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ORIGINAL ARTICLE

Performance evaluation of a UAV granule spreader in controlling rice striped stem borer (*Chilo suppressalis*)

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Abstract

The rice striped stem borer (*Chilo suppressalis)* is a significant pest of rice fields. This pest is mainly controlled using chemical methods. In this research, the various pest control techniques including solution pesticide spraying (Fipronil SC 5%, l · ha^{-1} or 50 g · ha^{-1} active substance) and granule spreading (Fipronil G 0.2%, 20 kg · ha^{-1} or 40g · ha^{-1} active substances) were evaluated. The study included the following treatments: solution pesticide spraying with a UAV sprayer, spraying with a knapsack mist blower (KMB) sprayer, spraying with a knapsack motorized lance (KML) sprayer, hand granule spreading (HGS), granule spreading with a UAV granule spreader, and control (no application). The treatments were carried out in a randomized complete block design (RCBD) with four replications. The results indicated that the average consumed solution volume was 207.3, 195.6, and 18.2 l · ha^{-1} for KML, KMB, and UAV sprayers, respectively. The UAV sprayer had the lowest drift at 13%, while the KML sprayer had the highest at 51.57%. The yield of granule pesticide spreading was found to be higher than that of solution pesticide spraying. The granule spraying methods were more efficient than solution pesticide spraying in controlling the pest. The efficiency of HGS and UAV granule spreader methods was 87.25% and 79.7%, respectively, while the efficiency of the UAV, KMB, and KML sprayers was 72.7%, 79.9%, and 77.8%, respectively. The results also showed that the granule-spreading methods were more effective in controlling live larvae than solution pesticide spraying. In terms of income increase, the UAV granule spreader was found to be more profitable than the UAV sprayer, KMB sprayer, and KML sprayer, with increases of $109.2, $112.6, and $83.5 per hectare, respectively. The study recommends the use of the UAV granule spreader for controlling rice striped stem borers based on technical and economic evaluations of different pesticide application methods.

Keywords: granule spreading, pest, solution spraying, sprayer, UAV

Introduction

Rice (*Oryza sativa L*) is the second most important crop in the world after wheat. One of the concerns regarding this crop is pest control, particularly the rice striped stem borer. About 4% of the total rice production loss is attributed to the damage caused by the striped stem borer pest. Damage from this pest is primarily observed in the larval stage (Khodabandeh 2009). The crop yield can decrease by 30–40 kg · ha^{-1}, therefore, if the pest is not controlled, it can lead to a yield decrease of up to 600 kg · ha^{-1}. Initially, the larvae feed on the membrane and leaf tissue, and later burrow into the leaf sheath, and then into the stem, causing damage (Majidi Shilsar 2015). The use of chemical control is considered to be the most important method in the world. Annually, nearly 4000 to 8000 tons of pesticides are used in the rice fields in Iran (Amuagholi *et al.* 2017). The UAV granule spreader can efficiently spread granules at the right time without damaging the crops, and in a much shorter time than ground sprayers. Farmers in the region have found that the granule spraying method is more effective than using liquid pesticides to control rice striped stem borer. This is because the striped stem borer hides inside the plant stem. With the granule spraying method, the granule pesticide is sprinkled into the water around the plant. The granules dissolve in the water and are absorbed by the plant stem. Therefore, using a granule UAV spreader can be an effective method to control pests in such situations (Majidi Shilsar *et al.* 2013). UAV sprayers have been used to control pests of peanut and rice fields in India. The field capacity of this sprayer at a 1 meter height above the crop with a forward speed of 3.6 km · h^{-1} for peanut and rice fields was 1.15 and 1.08 km · h^{-1}, respectively. The operating costs for these crops were reported as $4.8 and $5 per hectare, respectively. Increasing the spray height and liquid pressure improved the uniformity of the spraying, with the VMD[1] and NMD[2] at 345 and 270 µm, respectively (Yallappa 2017). Agricultural UAV sprayers offer the advantages of increasing spraying speed, improving operator health, and reducing volume rate consumption to 10 l · ha^{-1} (Shahrooz *et al.* 2020). Research has shown the effectiveness of UAV sprayers in controlling pests and reducing human diseases. Several studies have demonstrated the high effectiveness and reliability of UAV granule spreaders for granule pesticide application. Aerial spraying was considered an important and effective method to control arthropods (especially mesocots). Air blowing by six blowers downwards prevents the pesticide solution from drifting and increases the solution's penetration into the crop canopy effectively (Miller 2005). Studies to assess UAV spraying in rice fields at a height of 5 m and a forward speed of 3 m · s^{-1} revealed that the propeller's blowing action increased the penetration of droplets into the crop. The droplet deposition in both the upper and lower layers was higher than with conventional sprayers. The average sediment in the upper and lower layer was 28% and 26% of the total spraying, respectively. This indicated that the settlement of droplets in the lower layer accounted for 92.8% of the settlement in the upper layer. The drift of droplets into non-target areas was only 12.9% of the total spraying. The droplet drift was almost negligible at a distance of 50 m from the target area (Xinyu *et al.* 2014). Droplet settling and pest control with different UAV nozzles in two stages of rice cultivation showed that the nozzles which produced larger droplets had less drift. Choosing the type of nozzle in a UAV sprayer is important. The settling rate of droplets in three types of hydraulic nozzles LU110-01, LU110-015, and LU110-02 was studied to control the pest in rice crops. The results showed that the density of droplets sprayed by the LU110-01 nozzle was higher than other treatments, but it did not show a significant difference. The control rate of the pest in 7 days from the stage of tillering and flowering with the LU110-01 nozzle was 89.4% and 90.8%, respectively, and with the LU110-02 nozzle it was 67.6% and 58.5%, respectively. The results showed that choosing a nozzle with finer droplets can improve pest control (Chen *et al.* 2020). The effect of UAV forward speed and flight height on the settling of the pesticide droplets was investigated to control the brown rice weevil. The results showed that the droplets settling in the lower parts of the plant were maximum and the highest spraying uniformity was achieved when the spraying height was 1.5 m and the forward spraying speed was 5 m · s^{-1} (Qin *et al.* 2016). Nozzles with finer droplets can enhance pest control. Additionally, research has been conducted on the effect of UAV flight speed and altitude on the distribution of pesticide droplets for brown rice weevil control. Different methods of applying Fipronil pesticide, such as solution spraying and granule spreading with varying doses, were assessed to control rice striped stem borer across the first and second generations. The findings revealed that the treatment with the lowest level of contamination in the dried central bud during the first generation involved the first round of solution spraying at a rate of 1 liter per hectare. The contamination level of the first round of granule spraying and control was 5.5% and 12.2%, respectively. The contamination rate of bleached bunches in the second generation in the treatment of granule spraying and solution spraying with a dose of 0.5 l · ha^{-1} was 4.9% and 4.2%, respectively. Furthermore, the contamination rates for granule spraying and solution spraying with a dose of 1 liter per hectare were 56.5% and 56.1%, respectively. It was noted that the performance of the treatments, except the control treatment, did not differ significantly at the 1% probability level (Majidi Shilsar *et al.* 2013). The conducted research showed the low efficacy of solution spraying compared to granule spraying. On the other hand, common solution spraying has low field capacity and high operating costs so; the aim of this study was to control the second generation of the striped stem borer in paddy fields. The effectiveness of solution spraying and granular spreading was assessed. The efficacy of a UAV solution pesticide sprayer was compared with a UAV granule spreader. Also, economic and technical evaluations of different methods were conducted.

[1] Volume Median Diameter
[2] Number Median Diameter

Materials and Methods

The research was carried out at the Iran Rice Research Institute (IRRI) to control the second generation of stem borer pests in rice fields in June 2023. The institute is situated south of Rasht city on the road from Ghazvin city to Rasht city. The research involved land preparation, planting, cultivation, and irrigation methods across all experimental plots. The experiments were carried out using a randomized complete block design with six treatments and four replications. The experimental plot area was 300 square meters (30 m long and 10 m wide). The control plot without any chemical intervention was considered to assess the effectiveness of the experimental treatments. The experimental treatments were as follows:

1. Solution spraying using a UAV sprayer (Fipronil pesticide, 1 l · ha^{-1}).
2. Solution spraying using a KMB sprayer (Fipronil pesticide, 1 l · ha^{-1}).
3. Solution spraying using a KML sprayer (Fipronil pesticide, 1 l · ha^{-1}).
4. Granule distribution by hand (Fipronil 0.2% G 20 kg · ha^{-1}).
5. Granule application using a UAV spreader (Fipronil 0.2% G 20 kg · ha^{-1}).
6. Control (no chemical treatments applied).

The Fipronil pesticide was used in both 50SC (solution) and 0.2% G (Granule) forms. All sprayers were calibrated before use. The specifications of the experimental sprayers (spreaders) are presented in detail in Table 1.

The KML sprayer had a piston pump to deliver the pesticide solution to the cone nozzle. This sprayer was calibrated before spraying. The output of the nozzle was measured using graduated containers in three repetitions at specific times. To comply with the intended dosage, 120 ml of pesticide was mixed with 85.5 liters of water in the sprayer tank to spray 1200 m^{-2} (four plots of 300 m^{-2}). Field experiments were conducted when at least 20% of rice stalks were infected (Fig. 1). The pesticide was mixed with water in appropriate proportions according to the control method. The solution needed 2.18 liters for spraying 1200 m^{-2} (4 plots of 300 m^{-2}) with a UAV sprayer which was mixed with 120 ml of Fipronil pesticide.

The KMB sprayer's pesticide solution was directed to the nozzle by the force of gravity. The airflow caused the vacuum of the solution. The nozzle's output was measured in three repetitions using a graduated container for 1 minute. To cover 1200 m^{-2}, 120 ml of pesticide was mixed with 73.5 liters of water for spraying. The technical parameters measured included droplet drift, droplet settling on the crop, theoretical and effective field capacities, field efficiency, droplet covered surface, spraying uniformity, and spraying efficacy.

The sprayer drone was also equipped with a granule spraying system. This meant that for granule spraying operations, the granule distributor module was mounted on the drone and the solution spraying system was deactivated. The tank was used for both methods. Calibration for both methods was performed in the field and the drone was prepared to distribute the solution (granules) per hectare.

Spraying uniformity

Ten water-sensitive papers (WSP) were placed in the spraying path and on the crop before spraying. The

Table 1. Technical specifications of sprayers (spreaders)

UAV Sprayer/spreader		KML Sprayer		KMB Sprayer	
Parameter	Specification	Parameter	Specification	Parameter	Specification
Number of blowers	6	number of pumps	1	number of pumps	–
Number of nozzles	2	number of nozzles	1	number of nozzles	1
Nozzle type	micronair	nozzle type	hollow cone nozzle	nozzle type	drip
Pump flow rate (ml · min^{-1})	300–1500	pump flow rate [ml · min^{-1}]	5.8 l	pump flow rate [ml · min^{-1}]	–
UAV weight (empty tank)	11 kg	power supply	two-stroke engine	power supply	two-stroke engine
Power Supply	25.7 V 20 mA	power	1.01 hp	power in 1500 RPM	2.41 hp
Maximum take-off weight	18 kg	effective capacity	0.16 ha · h^{-1}	fan output	9 m^3 · min^{-1}
Tank capacity	10 l	tank capacity	25 l	tank capacity	14 l
Control system	RTK	pump type	piston type		
Temperature Range	15–45°C	pump pressure	25 bars		
Speed Rrange	0–10 m · s^{-1}				
Flight Duration	10–15 min				
Granule spreader	centrifugal type				

Fig. 1. Controlling stem borer pests in a rice farm using chemical pesticide. KML sprayer – A; KMB sprayer – B; UAV solution sprayer – C; UAV granule spreader – D

WSPs were collected and taken to the laboratory for analysis after spraying (Safari and Bagheri 2022). The analysis was conducted using an Excel program by forming the droplet frequency table to determine the VMD and NMD. The mean volume diameter (Zhua *et al*. 2011) was determined based on the diameter of the droplets in 50% volume. The volumetric and numerical average diameter was calculated, and the spraying quality coefficient was obtained from the ratio of VMD[3] to NMD[4]. After spraying, the WSPs were collected and scanned with a scanner (resolution of 300 dpi). The process of counting the number and size of stains was made using Image J software (Image J 1.52a, Wayne Rasband, National Institutes of Health, USA). The RGB images of WSPs were converted into binary images and scaled. After determining the appropriate threshold for each image, the stains were separated from the background, and the data were extracted. The volume median diameter and numerical median diameter of stains were obtained using Equation 1 (Srivastava *et al*. 2006):

$$D_{pq}^{p-q} = \left(\sum_{i-1}^{n} N_i \times D_i^{p} \sum_{i=1}^{n} N_i \times D_i^{q}\right)^{\frac{1}{p-q}},$$

where:
p and q – integer numbers, $p > q$. To calculate the numerical median diameter: q = 1, $p = 0$; to calculate the volume median diameter: $p = 3$ q = 0;
Di – droplet diameter for size group i (μm);
Ni – number of drops in size group I;
i – group size number;
n – number of size groups.

Distribution of the granules

The distribution of the granules is normally measured using Petri dishes. In this study, instead of Petri dishes, special trays were used to evaluate granule distribution and the amount of spray in a given area was determined (Fig. 2). Trays measuring 0.5 × 0.36 meters were used to calibrate and measure the distribution of granules. In each tray, the amount of granules distributed inside the tray was weighed and finally the total weight of the granules distributed in the area of the trays was determined. The distribution rate per hectare was calculated.

[3] Volume Median Diameter
[4] Number Mean Diameter

Fig. 2. Using the trays to determine distribution of drone granule rate

Droplet drift

Water-sensitive papers (WSP) were placed at regular 1 meter intervals perpendicular to the direction of forward speed (10 papers in total). After spraying, the papers were collected and the percentage that got wet from the toxic solution drops was measured. The results indicated the drift percentage (Kharim *et al.* 2019). The number of papers that were exposed to the toxic solution were determined and divided by the total number of papers, and finally the percentage of drift was calculated.

In another study, two methods using water-sensitive papers and fiberglass were investigated to measure spray uniformity and drift. The results showed that the method using water-sensitive papers had better efficiency and the settlement of solution droplets was 80% higher than that of fiberglass (Ahmad *et al.* 2022). The Lidar (Light Detection and Ranging) method is also used, although the technology for this method is not available in this region (Eduard *et al.* 2013). The drift in this study was measured according to the authors' own method and Kharim method (2019).

Covered surface (droplet density)

For the determination of the area covered by solution spraying methods, sensitive cards were placed in the spraying path. The droplet coverage area was measured using Equation 2 (Matthews 2004):

$$S_c = \frac{A_{at}}{A_t} \times 100, \quad (2)$$

where:
S_c – droplet coverage area (%);
A_{at} – total area of the droplets (mm^2);
A_t – total area (mm^2).

Field efficiency

The theoretical field capacity (TFC) was determined according to Equation 3. The effective field capacity (EFC) was based on the time taken to spray each test plot. According to equation 4, the field efficiency was calculated by finding the ratio of the effective field capacity to the theoretical field capacity (Sheikhigarjan *et al.* 2024):

$$C = \frac{V \times W}{10},$$

where:
V – forward speed (m · sec^{-1});
W – working width (m);
C_t – theoretical field capacity (ha · h^{-1}).

$$E = \frac{C_o}{C_t} \times 100, \quad (4)$$

where:
E – field efficiency (%);
C_o – effective field capacity (ha · h^{-1}).

Spraying efficacy

The rice stem borer has two to three generations. The second generation appeared from June 20 to the end of September 2023 in Gilan province. The economic threshold of the rice stem borer is when 2% of the white heads are affected, or when 8 to 10 early-stage larvae are observed in 100 plants. The number of 100 plants containing larvae was counted in each experimental plot before and after spraying. The pest control percentage was calculated using Henderson's formula: (Equation 5):

$$E_1 = \frac{1 - (C_b \times T_a)}{(C_a \times T_b)} \times 100,$$

where:
C_a – the number of live larvae of the control before spraying;
T_b – the number of live larvae of the treatment after spraying;
C_b – the number of live larvae of the control after spraying;
T_a – the number of live larvae of the treatment before spraying;
E_1 – efficacy (%).

The infected whitened plants that could be counted were identified and their percentage was determined

(Soleimani and Larijani 2012). Then, the data were analyzed by variance analysis and the average efficiency of the treatments was determined (Equation 6):

$$E_2 = \frac{WH_c - WH_t}{WH_c} \times 100,$$

where:
WH_C – the number of white heads in the 100 control rice stalks;
WH_t – the number of white clusters in the 100 stalks of treated rice;
E_2 – efficacy (%).

The number of white head-infested plants in each plot and the effectiveness of treatments were determined before and after treatment using Equation 6 (Soleimani and Larijani 2012). The efficacy of the treatments was analyzed by ANOVA, and the mean efficacy of treatments was compared using Tukey's test ($p < 0.05$).

Economic evaluation

The economic evaluation of treatments was conducted using the partial budgeting method. This method assesses changes that impact profitability by considering all inputs as constant. The aim was to calculate the reduction of costs and the increase in income from the new method, compared to the control method. Positive and negative effects of the methods were compared with the control method, and the differences between these effects were determined. The costs and income from UAV spreader, UAV spraying as well as traditional methods and manual granulation, were evaluated while considering the crop yield in each experimental plot. Income per hectare and net income were calculated based on the price of one kg of rice paddy in this area. Additionally, the cost of buying pesticides and the cost per hectare of spraying or granulation operations were determined according to the area's prices. Net income was calculated by subtracting costs from the gross income. The income of each method was then compared to the control treatment (without chemical control). The income of the control treatment was deducted from the income of the spraying or granulation method to identify the method with greater income difference, thus determining the suitable method for spraying or granulation operations. Following the determination of parameters, the results were analyzed using Duncan's multi-range test method at the 5% significance level and by SPSS 18 statistical software.

Results

In this research, different methods of rice stem borer pest control were investigated in terms of technical and economic aspects.

Volume rate consumption

The analysis of variance results indicated a significant difference between the experimental treatments in terms of the volume rate consumption at the 5% confidence level (Table 2). The KML sprayer had the highest volume rate consumption at 207.3 $l \cdot ha^{-1}$, while the UAV sprayer had the lowest at 18.2 $l \cdot ha^{-1}$. The KMB sprayer volume rate consumption was 195.6 $l \cdot ha^{-1}$, and the UAV granule spreaders were at 20.27 $kg \cdot ha^{-1}$ (Table 3). There was no significant difference in volume

Table 2. Analysis of variance parameters of spraying and granulation methods (mean square)

Sources	df	TFC	EFC	Field efficiency	Solution consumption	Drift	Yield	Income
Treatment	4	11.93**	9.64**	**284.22	**39769.89	1946.07**	52895.5**	48*
Error	15	0.012	0.006	21.35	60.072	6.1	2704.65	10.28

*,**significant difference at the probability level of 5% and 1%, respectively; ns – no significant difference

Table 3. Means comparison of spraying and granulation methods

Treatment	TFC [$ha \cdot h^{-1}$]	EFC [$ha \cdot h^{-1}$]	Field efficiency [%]	Solution/Granule consumption [$l \cdot ha^{-1}$ or $kg \cdot ha^{-1}$]	Drift [%]	Yield [$kg \cdot ha^{-1}$]	Income [$]
UAV solution sprayer	3.77 b	3.3 a	87.45 a	18.17 a	13 c	3778.75 b	306.3 b
KML sprayer	0.72 c	0.54 b	75.82 b	207.31 c	51.75 a	3853.25 b	332 b
KMB sprayer	0.71 c	0.5 b	70.31 b	195.65 b	29.75 b	3794.75 b	382.6 b
Manual granule spreading	0.72 c	0.5 b	69.62 b	20.35 a	0.00 d	4026.75 a	418.6 a
UAV granule spreader	3.96 a	3.4 a	85.82 a	20.27 a	0.00 d	3996.75 a	415.3 a
C.V	8.8	8.7	3.5	35	12.1	2.1	5.8

Similar letters do not have significant differences rate consumption between UAV granule spreader and manual granule spreading with 20.35 and 20.27 kg · ha^{-1}, respectively. These results align with Safari *et al.* (2009), defining KML as a high-consumption[5] sprayer, KMB as a low-consumption[6] sprayer, and the UAV sprayer as a very low-consumption[7] sprayer. The highest volume rate consumption was attributed to the KML sprayer, which constitutes approximately 40% of the sprayers used by farmers in Iran (Safari *et al*. 2009). The use of a UAV sprayer was an effective method of reducing volume rate consumption and operational difficulties, particularly considering the traffic conditions of KMB and KML sprayers in rice fields and the muddy nature of the fields. Granule spreading was an effective method for combating rice striped stem borer, with an average consumption of 20 kg · ha^{-1}. Through dissolving in water around the plant, the active substance of the pesticide was systematically absorbed by the plant, leading to eradication of the pest inside the plant stem.

Field efficiency

There was a significant difference between treatments in terms of TFC at the 5% level (refer to Tables 2 and 3). The TFC values for UAV, KML, KMB sprayers, manual granule spreading, and UAV granule spreader were 3.7, 0.7, 0.7, 0.7, and 3.9 ha · h^{-1}, respectively. The granule UAV spreader and UAV solution sprayer had the highest TFC values at 3.9 and 3.7 ha · h^{-1}, respectively. The EFC for these methods was 3.3 and 3.4 ha · h^{-1}, respectively, and there was no significant difference between these methods. The field efficiency of these methods was 87.4% and 85.8%, respectively, and no significant difference was found between the UAV sprayer and granule spreader methods.

The KMB and KML sprayers had low effective field capacity due to the zigzag movements of the user with low forward speed, unnecessary overlaps and moving in the mud. These factors led to time wastage and reduced field capacity. One of the limiting factors was the movement of the user in the mud for granulation spreading by hand, which effectively decreased the forward speed. In contrast, UAV spraying and UAV granule spreading prevented wasting time due to their high speed and clarity of route. The field efficiency of UAV solution spraying and UAV granule spreading was higher than other methods primarily because of the reduction of wasted time from consecutive rounds and refilling the UAV tank. Due to difficulties in maneuvering tractors and agricultural tools in rice fields, farmers often use the KMB and KML sprayers. These findings align with Norouzieh *et al.* (2023) who researched the best sprayer for controlling cotton pests. Their research highlighted that the choice of spraying method depends on the field size, type of pest, crop height, availability of sprayers, and spraying costs. The UAV sprayer demonstrated the best field efficiency and was the fastest spraying method, especially in large and flooded fields. Additionally, if the height of the crop bush poses a significant risk to the boll, the use of a UAV sprayer was recommended (Norouzieh *et al*. 2023).

Spraying efficacy

The evaluation of experimental plots before spraying revealed that the density of rice striped stem borer and plant damage percentage in the plots were relatively uniform. The average density of larvae was eight per square meter and the number of bleached clusters was 13–14 (Table 4). The chemical control treatments based on the number of bleached spikes and live larvae showed that the granulation method was the most effective in controlling rice striped stem borer in the first and second generations. The hand granulation method had the highest efficacy at 87.25%, followed by the UAV granule spreader method at 83.5%. The efficacy of the UAV sprayer was 72.75%. The density of whitened clusters also confirmed these results. The efficacy of the hand granulation method and the UAV granule spreader were 86.25% and 79.75%, respectively, while the UAV sprayer had an efficacy of 46.75%. Although the UAV sprayer reduced the number of live rice striped stem borer larvae to seven per square meter from the control of 25.9 larvae per square meter, it was less effective than the KML and KMB sprayers. The KMB sprayer had an average efficacy of 79.9% and did not show a statistically significant difference with hand granule spreading. However, the KML sprayer had a significant difference compared to hand granule spreading (Table 4). The density of live rice striped stem borer larvae was always more than the number of bleached clusters per unit area.

The research concluded that the UAV sprayer was effective in controlling the rice stem borer. However, it was found that spraying with KMB was more effective than using the UAV sprayer. The granule spreading methods, whether by the hand method or UAV spreader method, was more effective than foliage application to control the pest. The timing of application was found to play a crucial role in increasing the effectiveness of chemical control. UAV granule spreading had a higher field capacity than the hand method. The results of the research were consistent with those of Majidi Shilsar *et al.* (2013). The study evaluated the effects of Fipronil pesticide, in both solution and granular forms, on three generations of rice striped stem borer. The results indicated that the granule spraying

[5] More than 200 l · ha^{-1}
[6] Between 50–200 l · ha^{-1}
[7] Between 5–50 l · ha^{-1}

Table 4. Average cluster whiteness percentage, number of live larvae and efficacy percentage*

Treatment	Average white head rate [%]		Average number of live larvae		Efficacy [%]	
	before	after	before	after	white head [%]	live larvae [numbers]
Control	13.5 ± 0.15	20.34 ± 0.89 a	11.5 ± 0.16	25.92 ± 0.72 a	–	–
UAV granule spreader	13.5 ± 0.03	4.12 ± 0.23 c	11.67 ± 0.17	4.22 ± 0.66 a	79.75 ± 1.3 a	83.75 ± 2.5 ab
UAV solution sprayer	13.42 ± 0.15	10.8 ± 0.38 c	11.67 ± 0.17	7.07 ± 0.53 b	46.75 ± 1.9 b	72. 75 ± 2.05 c
Hand granule spreading	13.58 ± 0.15	2.76 ± 0.29 c	11.3 ± 0.27	3.3 ± 0.12 c	86.25 ± 1.4 a	87.25 ± 0.47 a
KMB sprayer	13.9 ± 0.11	9.25 ± 1.02 b	11.67 ± 0.4	5.22 ± 0.81 bc	54.5 ± 5.2 b	79.9 ± 3 abc
KML sprayer	13.57 ± 0.28	10.65 ± 0.98 b	11.85 ± 0.15	5.75 ± 0.67 bc	47.5 ± 4.9 b	77.88 ± 2.6 bc
df	518	518	518	518	4.15	4.15
F	1.34	77.6	1.35	185.3	30	5.59
Pr	0.29	0.0001	0.28	0.0001	0.0001	0.006
CV	2.4	14.6	3.05	14.7	10.7	5.85

*the active substance for the liquid application was 50 g · l^{-1} or 50 g · ha^{-1} and for granular application it was 0.2% (for 20 kg was 40 g · ha^{-1})

method was superior to the solution application of Fipronil pesticide across different generations (Majidi Shilsar *et al.* 2013).

Spraying uniformity

One crucial aspect of spraying is the uniformity of the droplets. When analyzing the WSPs placed in the spraying path, it was observed that the density of droplets in the central part of the line, perpendicular to the direction of movement, was higher than at the sides. These results showed that the density of droplets was higher near the nozzles. The spray width of the UAV sprayer was 5 meters, which covered the crop, exposing all parts of the crop's crown. According to the WSPs installed on the plants, the volume median diameter and numerical median diameter in the UAV sprayer were 384 and 286 microns, respectively. In comparison, the volume and numerical median diameter in the KMB sprayer were 735 and 263 microns, respectively. The size of the droplets and their density were relatively uniform in the UAV sprayer. The WSPs were completely wetted with the KML sprayer, indicating a lack of spraying uniformity. The spraying quality coefficient for the UAV sprayer and the KMB sprayer was 1.34 and 2.79, respectively, indicating the high quality of spraying with the UAV sprayer. In research conducted on cotton crops, the spraying quality coefficient was 2.95, 2.43, and 3.62 for the three methods of UAV sprayer, boom sprayer, and lance sprayer, respectively (Norouzieh *et al.* 2023). The boom sprayer was relatively superior to the UAV method, which was not consistent with the results of this research stating that the UAV sprayer was preferable to conventional methods.

Pesticide solution coverage

Three different methods of spraying – UAV sprayer, KML sprayer, and KMB sprayer were compared based on the coverage percentage of the toxic solution on WSP installed in the upper part of the plant. The coverage percentages were 3.7%, 7.4% and 6.3% for the UAV sprayer, KML sprayer, and KMB sprayer, respectively. The KML sprayer had a higher coverage percentage than the UAV sprayer and KMB sprayer. This was due to the high volume of the solution used, resulting in greater output. In contrast, the UAV sprayer's smaller volume and reduced number of droplets led to a smaller coverage area. Norouzieh *et al.* (2023) findings in a cotton field also supported these results, namely that the KML sprayer had the highest coverage and the UAV sprayer had the lowest coverage (Norouzieh *et al.* 2023).

Droplet drift

In all three solution treatments, WSPs were placed around the field, and there was a significant difference between the spraying methods in terms of drift at the 5% level. The KML sprayer had the highest drift percentage at 51.75%, while the UAV sprayer had the lowest at 13%. The KMB sprayer had a drift of 29.75%, falling between the KML and UAV sprayers. These results indicated that the UAV sprayer had less drift than the KML and KMB methods, as well as high spraying quality. This may be due to the blowers installed on the UAV sprayer, which direct the toxic droplets toward the target and the very low consumption of the toxic solution. In contrast, the KML and KMB sprayers resulted in coarse droplets falling to the lower side of the crop, contaminating the soil, and fine droplets being carried by the wind, increasing the drift percentage. The user's handling of the nozzle head and irregular spraying in both KML and KMB sprayers caused waste of the toxic solution and increased drift. Additionally, the droplet diameter in these sprayers varied with small and large droplets. The granule spraying methods had no drift due to the nature of the operation and the high specific gravity of the granules. The granules were spread directly around the plant, and the wind was not considered a limiting factor. This method was similar to the method of spreading fertilizers by hand or machine, making the operation easy. Furthermore, the user was not exposed to the toxic solution. These results were consistent with the findings of Majidi Shilsar *et al.* (2013) who recommended granule pesticides rather than the solution type to control striped stem borer in rice fields.

The spraying technologies were different. Drones equipped with micron nozzles have blowers that direct the solution droplets towards the target and reduce drift, but in a lance sprayer, despite the larger droplets, the drift increases due to the high-altitude droplet projection and the user's zigzag movements. An atomizer sprayer also has a blower unit, but the drift increases due to the high-altitude droplet projection.

Economic assessment

The income was calculated based on the price of 1 kilogram of rice[8] ($0.5) and the crop yield. The cost of spraying and granulation operations for each experimental treatment was recorded in Table 5. The net income was determined by subtracting the cost of spraying operations and volume rate consumption from the gross income. The net income of the spraying and granulation methods was compared with the control treatment (without spraying and granulation operations) using the partial budgeting method. The UAV sprayer method resulted in an additional income of $328.12 compared to the control treatment, with additional costs of $13.3 for spraying and $8.33 for the purchase of Fipronil toxic solution. The income from using the UAV sprayer, after deducting the costs, was $306.45. Similar calculations were performed for other treatments, and the obtained incomes were compared statistically.

The economic evaluation results revealed a significant difference in pesticide application methods at a 5% level. The income from hand granule spreading and the UAV granule spreader increased by $418.8 and $415.5 per hectare, respectively. The income increased by $306.3, $302.8, and $332 per hectare for the UAV sprayer, KMB sprayer, and KML sprayer, respectively; however, the differences were not statistically significant. There was no significant difference in income between the granule UAV spreader and hand granule spreading methods. The use of the granule UAV spreader resulted in decreased labor difficulties and increased field capacity, making it the recommended method. Furthermore, the income of the granule UAV spreader compared to the UAV sprayer, KMB sprayer, and KML sprayer was $109.2, $112.7, and $83.5 per hectare, respectively.

Discussion

This research evaluated the technical and economic aspects of using UAVs to spray solution or granular pesticides compared to conventional sprayers for controlling the striped stem borer in second-generation paddy fields. The key findings are as follows:

With KML, KMB and UAV sprayers, the volume rate consumption was 207.3, 195.6 and 18.17 $l \cdot ha^{-1}$, respectively. The KML sprayer had the highest volume

Table 5. Spraying and granulation methods compared to the control (partial budgeting)

Treatments	Positive effects		Negative effects		
	additional income	reduction in costs	reduction income	additional costs	net income
UAV sprayer	328.12	0	0	0.8 0.5	18.38
KMB sprayer	336.12	0	0	1.5 0.5	18.17
KML sprayer	365.37	0	0	1.5 0.5	19.92
Hand granule spreading	452.12	0	0	1.5 0.5	25.13
UAV granule spreader	437.12	0	0	0.8 0.5	24.93

Costs are in USD per hectare

[8] Hashemi Variety

rate consumption, KMB sprayer had lower volume rate consumption and the UAV sprayer had the lowest volume rate consumption. There was no significant difference in granule consumption between the UAV granule spreader and hand spreading.

The spraying quality coefficient for KMB and UAV sprayers was 2.79 and 1.34, respectively. The UAV method was preferable to the KMB and KML methods in terms of spraying uniformity.

Despite the presence of larger droplets, the droplet drift in the KML sprayer was higher than in the KMB and UAV sprayers.

The UAV sprayer and UAV granule spreader had higher field capacity than the KML, KMB, and hand granule spreading methods. These results indicated that the UAV sprayer and spreader were more time-efficient.

Granular spreading methods were more effective in terms of controlling the contamination percentage of bleached bunches than solution spraying. The hand granule spreading method with 86.25% and the UAV granule spreading with 79.75% were better than other methods. The granule spreading methods were preferred over solution application in terms of controlling live larvae. The hand granule method with 87.25% efficacy was better than the UAV granule spreader.

Economically, the income increases for the granule UAV spreader compared to the UAV sprayer, KMB sprayer, and KML sprayer methods were $109.2, $112.7, and $83.5 per hectare, respectively.

In conclusion, the granule spreading method was preferable to solution application for controlling rice stem borer, considering both technical and economic aspects. Between the two granule spreading methods, the UAV granule spreading was recommended due to its higher field capacity, greater efficiency, reduced labor requirements, shorter application time, and prevention of pest spread. From an economic standpoint, the granule spreading method was relatively more effective than solution spraying, and the use of UAV granule spreading was recommended.

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