Unmanned aerial vehicle (UAV)-assisted pesticide application for pest and disease prevention and control in rice

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Abstract: Unmanned Aerial Vehicles (UAVs) have emerged as innovative tools in agriculture, revolutionizing crop protection practices and the use of pesticide combinations to aid the management of insect pests and diseases in a single application. This research delves into assessing the efficacy of drone-based pesticide spraying utilizing combinations of pesticides to combat insect pests and diseases in rice cultivation. In kharif 2022, the physically compatible combination of insecticides (chlorantraniliprole 18.5% SC and tetraniliprole 200 SC) with fungicides (picoxystrobin 7.5%+tricyclazole 22.5% SC and tebuconazole 50%+trifloxystrobin 25% WG) were administered via drones and compared with conventional Taiwan sprayer. The results indicated that tebuconazole+trifloxystrobin, when applied via drones, exhibited the highest control efficacy against the brown spot, sheath blight, and sheath rot (47.8%, 77.4%, and 75.2% respectively). Moreover, combination treatment, i.e., tetraniliprole+(tebuconazole+trifloxystrobin), applied using a drone, achieved the most effective control (78.1%) against grain discoloration. Additionally, drone-based tetraniliprole application showed effectiveness against stem borer and whorl maggot (efficacy rates of 49.1%, 66.6%, and 60.7% for dead hearts, white ear, and whorl maggot, respectively). Overall, the pesticide combination treatment, i.e., tetraniliprole+(tebuconazole+trifloxystrobin), showed higher control efficacy against all the insect pests and diseases and recorded the highest grain yield of 7995 kg/hm^2 with an incremental cost-benefit ratio (ICBR) of (1:5.63) when sprayed with a drone. Overall, this study underscores the potential of drone-assisted pesticide application in effectively managing multiple insect pests and diseases in rice, offering superior precision, efficacy, efficiency, and yield.

Keywords: bio-efficacy, drone spraying, drone-based pest management, precision agriculture, pesticide combinations

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1 Introduction

Rice (*Oryza sativa* L.) is a vital global staple, and India ranks second in its production, encompassing approximately 45.7 million hm^2 of cultivation and producing an impressive 124.36 million t per year, accounting for 22% of the total global production[1]. However, this production gain resulting from input-intensive cultivation has brought about a significant rise in the incidence of various insect pests and diseases, posing a substantial threat to rice production. Among biotic challenges being faced by the farmers, the yellow stem borer (*Scirpophaga incertulas*), brown planthopper (*Nilaparvata lugens*), blast caused by *Magnaporthe oryzae*, bacterial leaf blight caused by *Xanthomonas oryzae* pv. *oryzae*, and sheath blight caused by *Rhizoctonia solani* Kühn stand out as the major entities responsible for inflicting severe economic losses in rice. One study reports that the extent of losses in rice grain yield was 27.9% by insect pests, 15.6% by diseases, and 37% by weeds[2].

Integrated pest and disease management (IPDM) strategies offer an effective means of crop protection by utilizing a combination of methods, such as cultural practices, biological control, and judicious use of pesticides. However, farmers often heavily rely on spraying pesticides, particularly insecticides and fungicides, due to their quick action, easy availability, and perceived reliability. The simultaneous occurrence of insect pests and diseases often necessitates the application of 2-3 pesticides at a time as a pesticide tank mixture. In addition, labor shortages have prompted farmers, both knowingly and unknowingly, to the use of pesticide mixtures. However, the utilization of pesticide combinations or mixtures poses several challenges. In some cases, physical incompatibility between the components of the mixture may lead to phytotoxicity or reduced efficacy, while in certain instances, it may even contribute to pesticide resistance development[3].

Over the last few decades, pesticide application in agriculture has traditionally been carried out through ground and aerial spraying methods. Developed countries like the USA and those of Europe have witnessed the development of various ground application equipment to meet diverse spray requirements[4]. However, knapsack sprayers commonly employed in ground spraying are associated with increased pesticide exposure for the operator, apart from ineffective chemical application[5]. According to the World Health Organization (WHO), an estimated 1 million humans annually are affected by acute poisoning through contact with pesticides. Alarmingly, the annual death rate attributed to pesticide poisoning ranges from 0.4% to 1.9%[6]. Taking cognizance

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of the problems associated with ground spraying using different kinds of equipment, there is an urgent need for safer and more efficient methods of pesticide application in crop protection.

In contrast, aerial application systems, particularly through the use of unmanned aerial vehicles (UAVs) or drones, offer a promising alternative as they offer precise and efficient application of pesticides, reducing wastage and achieving faster application, saving time and labor costs alongside offering greater potential in minimizing the operator exposure to highly toxic pesticides. Agricultural aerial spraying by drones is often the most economical and rapid method for providing efficient and effective applications for crop pest control, allowing for quick response time during sudden pest outbreaks[7].

UAVs have emerged as innovative tools in agriculture, revolutionizing crop protection practices. With the ability to be operated remotely or autonomously, UAV spraying has become an alternative plant protection equipment with increased safety, improved maneuverability, and enhanced efficiency in comparison to traditional ground spraying methods. These attributes, along with the timely coverage of larger areas and the ability to navigate complex terrains, make UAVs highly advantageous for pesticide application. The global drone market has witnessed significant growth, and according to market intelligence and advisory from Bureau of Indian Standards (BIS) research, it is estimated to reach a staggering $28.47 billion (approximately Rs. 2.09 lakh crores) by the end of 2023. Notably, the dominance of the United States, China, and Israel in the drone market has been prominent. India, however, is projected to contribute around 4.25% to the global market in 2022. The drone market in India is expected to reach $1.81 billion (Rs. 13 330 crores) by the end of the financial year (FY) 2026, with a compound annual growth rate (CAGR) of 14.61%[8].

Recognizing the immense potential of drone-based technologies in agriculture, the Government of India has taken proactive steps to facilitate the adoption of this groundbreaking technology in the agricultural sector by introducing pro-drone policies. In addition, the Ministry of Civil Aviation announced the updated Drone Rules of 2021, replacing the highly criticized UAS rules released in March 2021. The liberalized Drone Rules of 2021 are more permissive and are expected to remove all unnecessary operational and entry barriers and create a strong drone ecosystem in the country to make India a global hub for drones by 2030. The government's focus on bringing drone-based technologies into agriculture highlights the importance of embracing this innovation as a necessary tool for the future of precision agriculture. While addressing the nation in the historic Red Fort on the occasion of the 77th Anniversary of Independence, Prime Minister Narendra Modi announced the "Drone ki Udaan" initiative, a compelling scheme in which 15 000 Women's Self-Help Groups will receive training and financial support to operate and maintain drones[9]. To fast-track agri-drone adoption in India, the Drone Federation of India (DFI) and the Ministry of Agriculture have granted interim approval to 477 pesticides for drone usage[10]. This research investigates the efficacy of UAV-assisted pesticide application for multiple pests and diseases in rice, addressing the need for effective crop protection methods in modern agriculture.

2 Material and methods

The present study aimed to assess the viability of utilizing UAVs for the aerial application of physically compatible pesticide combinations to combat insect pests and diseases in rice cultivation. Building upon physical compatibility assessments, two insecticides (chlorantraniliprole 18.5% SC and tetraniliprole 200 SC) and two fungicides (picoxystrobin 7.5%+tricyclazole 22.5% SC and tebuconazole 50%+trifloxystrobin 25% WG) were selected to conduct a comprehensive investigation of their compatibility, bio-efficacy, and phytotoxicity in the field conditions. This investigation adopted an innovative drone-based pesticide application, which was compared with manual spraying using a Taiwan sprayer. The selection of these particular pesticides was made based on different factors, including the outcomes of the physical compatibility tests, observations of prevalent pests during the pre-count phase, cost-effectiveness of the pesticides, and their market availability.

2.1 Location of the experimental site

The present investigation was carried out at the Institute of Rice Research, Agricultural Research Institute, Rajendranagar, Hyderabad (50°18′N, 53°77′E), which is situated at an altitude of 542.6 m above the MSL during kharif (Vanakalam), 2022. According to Troll's classification, it comes under semi-arid tropics (SAT) and is located in the Southern Telangana agro-climatic zone of the Telangana state.

The variety of rice is Samba Mahsuri (BPT 5204). The net area of each plot per treatment/replication is 360 m^2, and the total plot area per treatment is 1650 m^2.

2.2 Spraying equipment

As shown in Figure 1a, the model of UAV (drone) used in this aerial spraying was battery motive AGRICOPTER AG 365 (Marut Dronetech Pvt. Ltd., Hyderabad, India), and the detailed specifications are presented in Table 1. The accuracy of the flight height and flight velocity was controlled by ground radar and a well-trained drone pilot. The nozzle tip used for the drone sprayer was XR 11 002 VP (Teejet Technologies India Pvt. Ltd., Bengaluru), an extended range flat fan type with a spray angle of 110° and operatable at a spray pressure of 1.400-2.06 bars (Figure 1b).

Table 1 Technical specifications of drone used in the experiment

Particulars	Parameter
Model	AGRICOPTER AG 365 with UIN UA00132S1EX
Service provider	Marut Dronetech Pvt. Ltd., Hyderabad
Dimensions	1920 mm×1820 mm×500 mm
Pay load capacity/volume	10 L
Endurance	20 min
Power battery	2 Nos. of 22 000 mAh (full charge in 45 min)
Number of nozzles	4 Nos.
Nozzle type	XR 11002VP (Extended range-Flat fan)
Spray angle of the nozzle and tip	110°
Spray pressure	1.40-2.06 bars
Pump pressure	1 MPa
Flight mode options	Manual/Semi-autonomous/Fully autonomous
Fail safe features	Return to home, hovering on signal lost
Spraying width	3-5 m
Max. flying speed	5.0 m/s
Max. flow velocity	200-800 mL/min

2.3 Application of treatments

At the maximum tillering stage, the incidence of stem borer (dead hearts), whorl maggot, and brown spot was observed in the field at 66 d after transplanting (DAT). Based on this observation,

a. Drone sprayer used in the experiment

b. Nozzle used in the experiment

c. Pesticide discharge from the drone nozzle

d. Manual spraying with Taiwan sprayer

Figure 1 Application of treatments in bio-efficacy field experiment

after attaining the economic threshold level (ETL), the first application of treatments (Table 2) was done at 67 DAT after collecting the pre-count data of the observed insect pests and diseases. The phytotoxicity observations were recorded at 1, 3, 5, 10, 15, and 20 d after the first spray. The second spray was taken up at 100 DAT after collecting the pre-count data of sheath blight, sheath rot, and stem borer (white ears). Phytotoxicity observations were once again recorded at similar intervals. At the time of the first spray, the initial GPS mapping of treatments and replications for autonomous drone spraying was done and the same maps were then utilized for the second application, ensuring consistency in treatment application within the field. To prevent the potential issue of drift and contamination between the treatments, a buffer zone of 5 m was maintained between adjacent treatments/replication. Each replication consisted of a minimum plot size of 360 m² to ensure adequate coverage during the drone-based pesticide application in rice. Consistency and standardization were maintained across all the treatments by following the recommended flight parameters outlined in Table 3. The crop-specific standard operating procedures (SOPs) for the application of pesticides with a drone were released by the Ministry of Agriculture and Farmers Welfare, government of India, and SOPs for drone-based pesticide application in rice developed by Varma et al.[11] were followed in the present investigation. While operating the drones in the field for experimenting, the weather conditions such as wind speed were measured using an Anemometer (Lutron, AM 4201, Taiwan), while a hand-held hygrometer (HTC, 288 CTH, China) was used to record temperature and relative humidity.

2.4 Experimental observations

Within each replication, a random selection of 10 plants was made within the valid observation zone, as illustrated in Figure 2. Observations on stem borer incidence were recorded from 10 randomly selected hills/replications at the maximum tillering stage (dead hearts, Figure 3b.) and at the reproductive stage (white ears, Figure 4c) before and after the application of pesticide mixtures and at 7 and 14 days after spraying (DAS). The percentage of dead hearts and white ears were calculated according to Equations (1) and (2)[12].

$$\text{Dead hearts} = \frac{\text{No of dead hearts}}{\text{Total no of tillers}} \times 100\% \tag{1}$$

$$\text{White ear} = \frac{\text{No of white ears}}{\text{Total no of panicle bearing tillers}} \times 100\% \tag{2}$$

Observations on whorl maggot incidence (Figure 3c) were recorded from 10 randomly selected hills/replications at vegetative stage during first spraying before and after the application of pesticide mixtures and at 7 and 14 DAS. The percentage of whorl

Table 2 Treatment details of the experiment

Trt. No.	Treatment particulars	Spraying equipment
T1	Chlorantraniliprole 18.5% SC @ 3.75 mL/L	Drone
T2	Tetraniliprole 200 SC @ 6.25 mL/L	Drone
T3	Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 25 mL/L	Drone
T4	Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	Drone
T5	Chlorantraniliprole 18.5% SC @ 3.75 mL/L+(Picoxystrobin 7.5%+Tricyclazole 22.5% SC) @ 25 mL/L	Drone
T6	Chlorantraniliprole 18.5% SC @ 3.75 mL/L+(Tebuconazole 50%+Trifloxystrobin 25% WG) @ 5 g/L	Drone
T7	Tetraniliprole 200 SC @ 6.25 mL/L+(Picoxystrobin 7.5%+Tricyclazole 22.5% SC) @ 25 mL/L	Drone
T8	Tetraniliprole 200 SC @ 6.25 mL/L+(Tebuconazole 50%+Trifloxystrobin 25% WG) @ 5 g/L	Drone
T9	Chlorantraniliprole 18.5% SC @ 0.4 mL/L+(Picoxystrobin 7.5%+Tricyclazole 22.5% SC) @ 2.66 mL/L	Taiwan sprayer
T10	Chlorantraniliprole 18.5% SC @ 0.4 mL/L+(Tebuconazole 50%+Trifloxystrobin 25% WG) @ 0.53 g/L	Taiwan sprayer
T11	Tetraniliprole 200 SC @ 0.6 mL/L+(Picoxystrobin 7.5%+Tricyclazole 22.5% SC) @ 2.66 mL/L	Taiwan sprayer
T12	Tetraniliprole 200 SC @ 0.6 mL/L+(Tebuconazole 50%+Trifloxystrobin 25% WG) @ 0.53 g/L	Taiwan sprayer
T13	Untreated Control	--

Note: SC: Suspension Concentrate; WG: Wettable Granules.

Table 3 Standard operating protocols (SOPs) followed for spraying treatments using drone

Drone spray parameters	SOPs followed
Flight height	2.5 m above the crop canopy
Flight speed	3.6 m/s
Nozzle type	XR 11 002 VP
Number of nozzles	4
Spray width	3.5 m
Spray volume	40 L/hm
Wind speed for drone fly	<5.0 m/s

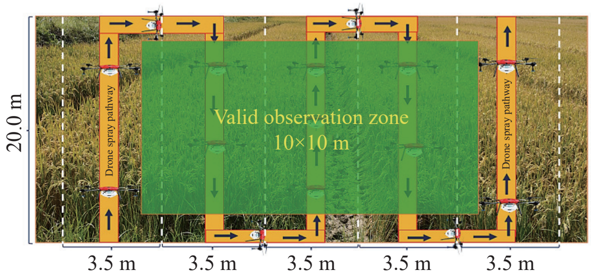

Figure 2 Layout of each treatment depicting the drone flying path

a. Brown spot b. Stem borer (dead hearts) c. Whorl maggot

Figure 3 Insect-pests and diseases observed during pre-count of 1st spray

a. Sheath blight b. Sheath rot c. Stem borer (White ears)

Figure 4 Insect pests and diseases observed during pre-count of 2nd spray

maggot incidence was calculated according to Equation (3).

$$\text{Whorl maggot incidence} = \frac{\text{No of whorl maggot damaged leaves}}{\text{Total no of leaves}} \times 100\% \quad (3)$$

Brown spot disease incidence (Figure 3a) was recorded from 10 randomly selected hills/replications during first spray, before and after the application of pesticide mixtures at 7 and 14 DAS.

$$\text{Brown spot incidence} = \frac{\text{No of infected leaves}}{\text{Total no of leaves}} \times 100\% \quad (4)$$

Observations on sheath blight disease severity (Figure 4a) were recorded from 10 randomly selected hills/replications during first spraying before and after the application of pesticide mixtures at 7 and 14 DAS and percent disease index was computed using the scale (Table 4) given by the standard evaluation system for rice[13].

Table 4 Scale of standard evaluation system for rice

Scale	Relative lesion height (RLH)
0	No infection observed
1	Lesions limited to lower 20% of the plant height
3	20%-30%
5	31%-45%
7	46%-65%
9	More than 65%

The percent disease index (PDI) was calculated according to Equation (5).

$$\text{PDI} = \frac{\text{Sum of disease ratings}}{\text{No of plants observed} \times \text{Maximum disease rating}} \times 100\% \quad (5)$$

Observations on sheath rot disease incidence (Figure 4b) were recorded from 10 randomly selected hills/replications, before and after the application of pesticide mixtures at 7 and 14 DAS.

$$\text{Sheath rot incidence} = \frac{\text{No of sheath rot infected tillers}}{\text{Total no of panicle bearing tillers}} \times 100\% \quad (6)$$

Incidence of grain discoloration was estimated by counting grains with more than 25% affected glume surface from the sample of 100 seeds collected per each replication in the treatments at the time of harvest. The percent grain discoloration was calculated according to Equation (7).

$$\text{Grain discoloration} = \frac{\text{No of discoloured grains}}{\text{Total no of grains in collected sample}} \times 100\% \quad (7)$$

The mean percent efficacy of pesticide combinations over control for brown spot, sheath blight, sheath rot, grain discoloration, stem borer, and whorl maggot were computed using Equation (8).

$$\text{Control efficacy} = \frac{C-T}{C} \times 100\% \quad (8)$$

where, C is the percent incidence in control; T is the percent incidence in treatment.

Observations on phytotoxicity were taken at 1, 3, 5, 10, 15, and 20 DAS with a 0-10 rating scale[14]. The observations were recorded individually for yellowing, stunting, chlorosis, necrosis, wilting, scorching, vein clearing, epinasty and hyponasty, etc., as per the phytotoxicity rating scale. The percent injury was calculated by Equation (9):

$$\text{Percent injury} = \frac{\text{Total grade points}}{\text{Maxgrade} \times \text{no of leaves observed}} \times 100\% \quad (9)$$

2.5 Efficiency indices

In the bio-efficacy field experiment, observations were taken to examine the efficiency of drone spraying over the traditional Taiwan sprayer, considering factors such as time and water saving, as well as yield improvement in pesticide application[15]. The study aimed to evaluate the effectiveness of drone spraying technology by comparing it with the conventional Taiwan sprayer.

2.6 Statistical analysis

The experimental data on various characteristics recorded throughout the course of investigation were statistically analyzed in randomized complete block design as per Gomez and Gomez[16]. Significant differences between treatments were calculated using analysis of variance (ANOVA) and Duncan's test (DMRT) at a significance level of 95% with the OPSTAT software package (Chaudhary Charan Singh, Haryana Agricultural University, Hisar, Haryana, India)[17]. Wherever statistical significance was observed, the critical difference (CD) at 0.05 level of probability was worked out for comparison. Non-significant comparison was indicated as NS.

3 Results and discussion

In the bio-efficacy evaluation during the kharif 2022, the selected insecticides (chlorantraniliprole 18.5% SC and tetraniliprole 200 SC) along with selected fungicides (picoxystrobin 7.5%+tricyclazole 22.5% SC and tebuconazole 50%+trifloxystrobin 25% WG) were sprayed using a drone (UAV) and compared with a Taiwan sprayer in rice fields for their effectiveness against brown spot, yellow stem borer (dead hearts), and whorl maggot of rice during the first spray, and sheath blight, sheath rot, grain discoloration, and yellow stem borer (white ears) during the second spray. This study marks the first of its kind in evaluation of the efficacy of pesticides applied using drone technology in rice cultivation.

3.1 Experimental results on pests and disease control

In this study, the variations in pests and disease incidence at 14 DAS are represented in Table 5. The control efficacy of insecticide and fungicide combinations applied using UAV and Taiwan sprayer against insect pests of rice (Figure 5) and against diseases (Figure 6) revealed that, for the first spray among the treatments tested, the treatment T4 (tebuconazole + trifloxystrobin) recorded the highest control efficacy against brown spot (47.8%), followed by T10, i.e., chlorantraniliprole + (tebuconazole + trifloxystrobin), with 44.7%. The treatment T2 (tetraniliprole) recorded the highest control efficacy against dead hearts (49.1%), followed by T8, i.e., tetraniliprole + (tebuconazole + trifloxystrobin), with 43.1%. Lastly, for whorl maggot, the treatments with the best control efficacy were T2 (tetraniliprole) with 60.7%, followed by T12, i.e., tetraniliprole + (tebuconazole + trifloxystrobin), with 52.5%. During the second spray, the best control efficacy against sheath blight (77.4%) was found with T4 (tebuconazole + trifloxystrobin), followed by T5, i.e., chlorantraniliprole + (picoxystrobin + tricyclazole), with 74.1%, and both were applied using a drone. Promising control efficacy against sheath rot was found with T4 (tebuconazole + trifloxystrobin, 75.2%), followed by T3, i.e., (picoxystrobin + tricyclazole, 72.1 %), which was applied with a drone. Regarding grain discoloration, the maximum control efficacy (78.1%) was found with T8, i.e., tetraniliprole + (tebuconazole + trifloxystrobin),

Table 5 Bio-efficacy of insecticide and fungicide combinations against insect pests and diseases of rice applied through drone and Taiwan sprayer under field conditions during *kharif* (*Vanakalam*), 2022

Trt. No.	Treatment details	YSB		WM/%	BS/%	SHB (PDI)/%	SHR/%	GD/%	Grain yield /kg·hm^{-2}
		DH/%	WE/%						
T1	Chlorantraniliprole 18.5% SC @ 3.75 mL/L	6.45^{ab}(14.65)*	6.85^{a}(15.04)	7.23^{ab}(15.54)	9.22^{c}(17.47)	51.85^{cd}(46.04)	18.44^{c}(25.40)	17.00^{c}(26.49)	5451^{hi}
T2	Tetraniliprole 200 SC @ 6.25 mL/L	4.23^{a}(11.83)	5.94^{a}(14.02)	5.67^{a}(13.70)	7.19^{bc}(15.52)	48.52^{c}(44.13)	19.61^{c}(26.23)	18.00^{c}(25.51)	5614^{hi}
T3	Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 25 mL/L	9.46^{d}(17.69)	15.21^{b}(22.80)	13.10^{d}(21.20)	3.09^{a}(10.08)	20.37^{ab}(26.45)	6.35^{ab}(14.44)	10.33^{ab}(17.34)	6024^{gh}
T4	Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	11.33^{d}(19.64)	17.09^{b}(24.83)	14.03^{d}(21.92)	2.62^{a}(9.30)	12.96^{a}(20.60)	4.44^{a}(12.11)	7.00^{a}(14.04)	6275^{gh}
T5	Chlorantraniliprole 18.5% SC @ 3.75 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 25 mL/L	8.36^{bc}(16.78)	8.97^{a}(17.38)	11.44^{bc}(19.70)	3.59^{a}(10.91)	12.96^{a}(20.60)	7.26^{ab}(15.38)	9.00^{b}(18.71)	6900de
T6	Chlorantraniliprole 18.5% SC @ 3.75 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	8.82^{bc}(17.25)	8.68^{a}(17.10)	10.38^{bc}(18.71)	3.28^{a}(10.43)	17.78^{ab}(23.99)	5.76^{ab}(13.83)	7.67^{ab}(15.97)	7726^{b}
T7	Tetraniliprole 200 SC @ 6.25 mL·L^{-1}+Picoxystrobin 7.5%+Tricyclazole 22.5% SC@ 25 mL/L	6.90^{abc}(15.20)	7.69^{a}(16.08)	6.91^{ab}(15.06)	3.63^{a}(10.97)	25.93^{ab}(30.56)	7.38^{ab}(15.66)	9.33^{ab}(17.68)	7459^{bc}
T8	Tetraniliprole 200 SC @ 6.25 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	6.21^{abc}(14.37)	7.68^{a}(16.06)	7.08^{ab}(15.35)	3.44^{a}(10.65)	16.67^{ab}(23.88)	5.69^{ab}(13.78)	6.33^{a}(14.04)	7995^{a}
T9	Chlorantraniliprole 18.5% SC @ 0.4 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 2.66 mL/L	5.60^{ab}(13.65)	7.85^{a}(16.15)	8.98^{bc}(17.42)	3.70^{a}(11.07)	14.81^{a}(22.34)	8.41^{b}(16.82)	9.67^{ab}(17.97)	6729^{ef}
T10	Chlorantraniliprole 18.5% SC @ 0.4 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 0.53 g/L	7.97^{ab}(16.38)	8.77^{a}(17.21)	8.49^{bc}(16.91)	3.21^{a}(10.32)	15.93^{a}(23.36)	5.79^{ab}(13.90)	8.33^{ab}(16.07)	7379^{bcd}
T11	Tetraniliprole 200 SC @ 0.6 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 2.66 mL/L	7.90^{bc}(16.12)	7.00^{a}(15.26)	9.03^{bc}(17.40)	3.22^{a}(10.31)	20.37^{ab}(26.77)	6.84^{ab}(14.99)	10.67^{b}(18.37)	7155^{cde}
T12	Tetraniliprole 200 SC @ 0.6 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 0.53 g/L	6.96^{abc}(15.25)	5.86^{a}(13.93)	6.82^{ab}(15.11)	3.28^{a}(10.42)	18.52^{ab}(25.42)	5.08^{ab} (12.97)	9.00^{ab}(17.07)	8098^{a}
T13	Untreated control	11.45^{d}(19.76)	18.07^{b}(25.12)	17.17^{e}(24.45)	10.93^{c}(14.08)	57.78^{d}(49.45)	27.16^{d}(31.39)	27.33^{d}(31.49)	4809^{j}
	Standard error (SE/m±)	1.00	1.08	0.97	0.68	2.93	1.07	1.42	172.65
	Critical difference CD (at 5% significance level)	2.94	3.19	2.86	2.01	8.62	3.16	4.19	506.94
	Coefficient of variation (CV/%)	10.81	10.62	9.45	10.12	17.24	10.68	12.82	4.34

Note: YSB: Yellow stem borer; DH: Dead hearts; WE: White ears; WM: Whorl maggot; BS: Brown spot; SHB: Sheath blight; PDI: Percent disease index; SHR: Sheath rot; GD: Grain discoloration. *Figures in parentheses are angular transformed values. Numerical superscript letters represent Duncan's multiple range test analysis. Figures in bold represent best-performing treatments.

followed by T4 (tebuconazole + trifloxystrobin) with 71.9%, and both were applied with drone. The best control efficacy for white ears was found with T2 (tetraniliprole) with 66.6%, followed by the combination treatment applied using Taiwan sprayer, T12, i.e., tetraniliprole + (tebuconazole + trifloxystrobin), with 60.0 %. None of the treatments induced any phytotoxicity symptoms such as yellowing, leaf tip drying, or vein clearing at any of the observed time points (1 DAS, 3 DAS, 5 DAS, 10 DAS, 15 DAS, and 20 DAS) after the first and second spray. This suggests that the selected pesticides alone and their combination treatments were safe and well-tolerated by rice plants at Taiwan and drone spraying concentrations. Hence, these combinations will be recommended to the farming community for safe use in rice. Further, drones as additional spraying equipment without changing the recommended dose of pesticide followed for ground spraying for the benefit of the farming community.

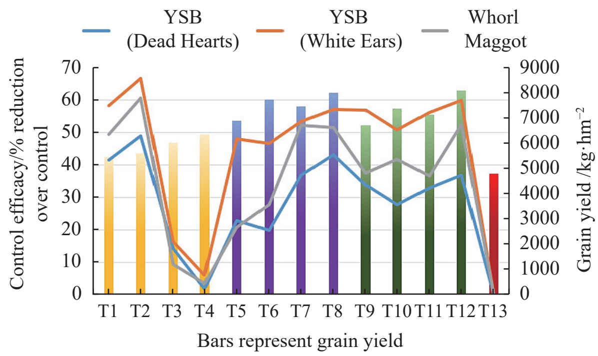

Figure 5 Control efficacy of insecticide and fungicide combinations applied using UAV and Taiwan sprayer against insect pests of rice

The results of the present study are in line with Wang et al.[18], who revealed that when chlorantraniliprole 18.5% SC was applied using a drone against rice stem borer, significantly higher control efficacy (more than 90% compared to untreated control) was achieved at flight height of 2-4 m and flight velocity of 3-4 m/s. These results support the current study's findings of the higher efficacy observed with chlorantraniliprole against stem borer (dead hearts). Effective pest control practices depend on proper application practices that deliver a quality spray. The better control efficacy achieved in drone spraying treatments compared to Taiwan sprayer treatments might be due to the higher droplet coverage and deposition in drone spraying treatments due to their fine droplets. Variables including pest species, location on the plant, spray system configuration, and environmental conditions all may have a significant effect on UAV application deposition and pest control efficacy[19]. Past research has proven the feasibility of low-volume spraying via UAVs in agrichemical applications to control pests and diseases[20,21].

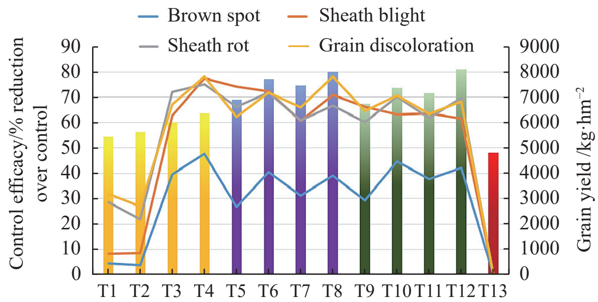

Figure 6 Control efficacy of insecticide and fungicide combinations applied using UAV and Taiwan sprayer against diseases of rice

3.2 Assessment of grain yield and incremental cost-benefit ratio of various treatments

The treatments T12 (tetraniliprole + tebuconazole + trifloxystrobin) applied with a Taiwan sprayer and T8 (tetraniliprole + tebuconazole + trifloxystrobin) applied with a drone exhibited the highest grain yields of 8098 and 7995 kg/hm². The untreated control had the lowest grain yield (4809 kg/hm²), confirming the importance of effective pest and disease management strategies in rice. The combination treatments sprayed via drones and Taiwan sprayer exhibited higher grain yield compared to individual pesticide application treatments irrespective of spraying equipment. The combination treatments sprayed via drone showed superior performance in terms of grain yield compared to Taiwan sprayer. These findings highlight the potential benefits of drones for pesticide application and enhanced productivity. Additionally, the study analyzed the incremental cost-benefit ratio to determine the economic feasibility of each treatment (Table 6). Among treatments

Table 6 Incremental cost-benefit ratio (ICBR) of various treatments

Trt. No.	Treatment details	Grain yield /kg·hm⁻²	Incremental yield over control /kg·hm⁻²	Incremental returns over control /INR·hm⁻²	Incremental cost of cultivation /INR·hm⁻²	ICBR
T1	Chlorantraniliprole 18.5% SC @ 3.75 mL/L	5451	642	13 098.93	5475	1: 2.39
T2	Tetraniliprole 200 SC @ 6.25 mL/L	5614	805	16 422.98	6420	1: 2.56
T3	Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 25 mL/L	6024	1215	24 795.25	5520	1: 4.49
T4	Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	6375	1566	31 943.18	6120	1: 5.22
T5	Chlorantraniliprole 18.5% SC @ 3.75 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 25 mL/L	6900	2091	42 650.92	9995	1: 4.27
T6	Chlorantraniliprole 18.5% SC @ 3.75 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	7726	2917	59 509.19	10 595	1: 5.62
T7	Tetraniliprole 200 SC @ 6.25 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC@ 25 mL/L	7459	2650	54 052.83	10 940	1: 4.94
T8	Tetraniliprole 200 SC @ 6.25 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 5 g/L	7995	3186	64 997.05	11 540	1: 5.63
T9	Chlorantraniliprole 18.5% SC @ 0.4 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 2.66 mL/L	6729	1920	39 176.56	9870	1: 3.97
T10	Chlorantraniliprole 18.5% SC @ 0.4 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 0.53 g/L	7379	2570	52 434.47	10 470	1: 5.01
T11	Tetraniliprole 200 SC @ 0.6 mL/L+Picoxystrobin 7.5%+Tricyclazole 22.5% SC @ 2.66 mL/L	7155	2346	47 864.81	10 815	1: 4.43
T12	Tetraniliprole 200 SC @ 0.6 mL/L+Tebuconazole 50%+Trifloxystrobin 25% WG @ 0.53 g/L	8098	3289	67 087.24	11 415	1: 5.88
T13	Untreated Control	4809	0.00	0.00	0.00	0.00

Note: Market price of paddy=20,400 INR/t, Cost of Chlorantraniliprole 18.5% SC (60 mL)=2237.5 INR/hm², Tetraniliprole 200 SC (100 mL)=2710 INR/hm², Picoxystrobin 7.5%+Tricyclazole 22.5% SC (400 mL)=2260 INR/hm², Tebuconazole 50%+Trifloxystrobin 25% (80 g)=2560 INR/hm² Spraying cost (hm²); Taiwan sprayer spraying charges =INR.875/- & Drone spraying charges =INR.1000/-.

tested, the highest cost-benefit ratio (1:5.88) was achieved with treatment T12, i.e., tetraniliprole + (tebuconazole + trifloxystrobin), followed by T8, i.e., tetraniliprole + (tebuconazole + trifloxystrobin) and T6, i.e., chlorantraniliprole + (tebuconazole + trifloxystrobin), which exhibited 1:5.63 and 1:5.62 ICBR, respectively. The combination treatments sprayed via drones showed higher ICBRs compared to Taiwan sprayer treatments except T12 (1:5.88), which exhibited the highest ICBR among all the pesticides tested in the present study. These findings highlight the potential benefits of using pesticide combinations and drone spraying technology to enhance rice crop productivity.

3.3 Efficiency indices for drone spraying of pesticide over Taiwan sprayer

There were significant efficiency improvements associated with drone spraying over manual spraying (Table 7). The drone spraying method resulted in a water saving of 89.3%, indicating a substantial reduction in water usage compared to manual spraying. Furthermore, drone spraying demonstrated a time saving of 73.3% compared to manual spraying. Time saving can be attributed to taking timely control measures; if a large-scale disease epidemic occurs in a particular area and crop, we can cover large areas within a short period to avoid yield losses. In terms of yield improvement, drone spraying showed a range of 2.48% to 4.36% increase compared to Taiwan sprayer treatments. This positive impact on yield can be attributed to several factors, including accurate and targeted pesticide application, uniform coverage, reduced drift, and minimized human error. The higher field capacity associated with drone spraying (8 hm^2/d or 20 acres/d) compared to the Taiwan sprayer (2 hm^2/d or 5 acres/d) highlights the operational efficiency of drones. Similarly, the higher labor productivity achieved through drone spraying (4 hm^2/labor day) compared to Taiwan sprayer (1 hm^2/labor day) emphasizes the potential use of labor utilization.

Table 7 Efficiency of drone spraying of pesticides over manual spraying (Taiwan sprayer)

Particulars	Efficiency indices/%
Water saving by drone spray over Taiwan spray	89.33%
Time saving by drone spray over Taiwan spray	73.33%
Yield improvement by drone spray over Taiwan spray	2.48%-4.36%
Field capacity • Drone spray • Taiwan spray	8 hm^2/d (20 acres/d) 2 hm^2/d (5 acres/d)
Labor productivity • Drone spray • Taiwan spray	4 hm^2/d (10 acres/labor day) 1 hm^2/d (2.5 acres/labor day)

4 Conclusions

The findings highlight the potential of drone spraying as a valuable tool in modern crop protection strategies, offering numerous benefits to farmers, the environment, and overall agricultural productivity by following the crop-specific SOPs for the safe use of pesticides using drones (UAVs) in crops given by the Ministry of Agriculture & Farmers Welfare, government of India. The drone spraying method resulted in a water saving of 89.3% and time saving of 73.3% compared to manual spraying. In terms of yield improvement, drone spraying showed a range of 2.48% to 4.36% increase compared to ground manual sprayers. With all the advantages driven by drone spraying, it also has some disadvantages including spray drift, vulnerability to adverse weather conditions like strong winds and rain, and limited flight time due to battery endurance. These can be addressed by future research on improvising drone technology. Overall, the present study supports the safety and effectiveness of the selected treatments in rice and highlights the potential advantage of using drone technology for pesticide spraying, both in terms of crop health and economic returns.

Successful implementation of drone technology can be achieved by assessing cost economics, adoption rates, and economic viability for successful integration of drone-based spraying among farmers and the establishment of custom hiring centers (CHCs) or hi-tech hubs. To achieve effective pest and disease management, integration of drone-embedded AI algorithms for detecting, diagnosing, and monitoring rice insect pests and diseases is crucial for timely and optimized pesticide applications. Investigating factors influencing pesticide drift and implementing strategies to minimize off-target effects during drone spraying, alongside designing spray formulations optimized for drone-based applications such as reducing foaming and ensuring physical compatibility, will lead to more efficient pest control.

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