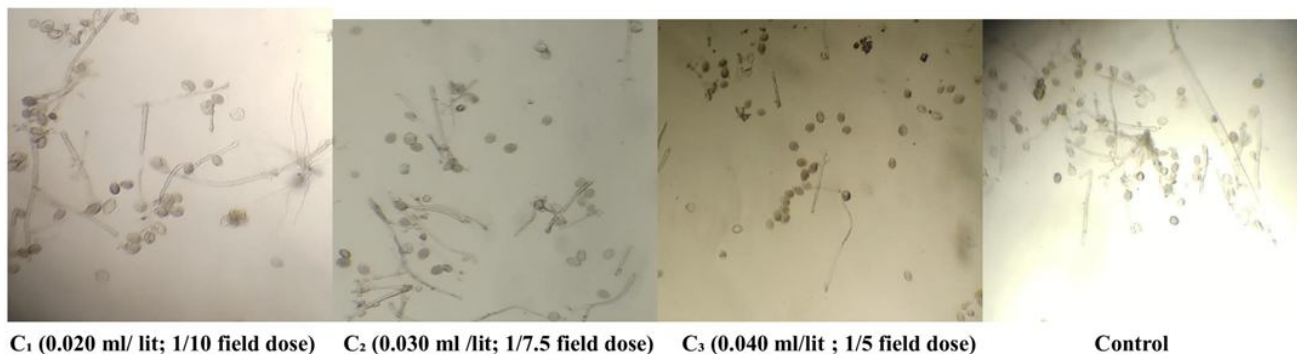


Fig. 4. Effect of Cyazofamid 34.5% SC on sporangial germination of *Plasmopara viticola* at different concentrations under *in vitro* conditions.

Moderate disease control was achieved with Mancozeb 75% WP and Zineb 75% WP, which recorded leaf PDI values of 14.63 per cent and 17.88 per cent and bunch PDI values of 12.62 per cent and 15.15 per cent, resulting in disease reduction ranging from 77.10 per cent to 81.33 per cent. These treatments produced yields between 12.30 and 13.30 tons/ha. In contrast, Propineb 70% WP and Copper oxychloride 50% WP were comparatively less effective, though significantly superior to the untreated control. The untreated control recorded the highest disease severity on leaves (77.61 PDI) and bunches (67.52 PDI), with the lowest yield of 4.36 tons/ ha.

Economic assessment of the treatments revealed considerable variation in cost benefit ratios (Table 5). Cyazofamid 34.5% SC resulted in the highest gross returns (Rs. 4,72,960 / ha) and maximum benefit cost (B:C) ratio of 2.36, owing to its superior disease control and yield performance. Amisulbrom 17.7% SC ranked second with a B:C ratio of 2.27, followed by Mancozeb 75% WP (2.11). Lower B:C ratios were recorded with Zineb 75% WP, Propineb 70% WP, and Copper oxychloride 50% WP, ranging from 1.77 to 1.97, reflecting comparatively reduced yields despite lower input costs. The untreated control resulted in a negative B:C ratio (-0.73) due to severe disease incidence and poor yield.

### Discussion

The present study demonstrated significant differences in the efficacy of Non-systemic fungicides

in suppressing sporangial germination of *P. viticola* under *in vitro* conditions, exhibiting a clear concentration-dependent response. Among the fungicides tested, Cyazofamid 34.5% SC exhibited the highest inhibition of sporangial germination at all tested concentrations, consistent with its specific mode of action targeting mitochondrial respiration at the Qi site, an essential metabolic pathway in oomycetes. (Grasso *et al.*, 2006; Gisi and Sierotzki, 2008). Previous studies have documented the high sensitivity of downy mildew sporangia to Qi-site inhibitors, noting rapid disruption of zoospore formation and germ tube development (Stewart *et al.*, 2008; Rotondo *et al.*, 2019).

The strong inhibitory activity observed with Mancozeb 75% WP and Zineb 75% WP confirms the effectiveness of multisite protectants, which attack multiple biochemical pathways in the pathogen, reducing the chance of resistance development (McGrath., 2004; Brent and Hollomon., 2007). Dithiocarbamate fungicides such as Mancozeb and Zineb are widely regarded as reliable protectants in oomycete disease management due to their broad biological activity and multi-target action (Mitani *et al.*, 2001; Gisi and Sierotzki., 2008). Their moderate-to-high inhibition values, particularly at the C<sub>3</sub> concentration, align with earlier reports demonstrating their ability to reduce sporulation and delay disease initiation under favorable conditions. (Gadoury *et al.*, 2012; Caffi *et al.*, 2016).

**Table 5:** Economic assessment of Non-systemic fungicides in grapevine downy mildew management

Tr. No.	Treatments	Dosage (ml or g/ha)	Cost of chemical (3 sprays) /ha (Rs.)	Cost of cultivation /ha (Rs.)	Total cost of cultivation (Rs.)	Yield (Tons/ha)	Gross returns (Rs./ha)	C:B Ratio
T <sub>1</sub>	Cyazofamid 34.5% SC	0.30 mL	15,000	1,85,000	2,00,000	15.20	4,72,960	2.36
T <sub>2</sub>	Amisulbrom 17.7% SC	0.56 mL	12,000	1,85,000	1,97,000	14.44	4,47,640	2.27
T <sub>3</sub>	Mancozeb 75% WP	3.0 g	10,000	1,85,000	1,95,000	13.30	4,12,300	2.11

T <sub>4</sub>	Zineb 75% WP	3.0 g	9,000	1,85,000	1,94,000	12.30	3,81,300	1.97
T <sub>5</sub>	Propineb 70% WP	4.5 g	8,000	1,85,000	1,93,000	11.77	3,64,870	1.89
T <sub>6</sub>	Copper oxychloride 50% WP	3.75 g	7,500	1,85,000	1,92,500	11.00	3,41,000	1.77
T <sub>7</sub>	Untreated Control	—	-	1,85,000	1,85,000	4.36	1,35,160	-0.73

In contrast, copper-based fungicides, including Copper oxychloride 50% WP and Copper hydroxide 53.8% DF, were comparatively less effective in reducing sporangial germination even at the highest concentration. Although copper compounds have long been used as broad-spectrum contact protectants, their primary mode of action is surface protection rather than systemic inhibition of pathogen development (Jones and Gross., 2006; Pscheidt and Ocamb., 2018). This finding is consistent with previous reports showing limited efficacy of copper protectants against *P. viticola* sporangia compared to more targeted chemistries (Caffi *et al.*, 2016; Rotondo *et al.*, 2019).

Field evaluation after the third spray corroborated the *in vitro* findings, demonstrating that fungicides effective in inhibiting sporangial germination provided superior disease suppression under vineyard conditions. Cyazofamid 34.5% SC recorded the lowest disease severity on both leaves and bunches, resulting in the highest yield per vine (20.08 kg) and per hectare (15.20 tons/ha). Such high field efficacy is consistent with earlier field trials indicating that Qi-site inhibitors can effectively manage primary infection and reduce secondary disease cycles in humid environments (Stewart *et al.*, 2008; Rotondo *et al.*, 2019). The improved canopy health associated with strong disease control likely contributed to enhanced photosynthetic efficiency and yield, as has been observed in grape downy mildew management studies (Calonnet *et al.*, 2004; Ghosh *et al.*, 2019).

Amisulbrom 17.7% SC also performed well under field conditions, ranking second in effectiveness with both leaf and bunch PDI values indicating high levels of disease reduction. This aligns with literature reporting amisulbrom's strong protective activity against oomycete pathogens, attributed to its inhibition of early stages of infection in free water (Parker and Gilbert., 2004; Pscheidt and Ocamb., 2018). Although its mode of action differs from that of multisite protectants and Qi inhibitors, its contribution to integrated management programmes has been highlighted in recent reviews of downy mildew management strategies (Caffi *et al.*, 2016; Dhillon *et al.*, 2021).

Moderate disease management achieved with Mancozeb 75% WP and Zineb 75% WP confirms their utility as foundational protectants, especially under high disease pressure. These protectants recorded

significant disease reductions and contributed to appreciable yield improvements compared to the untreated control (Gadoury *et al.*, 2012; Brent and Hollomon, 2007). Their broad-spectrum activity, while less potent than that of targeted inhibitors, remains valuable as part of a rotation strategy to mitigate resistance development and maintain long-term efficacy (FRAC., 2024; McGrath., 2004).

In contrast, Propineb 70% WP and Copper oxychloride 50% WP provided comparatively lower disease suppression and yield gains, but were still significantly superior to the untreated control. The untreated plots exhibited the highest disease severity (77.61 PDI on leaves and 67.52 PDI on bunches) with the lowest yield (4.36 tons/ha), underscoring the detrimental impact of downy mildew when unmanaged, which is well documented in grape pathology literature (Gessler *et al.*, 2011; Mugnai *et al.*, 1999).

Economic analysis further supported these observations, with Cyazofamid 34.5% SC yielding the highest gross returns (Rs 4,72,960/ha) and the maximum benefit–cost (B:C) ratio of 2.36, attributable to its superior disease control and yield performance. Amisulbrom 17.7% SC followed closely with a B:C ratio of 2.27, while Mancozeb 75% WP maintained a favourable ratio of 2.11. Although Zineb 75% WP, Propineb 70% WP, and Copper oxychloride 50% WP recorded comparatively lower B:C ratios (1.77–1.97), these protectants still offered economic returns above the cost of cultivation. The untreated control incurred a negative B:C ratio, highlighting the economic losses associated with unchecked downy mildew (Ghosh *et al.*, 2019; Dhillon *et al.*, 2021).

## Conclusion

The study revealed that among the Non-systemic fungicides evaluated, Cyazofamid 34.5% SC was the most effective in inhibiting *P. viticola* sporangial germination and suppressing downy mildew under field conditions, resulting in maximum yield and benefit–cost ratio. Amisulbrom 17.7% SC also demonstrated high efficacy, while Mancozeb 75% WP and Zineb 75% WP provided moderate to high disease management. Copper-based fungicides and Propineb 70% WP were comparatively less effective than the other treatments. The findings emphasize that the strategic use of Qi-site inhibitors along with multisite

protectants can ensure sustainable, economically viable management of grapevine downy mildew in India.

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