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Impact of Biopesticides Applied Alone and in Combination with Insecticides Using Drone and Taiwan Sprayer on Beneficial Fauna in Rice Ecosystem

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate the impact of biopesticides and insecticides applied *via* drones and taiwan sprayers, on beneficials in rice cultivation.
Study Design: Randomized Block Design (RBD).

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Place and Duration of Study: The present study was conducted at the Agricultural Research Station, Kampasagar, Nalgonda, during the *kharif,* 2023.
Methodology: The beneficial populations, specifically coccinellids and spiders, were monitored after two consecutive sprays. The population counts were recorded by following standardized sampling methods.
Results: The analysis of results revealed that mean coccinellid populations ranged from 3.33 to 6.67 per ten hills across treatments, with the highest population observed in the untreated control (T19), followed by *Bacillus thuringiensis* var*. kurstaki* 0.5% WP and insecticide combination treatments applied *via* drone. Spider populations demonstrated similar trends, with means ranging from 4.33 to 6.50, indicating non-significant differences across treatments. Drone spraying demonstrated better consistency in preserving natural enemy populations, likely due to precise droplet deposition and reduced pesticide drift.
Conclusion: The study underscores the potential of drone technology as an eco-friendly, efficient application method, enabling better conservation of beneficial fauna in rice ecosystems.

Keywords: Drone technology; biopesticides; coccinellids; spiders; pesticide application.

1. INTRODUCTION

Rice is a staple food for over three billion people globally, forms the backbone of food security in many countries. The rice agro-ecosystem harbours a rich diversity of arthropods, including herbivores, predators, parasitoids, saprophytes and pollinators, all of which contribute significantly to agricultural productivity (Bandumula*,* 2017; Acosta et al.*,* 2017; Ovawanda et al., 2016). However, intensive cultivation practices often the ecological balance in favour of herbivores, leading to increased pest pressures that threaten yields (Bambaradeniya & Edirisinghe, 2009; Birla et al., 2017).

Drones offer precision in pesticide application, improving efficiency and coverage while reducing wastage. However, the ecological consequences of drone-applied pesticides, particularly their impact on beneficials such as coccinellids and spiders, require careful consideration (Tigga et al.*,* 2017; Bhavana et al., 2022). While drone technology enhances pesticide application efficiency, it also raises concerns regarding the impact on non-target species. beneficials are vital for maintaining pest control in rice fields and their survival is influenced by factors such as pesticide selectivity, application methods and environmental conditions (Raut et al., 2023; Fritz et al., 2011).

While selective pesticides are less harmful to beneficial organisms, non-selective pesticides can significantly reduce populations of key beneficials, potentially causing pest resurgence and secondary outbreaks (Cohen et al., 1994; de Bastos Pazini et al., 2016). UAV spray parameters, including nozzle type and flight velocity, further affect deposition patterns and non-target organisms (Kobori & Amano, 2004; Srinivas & Madhumathi, 2005; Takada et al., 2001). Best Management Practices (BMPs) for drone applications emphasize optimizing these parameters to minimize drift and ecological harm (Li et al., 2019).

This article explores the effects of drone and taiwan sprayer applied pesticides on beneficial fauna in rice ecosystems, highlighting the balance between pest control efficacy and biodiversity conservation. It underscores the importance of integrating ecological principles with advanced drone technologies to ensure sustainable rice production systems.

2. MATERIALS AND METHODS

2.1 Location of Experiment

The study focusing on the effect of selected biopesticides and insecticides applied *via* drone and taiwan sprayer on beneficials in rice cultivation was conducted at Agricultural Research Station field in Kampasagar, Nalgonda (North Latitude: 15.3257° N, East Longitude: 76.3435° E) during *kharif,* 2023.

2.2 Experimental Design

The rice variety KNM 118 (Kunaram Sannalu) was chosen for cultivation. The nursery was maintained until transplantation, at 30 days after sowing (DAS), following a spacing of 15 cm × 15 cm. The experiment, was arranged in a Randomized Block Design (RBD) comprising 19 treatments, including a control (Table 1). Each treatment was replicated thrice. Plots, with a net area of 500 square meters, were demarcated with irrigation channels according to the design specifications. 120 kg N ha^{-1} as urea, 60 kg P_2O_5 ha^{-1} as single super phosphate and 60 kg K_2O ha^{-1} as muriate of potash was applied in main field. Nitrogen was applied in three equal splits at transplanting, maximum tillering and at panicle initiation stage. The recommended doses of phosphorus and potassium were applied as basal at the time of transplanting. Irrigation was administered as needed, and weeding activities were conducted as and when required. Subsequent doses of fertilizers were applied according to the prescribed schedule.

2.3 Spray Equipments

The UAV (drone), AGRICOPTER AG365 equipped with XR11002VP nozzles was used for aerial applications, flying at 2.5 m above the canopy and 3.6 m/s, with a 60% discharge rate. Flight paths were mapped to ensure accuracy, with a 5 m buffer zone to prevent drift and overlap. Comparatively, the taiwan sprayer, a manual 16 L tank flat-fan nozzle system, operated at 0.1 m height, 25 bar pressure, and delivered 375 L/ha with a 2 ha/day capacity.

To evaluate the impact of pesticide mixtures on beneficial fauna, coccinellid and spider populations were monitored across ten randomly selected hills per replication. Observations were recorded before spraying (pre-count) and at 7 and 14 days after spraying (DAS) during morning hours (06:00–09:00 AM). Standardized sampling methods were employed to ensure reliable data collection on the beneficial fauna.

2.4 Statistical Analysis

The mean population of beneficials were analysed by adopting Randomized Block Design (RBD) as suggested by Panse and Sukhatme (1985). Significant treatment differences were assessed using analysis of variance (ANOVA) at a significance level of 95% with SPSS software package.

Table 1. Treatment details

Trt. No.	Treatments	Dose (g or ml/l)
T1*	*B. thuringiensis* var. *kurstaki* 0.5% WP	27.21 g
T2*	Flubendiamide 39.35% SC @ 24 g a.i.	1.36 ml
T3*	Chlorantraniliprole 18.50% SC @ 30 g a.i.	4.08 ml
T4*	Cartap hydrochloride 50% SP @ 500 g a.i.	27.21 g
T5*	Tetraniliprole 18.18% SC @ 60 g a.i.	8.16 ml
T6*	*B. thuringiensis* var. *kurstaki* 0.5% WP + Flubendiamide 39.35% SC @ 24 g a.i.	27.21 g + 1.36 ml
T7*	*B. thuringiensis* var. *kurstaki* 0.5% WP + Chlorantraniliprole 18 .50% SC @ 30 g a.i.	27.21 g + 4.08 ml
T8*	*B. thuringiensis* var. *kurstaki* 0.5% WP + Cartap hydrochloride 50% SP @ 500 g a.i.	27.21 g + 27.21 g
T9*	*B. thuringiensis* var. *kurstaki* 0.5% WP + Tetraniliprole 18.18% SC @ 60 g a.i.	27.21 g + 8.16 ml
T10#	*Bacillus thuringiensis* var. *kurstaki* 0.5% WP	2.66 g
T11#	Flubendiamide 39.35% SC @ 24 g a.i.	0.13 ml
T12#	Chlorantraniliprole 18.50% SC @ 30 g a.i.	0.40 ml
T13#	Cartap hydrochloride 50% SP @ 500 g a.i.	2.66 g
T14#	Tetraniliprole 18.18% SC @ 60 g a.i.	0.80 ml
T15#	*B. thuringiensis* var. *kurstaki* 0.5% WP + Flubendiamide 39.35% SC @ 24 g a.i.	2.66 g + 0.13 ml
T16#	*B. thuringiensis* var. *kurstaki* 0.5% WP + Chlorantraniliprole 18 .50% SC @ 30 g a.i.	2.66 g + 0.40 ml
T17#	*B. thuringiensis* var. *kurstaki* 0.5% WP + Cartap hydrochloride 50% SP @ 500 g a.i.	2.66 g + 2.66 g
T18#	*B. thuringiensis* var. *kurstaki* 0.5% WP + Tetraniliprole 18.18% SC @ 60 g a.i.	2.66 g + 0.80 ml
T19*	Untreated Control (water)	-

(Central Insecticide Board and Registration Committee - (http://ppqs.gov.in/divisions/cib-rc/major-uses-of-pesticides), Per ha dose is diluted in 375 litres of water for Taiwan (#) sprayer and 36.75 litres for drone (*) spraying

3. RESULTS AND DISCUSSION

3.1 Effect of Biopesticide and Insecticides and Their Combinations on Coccinellids during *kharif,* 2023

The observations on population of coccinellids were recorded during *kharif*, 2023 across all the treatments. Nevertheless, they were observed starting from the early tillering phase and continued through to the grain filling stage of the crop (Tables 2 and 3). Perusal of data (Table 2) revealed that the mean populations of coccinellids one day before spraying ranged from 4.00 to 6.67, indicating stable and consistent beneficial populations The mean values after first spray (7 DAS and 14 DAS) indicates less drastic reductions in coccinellid populations across drone sprayed treatments. *B. thuringiensis* var. *kurstaki* 0.5% WP (BTK) + Tetraniliprole (T9) and BTK + Chlorantraniliprole (T7) maintained relatively higher populations, with average of 4.50 and 4.83, respectively. Flubendiamide alone (T2) exhibited the most significant reduction in population to 3.67. Populations dropped more sharply in most of the treatments applied *via* taiwan sprayer, with lower means such as 3.67 in Flubendiamide (T11) and 3.83 in BTK + Flubendiamide (T15). BTK (T10) performed relatively better, with a mean of 4.67, indicating moderate preservation of coccinellid populations.

Populations recovered more consistently, with means ranging from 3.83 (T6) to 5.67 (T1, T7, T9) in drone sprayed treatments after second spray. BTK alone (T1) and combinations like BTK + Chlorantraniliprole (T7) showed higher retention of coccinellids. The treatments applied *via* taiwan sprayer recorded population means ranging from 3.83 (T6) to 5.67 (T1, T7, T9). BTK alone (T1) and combinations like BTK + Chlorantraniliprole (T7) showed higher retention of coccinellids.

Overall, drone sprayed treatments showed more consistent preservation of coccinellid populations across both sprays. BTK-based combinations (e.g., T1, T7, T9) were particularly effective in sustaining beneficials. Whereas, taiwan sprayer treatments caused slight population declines and comparatively greater variability post-sprays.

3.2 Effect of Biopesticide and Insecticides Alone and Their Combinations on Spiders during *kharif,* 2023

Pre-treatment observations showed spider populations varied from 5.00 to 7.00, with uniform distribution across all the treatments (Table 3). Mean spider populations after first spray (7 DAS and 14 DAS) in drone sprayed treatments ranged from 4.67 (T6) to 6.00 (T1, T3), with the latter indicating better spider conservation. Combination treatments like BTK + Chlorantraniliprole (T7) and BTK + Tetraniliprole (T9) also preserved populations well, with means of 5.33 and 5.50, respectively. Flubendiamide (T2) had the sharpest decline to a mean of 4.00. Whereas in taiwan sprayer treatments the mean spider populations ranged from 4.33 (T11, T15) to 5.83 (T10, T18). BTK alone (T10) and BTK + Tetraniliprole (T18) preserved populations best, with mean values similar to drone applications. Cartap hydrochloride (T13) and Flubendiamide (T11) caused significant population reduction of spiders, with means of 4.67 and 4.33, respectively.

Similar trend was observed, with no significant differences observed regarding the spider population at second spray. Mean populations after second spray (7 DAS and 14 DAS) ranged from 4.33 (T2) to 6.17 (T1), with BTK-based treatments (e.g., T1, T9) showing better spider conservation among drone sprayed treatments. Combination treatments like BTK + Chlorantraniliprole (T7) also showed high retention with a mean of 5.67. Flubendiamide (T2) exhibited the sharpest decline, with a mean of 4.33. Mean populations after second spray ranged between 4.33 (T15) and 6.33 (T18), indicating higher variability in treatments applied *via* taiwan sprayer compared to drone. Treatments such as BTK (T10) and BTK + Tetraniliprole (T18) retained spider populations best, with means of 6.33 and 5.83, respectively. Cartap hydrochloride (T13) and Flubendiamide (T11) again showed lower means, at 4.83 and 4.33, respectively.

Overall, drone sprayed treatments (T1–T9) demonstrated more consistent spider population, with lower population declines after both sprays. BTK (T1) and combination treatments like BTK + Tetraniliprole (T9) and BTK + Chlorantraniliprole (T7) showed higher effectiveness in maintaining spider populations, with overall means above 5.50. Flubendiamide alone (T2) caused a sharper decline. Treatments applied *via* Taiwan Sprayer (T10–T18) showed more variation in population retention, with significant reductions in treatments like Flubendiamide (T11) and Cartap hydrochloride (T13). BTK (T10) and BTK + Tetraniliprole (T18) were safer in retaining spider populations, with overall means above 6.00.

Table 2. Effect of pesticide combination treatments on coccinellids during *kharif,* 2023

Trt. no.	Treatment details	Dose (g or ml/l)	Coccinellids per 10 hills						
			1st Spray				2nd Spray		
			Precount	I-7 DAS	I-14 DAS	Mean	II-7DAS	II-14 DAS	Mean
T1*	BTK 0.5% WP	27.21 g	5.00 (2.44)	4.67 (2.37)	5.67 (2.57)	5.17	5.33abc (2.52)	6.00 (2.64)	5.67
T2*	Flubendiamide 39.35% SC	1.36 ml	5.67 (2.57)	3.33 (2.08)	4.00 (2.23)	3.67	3.33cd (2.07)	4.33 (2.29)	3.83
T3*	Chlorantraniliprole 18.50% SC	4.08 ml	6.00 (2.64)	4.00 (2.23)	4.67 (2.37)	4.33	4.00abcd (2.23)	4.67 (2.38)	4.33
T4*	Cartap hydrochloride 50% SP	27.21 g	4.33 (2.29)	4.33 (2.29)	5.00 (2.44)	4.67	4.33abcd (2.31)	5.00 (2.44)	4.67
T5*	Tetraniliprole 18.18% SC	8.16 ml	6.00 (2.64)	4.00 (2.23)	4.33 (2.30)	4.17	4.00abcd (2.23)	4.00 (2.23)	4.00
T6*	BTK 0.5% WP + Flubendiamide 39.35% SC	27.21 g + 1.36 ml	5.00 (2.44)	3.67 (2.15)	4.33 (2.31)	4.00	3.67bcd (2.14)	4.00 (2.23)	3.83
T7*	BTK 0.5% WP + Chlorantraniliprole 18.50% SC	27.21 g + 4.08 ml	6.33 (2.71)	4.67 (2.37)	5.00 (2.44)	4.83	4.00abcd (2.23)	5.33 (2.52)	4.67
T8*	BTK 0.5% WP + Cartap hydrochloride 50% SP	27.21 g + 27.21 g	6.67 (2.76)	4.00 (2.23)	3.33 (2.06)	3.67	3.33cd (2.08)	4.67 (2.37)	4.00
T9*	BTK 0.5% WP + Tetraniliprole 18.18% SC	27.21 g + 8.16 ml	6.33 (2.70)	4.33 (2.29)	4.67 (2.38)	4.50	4.33abcd (2.31)	5.00 (2.44)	4.67
T10#	BTK 0.5% WP	2.66 g	5.67 (2.58)	5.00 (2.44)	4.33 (2.30)	4.67	5.67ab (2.58)	5.67 (2.58)	5.67
T11#	Flubendiamide 39.35% SC	0.13 ml	6.00 (2.64)	3.67 (2.15)	3.67 (2.16)	3.67	3.00d (1.99)	4.00 (2.23)	3.50
T12#	Chlorantraniliprole 18.50% SC	0.40 ml	6.33 (2.70)	4.33 (2.29)	5.33 (2.52)	4.83	3.33cd (2.08)	5.00 (2.44)	4.17
T13#	Cartap hydrochloride 50% SP	2.66 g	5.33 (2.51)	4.67 (2.37)	4.67 (2.38)	4.67	2.67d (1.88)	4.67 (2.37)	3.67
T14#	Tetraniliprole 18.18% SC	0.80 ml	4.67 (2.37)	4.00 (2.23)	5.67 (2.58)	4.83	3.00d (1.99)	4.33 (2.30)	3.67
T15#	BTK 0.5% WP + Flubendiamide 39.35% SC	2.66 g + 0.13 ml	4.33 (2.31)	3.67 (2.16)	4.00 (2.23)	3.83	3.33cd (2.06)	4.67 (2.37)	4.00

Trt. no.	Treatment details	Dose (g or ml/l)	Coccinellids per 10 hills						
			1st Spray				2nd Spray		
			Precount	I-7 DAS	I-14 DAS	Mean	II-7DAS	II-14 DAS	Mean
T16#	BTK 0.5% WP + Chlorantraniliprole 18.50% SC	2.66 g + 0.40 ml	5.33 (2.51)	4.00 (2.23)	3.67 (2.16)	3.83	3.67[bcd] (2.16)	5.33 (2.51)	4.50
T17#	BTK 0.5% WP + Cartap hydrochloride 50% SP	2.66 g + 2.66 g	5.00 (2.44)	4.67 (2.37)	5.67 (2.58)	5.17	3.00[d] (1.99)	5.67 (2.58)	4.33
T18#	BTK 0.5% WP + Tetraniliprole 18.18% SC	2.66 g + 0.80 ml	4.00 (2.23)	4.33 (2.29)	4.00 (2.23)	4.17	4.00[abcd] (2.23)	5.33 (2.52)	4.67
T19*	Control (water spray)	-	5.00 (2.44)	4.00 (2.23)	6.00 (2.64)	5.00	6.00[a] (2.64)	6.67 (2.77)	6.33
	CD		NS	NS	NS		0.39	NS	
	SE(m)		-	-	-		0.13	-	
	CV		-	-	-		10.55	-	

Values in the parentheses are √x+1

Table 3. Effect of pesticide combination treatments on spiders during *kharif,* 2023

Trt. no.	Treatment details	Dose (g or ml/l)	Spiders per 10 hills						
			1st Spray				2nd Spray		
			Precount	I-7 DAS	I-14 DAS	Mean	II-7DAS	II-14 DAS	Mean
T1*	BTK 0.5% WP	27.21 g	6.67 (2.77)	5.67 (2.58)	6.33 (2.71)	6.00	5.33 (2.51)	7.00 (2.83)	6.17
T2*	Flubendiamide 39.35% SC	1.36 ml	5.33 (2.52)	3.33 (2.08)	4.67 (2.38)	4.00	3.67 (2.16)	5.00 (2.44)	4.33
T3*	Chlorantraniliprole 18.50% SC	4.08 ml	6.00 (2.64)	5.33 (2.51)	6.00 (2.64)	5.67	5.00 (2.44)	6.00 (2.64)	5.50
T4*	Cartap hydrochloride 50% SP	27.21 g	5.67 (2.58)	5.00 (2.44)	5.67 (2.58)	5.33	5.33 (2.52)	6.67 (2.77)	6.00
T5*	Tetraniliprole 18.18% SC	8.16 ml	7.00 (2.83)	4.67 (2.37)	5.33 (2.52)	5.00	4.67 (2.38)	6.33 (2.70)	5.50
T6*	BTK 0.5% WP + Flubendiamide 39.35% SC	27.21 g + 1.36 ml	5.00 (2.44)	4.33 (2.31)	5.00 (2.45)	4.67	4.00 (2.23)	5.33 (2.48)	4.67
T7*	BTK 0.5% WP + Chlorantraniliprole 18.50% SC	27.21 g + 4.08 ml	5.67 (2.57)	5.00 (2.44)	5.67 (2.58)	5.33	5.00 (2.44)	6.33 (2.71)	5.67
T8*	BTK 0.5% WP + Cartap hydrochloride50% SP	27.21 g + 27.21 g	6.00 (2.64)	4.67 (2.38)	6.67 (2.77)	5.67	4.33 (2.31)	5.67 (2.57)	5.00
T9*	BTK 0.5% WP + Tetraniliprole 18.18% SC	27.21 g + 8.16 ml	5.67 (2.58)	5.00 (2.44)	6.00 (2.65)	5.50	5.00 (2.44)	6.67 (2.77)	5.83
T10#	BTK 0.5% WP	2.66 g	6.33 (2.71)	5.33 (2.52)	6.33 (2.71)	5.83	5.33 (2.52)	7.33 (2.89)	6.33
T11#	Flubendiamide 39.35% SC	0.13 ml	6.00 (2.64)	4.00 (2.23)	4.67 (2.38)	4.33	4.00 (2.23)	4.67 (2.38)	4.33
T12#	Chlorantraniliprole 18.50% SC	0.40 ml	6.67 (2.76)	4.67 (2.38)	5.33 (2.52)	5.00	4.33 (2.31)	5.67 (2.58)	5.00
T13#	Cartap hydrochloride 50% SP	2.66 g	6.33 (2.71)	3.67 (2.16)	5.67 (2.58)	4.67	4.33 (2.31)	5.33 (2.52)	4.83
T14#	Tetraniliprole 18.18% SC	0.80 ml	7.00 (2.83)	4.67 (2.38)	5.33 (2.52)	5.00	5.00 (2.44)	5.67 (2.58)	5.33
T15#	BTK 0.5% WP + Flubendiamide 39.35% SC	2.66 g + 0.13 ml	6.00 (2.64)	4.33 (2.31)	5.00 (2.45)	4.67	3.67 (2.16)	5.00 (2.44)	4.33

Trt. no.	Treatment details	Dose (g or ml/l)	Spiders per 10 hills						
			1st Spray				2nd Spray		
			Precount	I-7 DAS	I-14 DAS	Mean	II-7DAS	II-14 DAS	Mean
T16#	BTK 0.5% WP + Chlorantraniliprole 18.50% SC	2.66 g + 0.40 ml	6.33 (2.71)	5.33 (2.52)	6.00 (2.65)	5.67	5.00 (2.44)	6.00 (2.64)	5.50
T17#	BTK 0.5% WP + Cartap hydrochloride50% SP	2.66 g + 2.66 g	6.67 (2.76)	5.00 (2.44)	5.67 (2.58)	5.33	4.67 (2.37)	5.33 (2.52)	5.00
T18#	BTK 0.5% WP + Tetraniliprole 18.18% SC	2.66 g + 0.80 ml	7.00 (2.83)	5.33 (2.52)	6.33 (2.71)	5.83	5.00 (2.44)	6.33 (2.71)	5.67
T19*	Control (water spray)	-	6.00 (2.64)	5.67 (2.58)	6.67 (2.77)	6.17	5.67 (2.58)	7.33 (2.87)	6.50
	CD		NS	NS	NS		NS	NS	
	SE(m)		-	-	-		-	-	
	CV		-	-	-		-	-	

Values in the parentheses are √x+1

Drone spraying demonstrated superior performance in conserving both coccinellid and spider populations due to optimized application, with treatments combining BTK showing the best results, likely due to uniform application coverage and optimized droplet size. Taiwan spraying was less consistent, with higher variability and sharper declines in spider populations compared to drone applied treatments, particularly for chemical insecticides like Flubendiamide and Cartap hydrochloride, possibly due to uneven spray distribution or higher pesticide deposition in certain areas. However, BTK-based treatments also performed relatively well under this method.

The results consistently highlight that pesticides like chlorantraniliprole and cartap hydrochloride are selective, targeting lepidopteran pests with minimal impact on non-target beneficials such as arachnids and terrestrial predators. The present study agreed that spider populations, key beneficials in rice fields, showed negligible reductions, aligning with Mukherjee et al. (2009) and Rahaman and Stout (2019). Predator population trends remained stable in pesticide-treated and untreated fields, peaking during the grain formation stage, corroborating findings by Rattanapum (2012) and Acosta et al. (2017). However, while chlorantraniliprole demonstrated the lowest toxicity to diverse predators (Rahaman & Stout, 2019), granular cartap hydrochloride reduced soft-bodied parasitoids and generalist predators like dragonflies by 20–50% (Sravanthi et al*.,* 2015). This contrast highlights variability in predator susceptibility based on pesticide type and formulation. Both studies underscore the need for careful selection of pesticides to preserve beneficial fauna.

4. CONCLUSION

The study demonstrated that drone-based pesticide applications were safer to beneficial arthropod populations, including coccinellids and spiders. Treatments integrating biopesticides with selective insecticides showed minimal impact on beneficial fauna emphasizing their potential for eco-friendly pest management. The precision and efficiency of drones, combined with reduced non-target effects, highlight their viability for sustainable rice cultivation. Adoption of such technologies can optimize pest control while conserving agroecosystem health. However, conducting long-term monitoring to evaluate the cumulative effects of drone-applied biopesticides and insecticides on broader non-target fauna, including pollinators and soil microorganisms could further strengthen the knowledge base and practical application of drone-based biopesticide systems, advancing sustainable agriculture practices.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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