



Comparative efficacy of new-generation fungicides against major fungal diseases of rice

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Abstract

A field study was conducted during the kharif seasons of 2023 and 2024 at the Rice Research Unit, Agricultural Research Institute, Rajendranagar, using a randomised block design (RBD) with 8 treatments and 4 replications to evaluate the efficacy of seven multi-active combination fungicides against three predominant fungal diseases of rice in Telangana, namely sheath blight, blast and grain discolouration, which limit rice productivity and grain quality under intensive production systems. Significant differences were observed among the fungicidal treatments in terms of disease suppression, grain yield and economic returns ($p < 0.05$). Pooled analysis revealed that Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % emulsifiable concentrate (EC) was the most effective treatment, registering the lowest sheath blight severity of 21.8 % and an area under the disease progress curve (AUDPC) of 563.3, compared to the untreated control, which exhibited 59.2 % severity and an AUDPC of 1439.6. The above combination fungicide also recorded a lower percentage of neck blast and grain discolouration (4.9 % and 13.7 %, respectively) compared to the untreated control (16.6 % and 27.2 %, respectively). Furthermore, the Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC treatment accrued the highest pooled grain yield (6142 kg ha^{-1}) with a 31.9 % increase in yield over the untreated control and the highest incremental cost–benefit ratio (1 : 5.5). These findings indicate that the combination fungicide Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC, representing the strobilurin, triazole and imidazole fungicide groups, is an effective option for the simultaneous management of major fungal diseases of rice while improving grain yield and economic returns under field conditions.

Keywords: disease management; fungicides; grain discolouration; neck blast; sheath blight

Received: 03 July 2026. **Accepted:** 03 September 2026. **Published:** 13 October 2026.

Cite this article: Kiran BT, Rama GVN, Damodar RCh. Comparative efficacy of new-generation fungicides against major fungal diseases of rice. Plant Science Today. 2026;13(sp9):01-12. <https://doi.org/10.14719/pst.16526>

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops and serves as the staple food for more than half of the global population (1). Asia accounts for over 90 % of global rice production and consumption, highlighting the crop's critical role in food security and rural livelihoods. India is currently one of the world's leading rice-producing countries, cultivating rice on approximately 47.8 million hectares and producing over 137.8 million tonnes. In Telangana, rice is the principal food crop, occupying nearly 4.6 million hectares and playing a vital role in the state's agricultural economy and food security (2–4).

Despite continuous improvements in crop production technologies, rice productivity is constrained by several biotic and abiotic stresses. Yield losses caused by biotic stresses are around 52 %, of which nearly 31 % are due to numerous fungal and bacterial diseases affecting the crop. Among all the diseases affecting the crop, sheath blight, blast and grain discolouration are economically important diseases of rice, which occur widely across major rice-growing

regions. Under favourable environmental conditions, these diseases can cause substantial yield losses and adversely affect grain quality, thereby reducing market value and profitability (2, 5).

Sheath blight, caused by *Rhizoctonia solani* Kuhn, is widely considered one of the most destructive diseases of rice. The disease is favoured by dense crop canopies, excessive nitrogen fertilisation and high humidity conditions that commonly prevail in intensive rice production systems. The pathogen survives between cropping seasons through sclerotia and mycelial fragments in soil and crop residues, making disease management particularly challenging (6–8). Yield losses ranging from 5–10 % under moderate disease pressure to more than 50 % during severe epidemics have been reported.

Rice blast, caused by *Magnaporthe oryzae* B.C. Couch, is regarded as the most devastating disease of rice and has been reported in more than 80 countries. The pathogen infects rice at different growth stages, causing leaf, node, collar and neck blast symptoms. Among these, neck blast is particularly

damaging because infection at the panicle neck directly interferes with grain filling, resulting in yield losses ranging from 10 % to complete crop failure, depending on cultivar susceptibility and environmental conditions (3, 9, 10).

Grain discolouration is a disease complex associated with several fungal pathogens, including *Bipolaris oryzae*, *Curvularia lunata*, *Alternaria padwickii* and *Fusarium* spp. The disease adversely affects grain appearance, seed germination, milling quality and market acceptability, thereby reducing both yield and grain quality. Consequently, grain discolouration has emerged as an important quality-related disease in rice production systems (2, 11).

Although host resistance and cultural practices contribute to disease suppression, their effectiveness is often limited under high disease pressure and favourable environmental conditions. Furthermore, the availability of durable resistance sources against multiple rice diseases remains limited due to the continuous evolution of pathogen populations. Consequently, fungicides continue to play a vital role in integrated disease management programmes aimed at protecting yield and grain quality (9, 12). Recent advances in fungicide chemistry have led to the development of combination fungicides containing dual or triple active ingredient fungicide formulations with different modes of action. These combination formulations effectively suppress multiple fungal infections simultaneously, offering a robust alternative to conventional single mode of action fungicides, as multiple fungal diseases frequently co-occur during different phenological stages of the rice crop (13). These formulations generally provide broader-spectrum disease management, improved residual activity and enhanced resistance management compared with single-site fungicides. Combination products based on strobilurins, triazoles and other systemic fungicides have shown promising efficacy against major rice diseases and have contributed to improved grain yield and quality in several studies (10, 11, 14, 15). The study hypothesised that new-generation combination fungicides with complementary modes of action would provide broad-spectrum and effective suppression of major fungal diseases of rice, thereby improving grain yield and economic returns. However, increasing concerns regarding fungicide resistance, environmental contamination and sustainability necessitate the evaluation of newer fungicidal combinations under field conditions. Comparative information on the efficacy of recently introduced dual or triple active ingredient fungicide formulations against sheath blight, neck blast and grain discolouration remains limited. Therefore, the present investigation was undertaken to evaluate selected fungicidal molecules for the management of these major rice diseases and to assess their effects on disease suppression, grain yield and economic returns under field conditions.

2. Materials and Methods

Experimental site

Field experiments were conducted during the kharif seasons of 2023 and 2024 at the Rice Research Unit, Agricultural Research Institute, Rajendranagar, Hyderabad, Telangana, India. The experimental site is located at approximately 17.32° N latitude and 78.40° E longitude, with an altitude of about 542 m above mean sea level. The region falls under the Southern Telangana agro-climatic zone and is characterised by predominantly clay loam to clay soils. The soil at the experimental site had a pH ranging from 7.8–8.0, an electrical conductivity of 1.08 dS m⁻¹ and an organic carbon content of 0.42 %. The soil had a clay loam texture, comprising 40 % sand, 32 % silt and 28 % clay. All the standard agronomic practices recommended by Professor Jayashankar Telangana State Agricultural University for irrigated rice cultivation in the region were followed for all the treatments throughout the cropping period.

Weather conditions during the crop growing season

Meteorological data recorded during the crop growing seasons (July–November) of 2023 and 2024 were obtained from the Agro-Meteorological Observatory, Agricultural Research Institute, Rajendranagar, Hyderabad. During 2023, the experimental site received a cumulative rainfall of 705.0 mm over 32 rainy days, whereas 783.7 mm of rainfall was recorded over 40 rainy days during 2024. Monthly maximum and minimum temperatures ranged from 29.2–32.0 to 19.8–23.3 °C, respectively, during 2023, while the corresponding observatory records for 2024 indicated values of 17.1–23.3 and 29.8–31.6 °C, respectively. Morning relative humidity ranged from 85–90 % in 2023 to 80.7–88.9 % in 2024, while evening relative humidity varied from 42–71 % to 43–68.3 %, respectively.

Crop establishment and experimental design

A highly blast-susceptible rice variety, Tellahamsa, was used in the study. Seedlings were raised in a nursery and transplanted at a spacing of 15 × 15 cm following standard agronomic practices recommended by Professor Jayashankar Telangana State Agricultural University. Fertilisers were applied at 180 : 60 : 40 kg N : P₂O₅ : K₂O ha⁻¹. Nitrogen was applied in split doses at active tillering and panicle initiation stages, while the entire dose of phosphorus and potassium was applied as a basal application before transplanting. Irrigation and crop management practices were maintained uniformly across all treatments. The experiment was laid out in a randomised block design (RBD) comprising 8 treatments with 4 replications. Each experimental plot was maintained according to the prescribed layout and separated by suitable buffer zones to prevent spray drift into adjacent treatment plots. The treatments comprised different fungicidal formulations evaluated against fungal diseases, namely sheath blight, neck blast and grain discolouration of rice (Table 1).



Table 1. Treatment details of fungicides evaluated against major diseases of rice

Treatment No.	Fungicide	Mode of action	Dose (g or mL/ha)
T ₁	Mancozeb 50 % + Thiophanate methyl 25 % WG	Multi-site activity + mitosis inhibitor	1500 g
T ₂	Kasugamycin 5 % + Copper oxychloride 45 % WP	Protein synthesis inhibitor (30S ribosome) + multi-site disruption of enzymes and cellular functions	700 g
T ₃	Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC	QoI inhibitor + DMI ergosterol biosynthesis inhibitors	1750 mL
T ₄	Fenoxanil 5 % + Isoprothiolane 30 % EC	Melanin biosynthesis inhibitor + phospholipid biosynthesis inhibitor	1000 mL
T ₅	Azoxystrobin 14 % + Epoxiconazole 9 % SC	QoI inhibitor + DMI ergosterol biosynthesis inhibitor	750 mL
T ₆	Picoxystrobin 7.05 % + Propiconazole 11.7 % SC	QoI inhibitor + DMI ergosterol biosynthesis inhibitor	1000 mL
T ₇	Tebuconazole 50 % + Trifloxystrobin 25 % WG	DMI ergosterol biosynthesis inhibitor + QoI inhibitor	200 g
T ₈	Untreated control (water spray)	-	-

WG: water-dispersible granule; WP: wettable powder; EC: emulsifiable concentrate; SC: suspension concentrate; QoI: quinone outside inhibitor; DMI: demethylation inhibitor.

Pathogen inoculation and disease development

A virulent isolate of *R. solani* obtained from the Institute of Rice Research, Rajendranagar, was identified based on cultural and morphological characteristics and further confirmed by pathogenicity testing through the fulfilment of Koch's postulates. It was multiplied on sterilised typha stem bits and used for artificial inoculation at the maximum tillering stage on randomly tagged plants under field conditions. The colonised bits were inserted between the leaf sheath and culm of selected tillers to facilitate uniform sheath blight development, whereas neck blast and grain discolouration developed naturally under prevailing epiphytotic conditions within the same experimental field.

Fungicide application

Fungicides were applied at the dosages recommended by the Central Insecticides Board and Registration Committee (CIB&RC), Government of India, using a battery-operated knapsack sprayer fitted with a hollow-cone nozzle and calibrated to deliver a spray volume of 500 L/ha. The spray suspension was prepared thoroughly before each application. Two foliar applications were made during the crop season, with the first applied at the onset of sheath blight and the second 15 days later. Fungicide spray solutions were prepared freshly before each application and sprayed uniformly over the crop canopy during the morning hours under favourable weather conditions. Untreated control plots received a water spray alone. Details of the fungicides evaluated in the study, including active ingredients and recommended dosages, are presented in Table 1. Furthermore, trade names and manufacturers details are enclosed in Supplementary Table 1.

Disease assessment

Sheath blight severity was recorded before fungicide application as a pre-count and at 7 and 15 days after each spray from 20 randomly tagged hills per

replication. The disease severity was assessed using the standard evaluation system (SES) for rice scale (Table 2) (16) and expressed as the percent disease index (PDI) following wheeler (17).

$$PDI = \frac{\Sigma(\text{Disease ratings})}{\text{Total no. of observations} \times \text{maximum dise}}$$

where PDI: percent disease index.

Neck blast severity was recorded on randomly selected 20 plants at the milky to maturity stage by using the SES scale (Table 3). Likewise, grain discolouration severity was assessed at crop maturity using the SES scale (Table 3) (16).

The AUDPC was calculated according to Shaner and Finney (18).

$$AUDPC = \sum \frac{Y_i + Y_{i+1}}{2} (t_{i+1} - t_i)$$

where Y_{i_i} = disease severity (PDI) at time t_i ; t_i = time interval (days).

Table 2. The standard evaluation system (SES) scale is used for the assessment of sheath blight severity in rice

Score	Relative lesion height (RLH)
0	No infection observed
1	Lesions limited to lower 20 % of plant height
3	20–30 %
5	31–45 %
7	46–65 %
9	>65 %



Table 3. The standard evaluation system (SES) scale is used for the assessment of neck blast and grain discolouration severity in rice

Score	Percent infected panicles (neck blast)	Grain discolouration (%)
0	No disease observed	No discolouration
1	Less than 5 %	<1 %
3	5–10 %	1–5 %
5	10–25 %	6–25 %
7	25–50 %	26–50 %
9	More than 50 %	51–100 %

Yield and economic analysis

Grain yield was recorded from the net plot area at harvest and converted to kg ha⁻¹. Economic analysis was carried out by estimating the cost of fungicide application, gross returns, net returns and incremental cost-benefit ratio (ICBR) based on the prevailing market price of paddy during the study period. The cost of cultivation included the common costs incurred for crop production, while the additional cost of cultivation for each fungicide treatment included the cost of the respective fungicide and its application. Gross returns were calculated based on grain yield and the prevailing market price of paddy (minimum support price). Additional returns over the untreated control were calculated as the difference between the gross returns of each fungicide treatment and the untreated control. The ICBR was calculated as the ratio of additional returns over the untreated control to the additional cost of cultivation.

Statistical analysis

The PDI data were angular (arcsine square-root) transformed prior to analysis. Data were subjected to analysis of variance (ANOVA) appropriate for a RBD following the procedure described in a previous study (19). Treatment means were separated using Duncan's multiple range test (DMRT) at $p \leq 0.05$. For pooling the data across 2 years, Bartlett's test for homogeneity of error variance was conducted, which indicated homogeneous error variances. Statistical analyses were performed using Online Package for Agricultural Statistics (OPSTAT) software (20).

3. Results

Effect of fungicidal treatments on major fungal diseases of rice during kharif, 2023

The sheath blight severity was uniform across the treatments during the pre-treatment stage. Following fungicide application, significant differences were observed among treatments in suppressing sheath blight development at different times of observation. Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % emulsifiable concentrate (EC) (T₃) recorded the lowest sheath blight severity throughout the observation period and registered the minimum disease severity (19.7 %) at 15 days after the second spray (Fig. 1). The same treatment also recorded the lowest AUDPC value (631.4), indicating effective suppression of disease progression. T₅ (Azoxystrobin 14 % + Epoxiconazole 9 % suspension concentrate (SC)) and T₇ (Tebuconazole 50 % + Trifloxystrobin 25 % water-dispersible granule (WG)) were the next most effective treatments, while the untreated control recorded the highest sheath blight severity and AUDPC (1408.6).

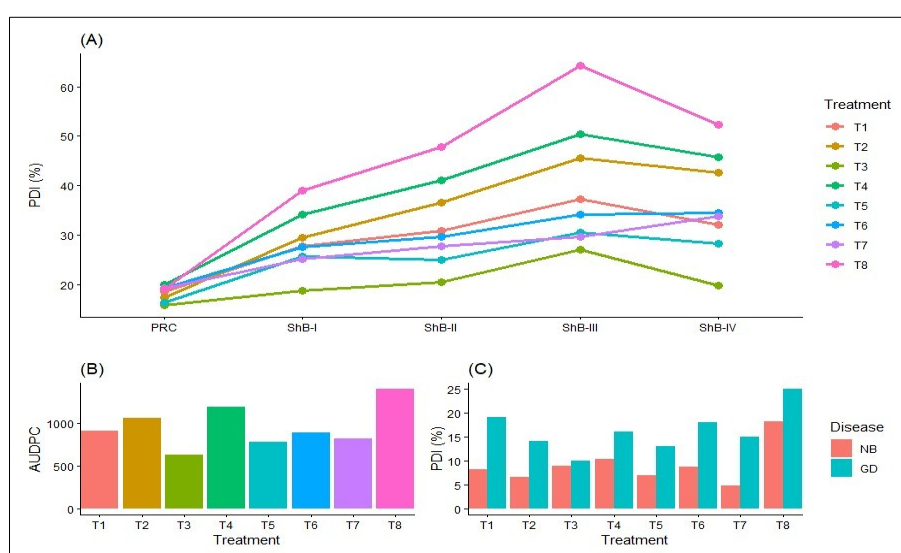


Fig. 1. Effect of fungicidal treatments. A: on sheath blight severity (PDI); B: AUDPC for sheath blight (ShB); C: neck blast (NB) and grain discolouration (GD) diseases of rice during kharif, 2023. PDI: percent disease index; AUDPC: area under the disease progress curve; ShB-I: 7 days after 1st spray; ShB-II: 15 days after 1st spray; ShB-III: 7 days after 2nd spray; ShB-IV: 15 days after 2nd spray.

Neck blast severity differed significantly among treatments. Tebuconazole 50 % + Trifloxystrobin 25 % WG (T₇) recorded the lowest neck blast severity (4.7 %), followed by Kasugamycin 5 % + Copper oxychloride 45 % wettable powder (WP) (T₂) with 6.6 % and Azoxystrobin 14 % + Epoxiconazole 9 % SC (T₅) with 6.9 % neck blast, while the untreated control recorded the highest severity (18.2 %). Similarly, grain discolouration was significantly reduced by fungicide application, wherein T₄ viz Fenoxanil 5 % + Isoprothiolane 30 % EC, recorded the lowest grain discolouration severity (10.0 %), followed by T₅ (13.0 %) and T₂ (14.0 %), whereas the untreated control recorded the highest severity (25.0 %). Among the treatments, Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC (T₃) recorded the highest grain yield (6272 kg ha⁻¹), followed by T₅ (6121 kg ha⁻¹) and T₇ (6100 kg ha⁻¹), while the untreated control recorded the lowest (4629 kg ha⁻¹) grain yield (Fig. 2).

Effect of fungicidal treatments on major fungal diseases of rice during kharif, 2024

Fungicidal treatments significantly reduced sheath blight severity compared with the untreated control. During 2024, Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC (T₃) was found to be the most effective fungicide combination and recorded the lowest disease severity across all the observation periods, resulting in the minimum AUDPC value (495.3) (Fig. 3). In addition, T₇ and T₅ also effectively suppressed sheath blight development, recording AUDPC values of 634.2 and 638.0 respectively whereas the untreated control recorded the highest AUDPC (1470.6). Significant differences were also observed in neck blast severity, wherein T₃ recorded the lowest disease severity (1.0 %), followed by T₅ (2.3 %), compared with the untreated control (15.1 %). Similar to the observations made during 2023, T₄ recorded the lowest grain discolouration (10.0 %), while the untreated control recorded the highest severity (29.2 %). Grain yield was significantly

influenced by fungicide treatments during kharif, 2024 (Fig. 2). Although treatment T₇ recorded the highest grain yield (6076 kg ha⁻¹), it was statistically on par with T₆ (6030 kg ha⁻¹), T₃ (6012 kg ha⁻¹) and T₅ (5984 kg ha⁻¹). Although T₃ provided superior disease suppression, grain yield is influenced by multiple factors in addition to disease control, including environmental conditions and crop physiological responses. All the fungicide treatments accrued significantly higher yield than the untreated control (4686 kg ha⁻¹).

Pooled efficacy of fungicides against major fungal diseases of rice (2023–2024)

Pre-treatment sheath blight severity did not differ significantly among treatments, indicating uniform disease distribution before fungicide application. Bartlett's test for homogeneity of variance was non-significant ($p > 0.05$), confirming the homogeneity of error variances and further validation for combining the data for pooled statistical analysis. Significant treatment effects were observed following fungicide application at all subsequent observation periods (Table 4) and a correlation heat map based on pooled data is presented in Fig. 4. Although sheath blight severity was recorded across the different times of observations, data recorded 15 days after the second spray were considered for comparison of treatment effects in the pooled analysis. Among the fungicides evaluated over two seasons, T₃ (Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC) recorded the lowest sheath blight severity at 15 days after the second spray (21.8 %) and the lowest AUDPC value (563.3), indicating effective suppression of disease development throughout the crop growth period. Treatments T₅ and T₇ were the next best treatments, recording comparatively lower disease severity (29.5 % and 30.0 % respectively) and AUDPC values (708.6 and 727.7 respectively) than the remaining fungicidal treatments. The untreated control consistently registered the highest disease severity (59.2 %) and AUDPC (1439.6).

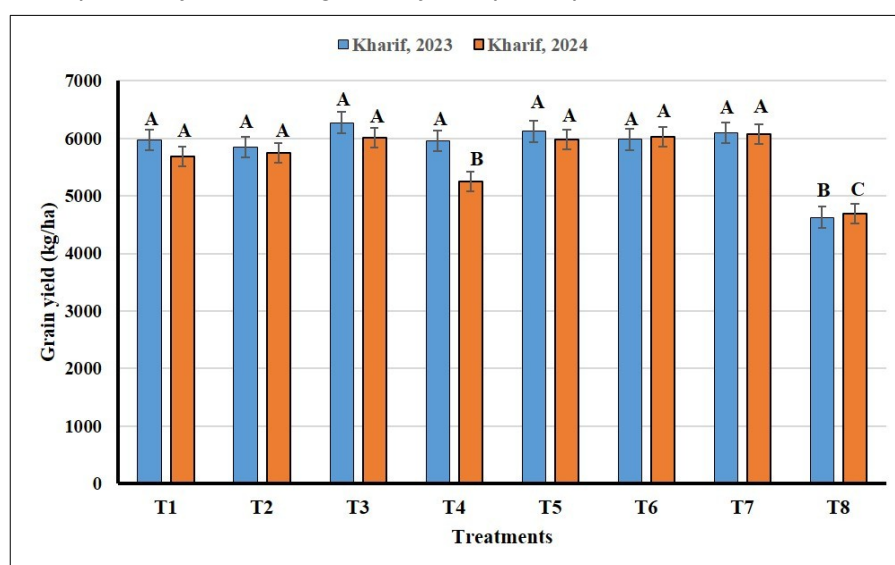


Fig. 2. Grain yield recorded in various treatments during kharif, 2023 and 2024 at Rice Research Unit, Agricultural Research Institute, Rajendranagar. A–C: Statistical groups for the Duncan test.

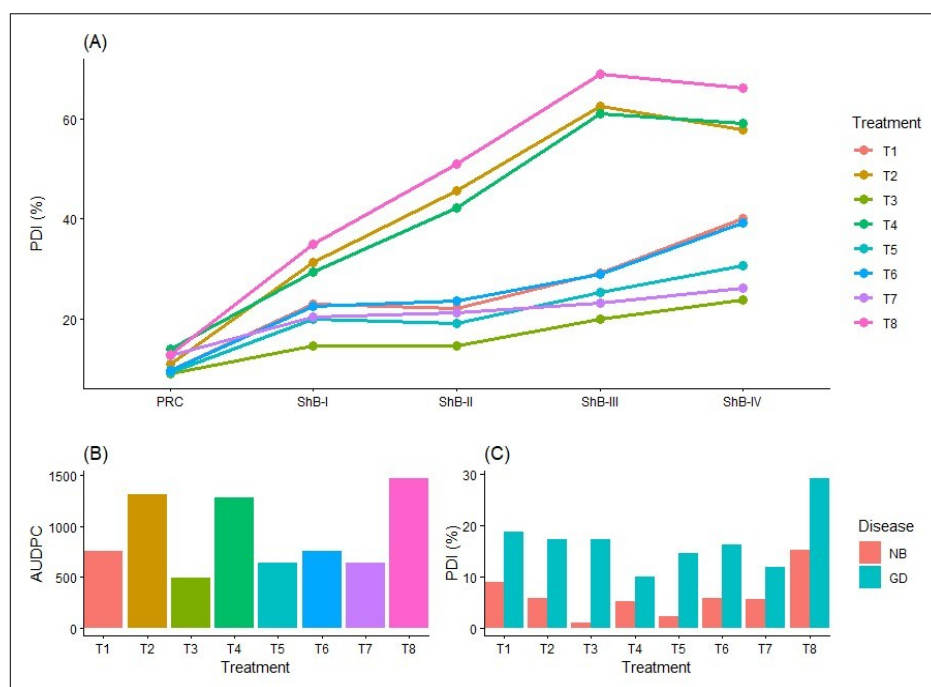


Fig. 3. Effect of fungicidal treatments. A: sheath blight severity (PDI); B: AUDPC for sheath blight (ShB); C: neck blast (NB) and grain discolouration (GD) diseases of rice during kharif, 2024. PDI: percent disease index; AUDPC: area under the disease progress curve; ShB-I: 7 days after 1st spray; ShB-II: 15 days after 1st spray; ShB-III: 7 days after 2nd spray; ShB-IV: 15 days after 2nd spray.

Table 4. Pooled efficacy of fungicidal treatments against sheath blight, neck blast and grain discolouration in rice during kharif, 2023 and 2024

Treatment	Sheath blight severity (PDI)					AUDPC	Neck blast severity	GD severity	Grain yield (kg/ha)
	ShB (PRC)	ShB-I	ShB-II	ShB-III	ShB-IV				
T ₁ : Mancozeb 50 % + Thiophanate methyl 25 % WG at 3 g/L	14.1 ^{bc} (22.1)	25.4 ^b (30.2)	26.5 ^c (30.9)	33.2 ^c (35.2)	36.1 ^c (36.9)	832.2	8.5 ^b (16.7)	18.7 ^b (25.6)	5825 ^b
T ₂ : Kasugamycin 5 % + Copper oxychloride 45 % WP at 1.4 g/L	14.2 ^{bc} (22.1)	30.3 ^b (33.4)	41.0 ^b (39.8)	54.0 ^b (47.3)	50.2 ^b (45.1)	1190.8	6.2 ^b (14.3)	15.9 ^b (23.3)	5793 ^b
T ₃ : Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC at 3.5 mL/L	12.4 ^d (20.6)	16.6 ^d (23.8)	17.6 ^d (24.6)	23.5 ^d (29.0)	21.8 ^d (27.8)	563.3	4.9 ^c (12.7)	13.7 ^c (21.7)	6142 ^a
T ₄ : Fenoxanil 5 % + Isoprothiolane 30 % EC at 2.0 mL/L	16.9 ^a (24.3)	31.7 ^a (34.2)	41.6 ^b (40.1)	55.7 ^b (48.3)	52.4 ^a (46.4)	1236.6	7.7 ^b (15.9)	13.2 ^c (21.3)	5603 ^b
T ₅ : Azoxystrobin 14 % + Epoxiconazole 9 % SC at 1.5 mL/L	12.7 ^{cd} (20.9)	22.8 ^c (28.5)	22.1 ^c (28.0)	27.8 ^c (31.8)	29.5 ^c (32.8)	708.6	4.6 ^c (12.3)	13.9 ^c (21.7)	6053 ^a
T ₆ : Picoxystrobin 7.05 % + Propiconazole 11.7 % SC at 2.0 mL/L	14.4 ^{bc} (22.3)	25.1 ^b (30.0)	26.7 ^c (31.1)	31.4 ^c (34.1)	36.8 ^c (37.2)	822.2	7.2 ^b (15.1)	17.0 ^b (24.2)	6006 ^a
T ₇ : Tebuconazole 50 % + Trifloxystrobin 25 % WG at 0.4 g/L	15.9 ^{ab} (23.5)	22.7 ^c (28.4)	24.4 ^c (29.6)	26.4 ^d (30.9)	30.0 ^c (33.2)	727.7	5.1 ^c (13.0)	13.2 ^c (21.3)	6088 ^a
T ₈ (control)	15.9 ^{ab} (23.6)	36.9 ^a (37.4)	49.4 ^a (44.6)	66.5 ^a (54.7)	59.2 ^a (50.3)	1439.6	16.6 ^a (24.1)	27.2 ^a (31.4)	4657 ^c
SE(m)±	0.9	1.1	1.2	1.2	1.5	—	1.2	1.2	87.9
CD (5 %)	NS	3.5	3.6	3.6	4.5	—	3.5	3.4	259.4
CV (%)	10.9	7.7	7.3	6.2	7.8	—	15.4	9.7	3.1

Values are mean of each 4 replications of two seasons. Figures in parentheses are angular transformed values; means followed by different lowercase letters within a column are significantly different at $p = 0.05$ according to DMRT. PDI: percent disease index; AUDPC: area under disease progression curve; ShB: sheath blight; GD: grain discolouration; ShB-I: 7 days after 1st spray; ShB-II: 15 days after 1st spray; ShB-III: 7 days after 2nd spray; ShB-IV: 15 days after 2nd spray; WG: water-dispersible granule; WP: wettable powder; EC: emulsifiable concentrate; SC: suspension concentrate.

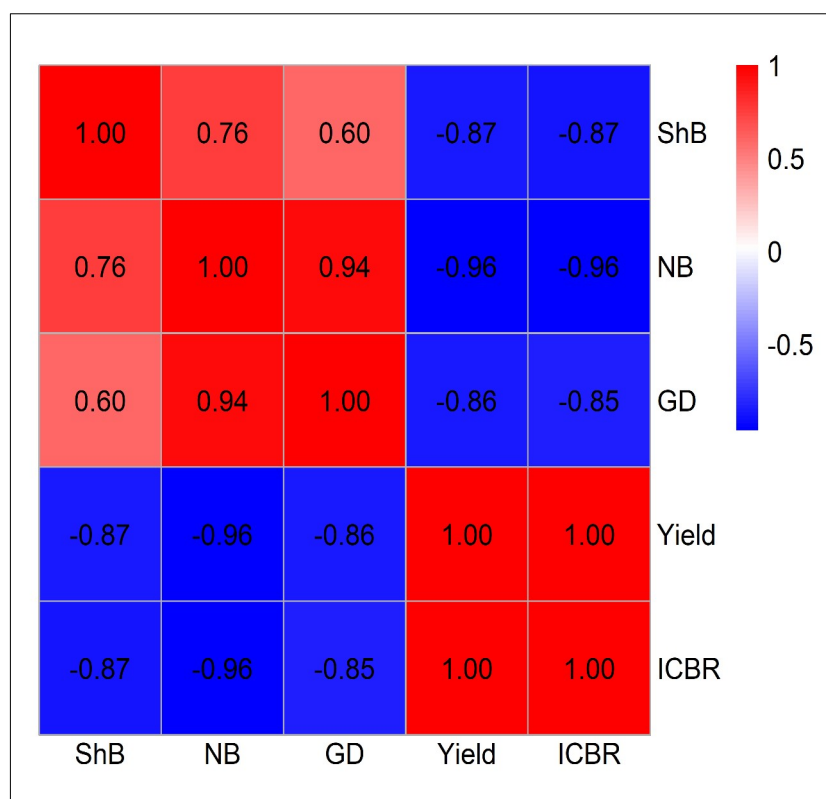


Fig. 4. Correlation heat map based on pooled data over two years (kharif, 2023 and 2024). ShB: sheath blight; NB: neck blast; GD: grain discolouration; ICBR: incremental cost-benefit ratio.

Neck blast severity was significantly reduced in T_5 (4.6 %), followed by T_3 (4.9 %) and T_7 (5.1 %) compared to the highest severity (16.6 %) in the untreated control. Similarly, grain discolouration was significantly low in T_4 , Fenoxanil 5 % + Isoprothiolane 30 % EC and T_7 , Tebuconazole 50 % + Trifloxystrobin 25 % WG (13.2 %), followed closely by Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC (T_3 , 13.7 %) and Azoxystrobin 14 % + Epoxiconazole 9 % SC (T_5 , 13.9 %), while the untreated control recorded the highest grain discolouration (27.2 %). The reduction in disease severity was reflected in grain yield. Treatment T_3 recorded the highest pooled grain yield (6142 kg ha⁻¹), followed by T_7 (6088 kg ha⁻¹), T_5 (6053 kg ha⁻¹) and T_6 (6006 kg ha⁻¹). All fungicidal treatments realised significantly higher grain yield than the untreated control (4657 kg ha⁻¹).

Economic analysis revealed that treatment T_3 achieved the highest ICBR of 5.5, making it the most economically profitable option for the management of major fungal diseases of rice. The higher ICBR observed in T_3 reflects its superior ability to convert disease control benefits into economic returns under field conditions. The subsequent most effective treatments were T_7 , T_5 and T_6 , which demonstrated ICBR values of 5.4, 5.3 and 5.2 respectively. These treatments exhibited higher economic efficiency than the other fungicidal treatments. The marginal difference in ICBR among T_7 , T_5 and T_6 suggests that these fungicides are not only economically viable but also have the potential to deliver profitable disease management within rice production systems.

Treatments T_1 and T_2 recorded ICBR values of 4.6 and 4.5 respectively indicating moderate economic advantage over the untreated control. Among the fungicidal treatments, T_4 recorded the lowest ICBR of 3.9, although it still showed a positive economic return. Overall, T_3 was found to be the most economically viable treatment, followed by T_7 , T_5 and T_6 based on their superior ICBR (Table 5). The year wise ICBR (2023 and 2024) data was presented in Supplementary Table 2 and 3.

Principal component and correlation analyses

Principal component analysis (PCA) was performed using pooled data for sheath blight, neck blast, grain discolouration, grain yield and incremental cost-benefit ratio (ICBR) to examine relationships among treatments and response variables (Fig. 5). The first two principal components explained 98.5 % of the total variation, with PC1 and PC2 accounting for 89.6 % and 8.9 %, respectively. The disease-related variables (sheath blight, neck blast and grain discolouration) were negatively associated with grain yield and ICBR, indicating that lower disease severity was associated with increased productivity and profitability. Treatments T_3 , T_5 and T_7 were positioned closer to the grain yield and ICBR vectors and farther from disease variables, reflecting their favourable performance across the measured parameters. In contrast, the untreated control was associated with higher disease severity and lower yield and economic returns. Correlation analysis further revealed negative associations between disease parameters and grain yield, whereas grain yield was positively correlated with ICBR.

Table 5. Pooled economic analysis (2023–24) of fungicidal treatments for management of major diseases of rice

Treatment No.	Mean grain yield (q/ha)	Additional yield over control (q/ha)	Additional cost of cultivation (Rs/ha)	Additional returns over control (Rs/ha)	Incremental net B : C ratio
T ₁ : Mancozeb 50 % + Thiophanate methyl 25 % WG at 3 g/L	58.3	11.7	5837.2	26214	1 : 4.5
T ₂ : Kasugamycin 5 % + Copper oxychloride 45 % WP at 1.4 g/L	57.9	11.4	5804.9	25538	1 : 4.6
T ₃ : Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC at 3.5 mL/L	61.4	14.8	6156.8	33346	1 : 5.5
T ₄ : Fenoxanil 5 % + Isoprothiolane 30 % EC at 2.0 mL/L	56.0	9.5	5612.5	21101	1 : 3.9
T ₅ : Azoxystrobin 14 % + Epoxiconazole 9 % SC at 1.5 mL/L	60.5	14.0	6066.5	31361	1 : 5.3
T ₆ : Picoxystrobin 7.05 % + Propiconazole 11.7 % SC at 2.0 mL/L	60.1	13.5	6019.5	30359	1 : 5.2
T ₇ : Tebuconazole 50 % + Trifloxystrobin 25 % WG at 0.4 g/L	60.9	14.3	6102.3	32188	1 : 5.4
T ₈ (control)	46.6	0	0	0	–

Minimum support price (MSP) of paddy (common grade): Rs. 2300/quintal during 2024–25. WG: water-dispersible granule; WP: wettable powder; EC: emulsifiable concentrate; SC: suspension concentrate.

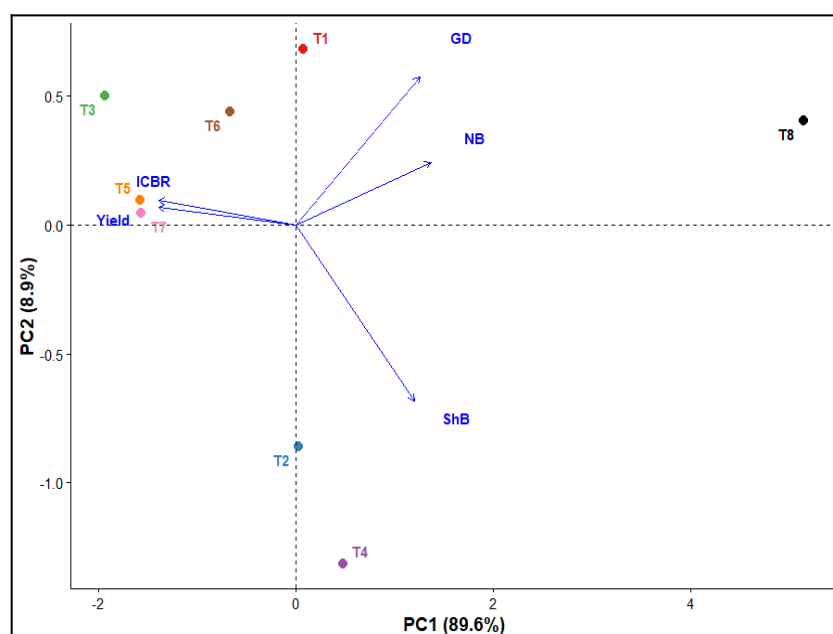


Fig. 5. PCA biplot based on pooled data of two years (kharif, 2023 and 2024). PCA: principal component analysis; PDI: percent disease index; AUDPC: area under the disease progress curve; ICBR: incremental cost–benefit ratio; GD: grain discolouration; ShB: sheath blight; NB: neck blast.

4. Discussion

The present study demonstrated that fungicidal treatments significantly reduced sheath blight, neck blast and grain discolouration of rice compared with the untreated control, resulting in higher grain yield and economic returns. Among the evaluated fungicides, Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC (T₃) consistently recorded the lowest sheath blight severity and AUDPC values across both years,

indicating effective suppression of disease development throughout the crop growth period. The superior performance of this treatment may be attributed to the complementary action of azoxystrobin, tebuconazole and prochloraz, which provide preventive, curative and protective activity through multiple modes of action (21). azoxystrobin inhibits mitochondrial respiration, while tebuconazole and prochloraz interfere with ergosterol biosynthesis, thereby restricting rapid fungal growth and curtailing disease progression.

The high level of sheath blight suppression achieved with Azoxystrobin-based fungicide combinations is consistent with previous field investigations. Azoxystrobin-based mixtures have been shown to effectively reduce the sheath blight severity while improving grain yield and economic returns (22). Comparable levels of disease control have also been achieved with Azoxystrobin 11 % + Tebuconazole 18.3 % SC, which has been identified as one of the most effective formulations against sheath blight management in rice (13). Similar observations on the reduction of sheath blight and increased grain yield following the application of Azoxystrobin + Tebuconazole have been documented under field conditions (23), while Azoxystrobin + Difenconazole has been reported to reduce sheath blight severity by more than 80 % and produce higher grain yield (24). The consistent performance of these Strobilurin-triazole combinations are likely to be associated with the complementary activity of quinone outside inhibitor (QoI) and demethylation inhibitor (DMI) fungicides, providing both preventive and curative actions against *R. solani*, prolonged residual protection and limiting pathogen colonisation and disease progression.

The comparatively low AUDPC values recorded in T₃, T₅ and T₇ indicate sustained suppression of disease throughout the crop growth period. Lower AUDPC values reflect prolonged residual activity of the fungicides and effective protection of the crop canopy, thereby limiting disease development during critical growth stages and contributing to improved grain filling and higher yield. A corresponding reduction in neck blast incidence was also evident in fungicide-treated plots, with T₅, T₃ and T₇ providing the greatest level of protection over untreated control. The high efficacy of Trifloxystrobin + Tebuconazole against both leaf blast and neck blast, accompanied by increased grain yield and economic returns, has also been consistently demonstrated under field conditions (10, 12, 15). In addition, effective blast suppression by Trifloxystrobin + Tebuconazole has been attributed to the complementary activity of the two fungicides, resulting in broader-spectrum disease control and prolonged crop protection (9). The effectiveness of Kasugamycin 5 % + Copper oxychloride 45 % WP (T₂) against neck blast is likewise supported by earlier studies that demonstrated a significant reduction in blast severity (25). The superior performance of these fungicide combinations is likely associated with the integration of systemic and protectant mode of action, which provide extended residual activity, interrupt pathogen infection at multiple stages and reduce disease progression, ultimately leading to enhanced crop productivity.

All the fungicidal treatments reduced grain discolouration compared to the untreated control, although differences among the best-performing treatments were relatively small. The treatments T₄, T₇, T₃ and T₅ recorded the lowest grain discolouration severity. The superior performance of the triple fungicide combination (Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC) may be explained by the complementary modes of action of its components, particularly the activity

of prochloraz against *Fusarium* spp., a major contributor to the rice grain discolouration complex. The broad-spectrum fungicides containing strobilurin and triazole components effectively reduced glume discolouration complex and improved grain quality parameters. Comparatively better performance of Fenoxanil 5 % + Isoprothiolane 30 % EC (T₄) against grain discolouration, despite its lower efficacy against sheath blight, may reflect differences in fungicidal activity against the diverse pathogen complexes associated with these diseases (11). Although the fungicide combinations evaluated in the present study provided effective disease suppression, their repeated use may impose selection pressure for fungicide-resistant pathogen populations. Recent studies have demonstrated resistance risk in *R. solani* to commonly used fungicides, including azoxystrobin, while resistance to QoI fungicides has also been reported in *M. oryzae*. In particular, trifloxystrobin-resistant *M. oryzae* mutants showed positive cross-resistance to azoxystrobin (26, 27). Therefore, rotation or alternation of fungicides with different modes of action and integration with non-chemical disease management practices are recommended to minimise resistance development.

The reduction in disease severity was accompanied by a corresponding increase in grain yield and profitability. Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC (T₃) produced the highest pooled grain yield and incremental cost-benefit ratio (ICBR), followed by T₇ and T₅, indicating that effective disease management translated directly into improved economic returns. Similar improvements in grain yield following successful fungicidal management of major rice diseases were well documented (2, 10, 22, 23, 28). The close association between effective disease control and enhanced economic returns has also been demonstrated under field conditions (15), highlighting the value of fungicides that combine broad-spectrum disease control with sustained crop protection. The superior economic returns of the most effective treatments are likely a consequence of reduced disease pressure during critical crop growth stages, resulting in greater retention of photosynthetically active foliage, improved grain filling and ultimately higher marketable yield. These results emphasise that fungicide selection should be based not only on disease suppression but also on its contribution to productivity and economic sustainability.

Overall, the present investigation demonstrated that modern combination fungicides containing strobilurin and triazole molecules, along with imidazole, provide effective and broad-spectrum management of sheath blight, neck blast and grain discolouration in rice. Although the present study focused on commercially available broad-spectrum strobilurin-triazole based fungicide combinations, recent succinate dehydrogenase inhibitor (SDHI)-based fungicides, particularly thifluzamide-containing formulations, have emerged as promising alternatives against sheath blight of rice. Future studies should include SDHI-based combinations as benchmark treatments to enable comprehensive comparisons with newer fungicide molecules.



5. Conclusion

The present study demonstrated that fungicide efficacy varied among diseases and between seasons under kharif rice conditions at Rajendranagar, Hyderabad, Telangana. Among the treatments evaluated, Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC (T₃) provided the most consistent suppression of sheath blight across the two seasons and recorded the highest pooled grain yield. Tebuconazole 50 % + Trifloxystrobin 25 % WG (T₇) and Azoxystrobin 14 % + Epoxiconazole 9 % SC (T₅) also performed effectively and may be considered as alternative options depending on the predominant disease and disease pressure. These findings indicate that fungicide selection should be guided by the target disease, seasonal disease pressure and expected disease development rather than by a single treatment approach. For sustainable management of sheath blight, neck blast and grain discolouration, the use of effective fungicides should be integrated with appropriate cultural practices, resistant cultivars and biological control measures. Such an integrated approach can improve disease suppression, maintain yield stability and reduce reliance on repeated fungicide applications and the associated risk of fungicide resistance.

Acknowledgements

The authors are grateful to the Rice Research Unit, Agricultural Research Institute, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad and the ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad, Telangana, for providing field facilities and necessary financial support to conduct the experiments.

Authors' contributions

KBT carried out the field experiment, involved in compilation and analysis of the data, drafting of the manuscript and reviewing. NRGV participated in designing of the study, monitoring, article writing, reviewing and editing. CDR involved in monitoring, supervision and reviewing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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Supplementary Files

Supplementary Table 1. Fungicides, trade names and sources used in the study

Fungicide	Trade name	Source
Mancozeb 50 % + Thiophanate methyl 25 % WG	Juniper	SWAL Corporation Ltd., Mumbai
Kasugamycin 5 % + Copper oxychloride 45 % WP	Konika	Dhanuka Agritech Ltd., Hyderabad
Azoxystrobin 5.1 % + Tebuconazole 9.1 % + Prochloraz 18.2 % EC	Almagor	Adama India Pvt. Ltd., Hyderabad
Fenoxanil 5 % + Isoprothiolane 30 % EC	Achibu	Nichino India Pvt. Ltd., Hyderabad
Azoxystrobin 14 % + Epoxiconazole 9 % SC	Mentor	Crystal Crop Protection Ltd., Ahmedabad
Picoxystrobin 7.05 % + Propiconazole 11.7 % SC	Galileo Way	Dupont India Pvt. Ltd., Gujarat
Tebuconazole 50 % + Trifloxystrobin 25 % WG	Nativo	Bayer CropScience Ltd., Mumbai

WG: water-dispersible granule; WP: wettable powder; EC: emulsifiable concentrate; SC: suspension concentrate.

Supplementary Table 2. Year wise economic analysis of fungicidal treatments for management of major diseases of rice during kharif, 2023

Treatment No.	Mean grain yield (q/ha)	Additional yield over control (q/ha)	Additional cost of cultivation (Rs/ha)	Additional returns over control (Rs/ha)	Incremental cost-benefit ratio
T ₁	59.7	13.4	5981.4	29498	1 : 3.9
T ₂	58.4	12.2	5856.2	26766	1 : 3.6
T ₃	62.7	16.4	6288.4	36195	1 : 4.8
T ₄	59.6	13.3	5973.3	29322	1 : 3.9
T ₅	61.2	14.9	6135.9	32869	1 : 4.4
T ₆	59.8	13.5	5995.5	29807	1 : 4.0
T ₇	61.0	14.7	6114.7	32406	1 : 4.3
T ₈	46.3	0	0	0	—

Minimum support price (MSP) of paddy (common grade): Rs. 2300/quintal during 2023–24.

Supplementary Table 3. Year wise economic analysis of fungicidal treatments for management of major diseases of rice during kharif, 2024

Treatment No.	Mean Grain yield (q/ha)	Additional yield over control (q/ha)	Additional cost of cultivation (Rs/ha)	Additional returns over control (Rs/ha)	Incremental cost-benefit ratio
T ₁	56.8	10.0	5693.0	22931	1 : 3.0
T ₂	57.4	10.6	5753.6	24311	1 : 3.2
T ₃	60.1	13.3	6025.3	30498	1 : 4.1
T ₄	52.5	5.6	5251.6	12880	1 : 1.5
T ₅	59.8	13.0	5997.0	29854	1 : 4.0
T ₆	60.3	13.4	6043.4	30912	1 : 4.1
T ₇	60.8	13.9	6089.9	31970	1 : 4.2
T ₈	46.9	0	0	0	—

Minimum support price (MSP) of paddy (Common grade): Rs. 2300/quintal during 2024–25.