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A comparative study of drone and manual herbicide application for weed management in wet direct-seeded rice (*Oryza sativa* L.)

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Abstract

A field experiment was conducted at Tamil Nadu Agricultural University, Coimbatore, during the *Navarai* season (January-April) of 2024 to assess the efficiency of drone-based herbicide application in terms of weed control, energy use, and cost effectiveness in wet direct-seeded rice (*Oryza sativa* L.). The study compared the effectiveness of weed control using herbicide combinations applied as pre-emergence followed by early post-emergence, with both drone and knapsack sprayer. The treatments included the application of pretilachlor followed by early post-emergence bispyribac sodium, and pyrazosulfuron followed by penoxsulam + cyhalofop butyl, using both drone and knapsack sprayer. Additionally, weed-free and unweeded control plots were included. Results indicated that the application of pretilachlor followed by bispyribac sodium using a drone sprayer significantly reduced weed density and weed dry weight compared to the unweeded plot. This treatment also resulted in a higher grain yield (5286 kg ha^{-1}). Moreover, drone application of pretilachlor followed by bispyribac sodium provided a higher net return (₹ 51631/ha), benefit-cost ratio (2.17), energy-use efficiency (9.53), and energy productivity (0.30 kg/MJ). The experiment concluded that drone-based spraying of pretilachlor followed by bispyribac sodium is an effective weed management strategy for wet direct-seeded rice, offering superior yield attributes, energy use efficiency, and profitability.

Keywords

Direct-seeded rice; unmanned aerial vehicles (UAVs); herbicides; pretilachlor; weed control efficiency

Introduction

Rice (*Oryza sativa* L.) is the staple food for over 50% of the world's population. In 2018, it was cultivated on 167 million ha, producing more than 782 million tons (1). Rice is grown in over 100 countries, with Asia accounting for 90% of global rice production (2). However, traditional rice transplanting faces several challenges, including water scarcity, labour shortages, and the effects of climate change (3, 4). As a result, direct-seeded rice (DSR) has emerged as a promising alternative, offering benefits such as reduced water and labour demands, lower production costs, and a decreased global warming potential compared to transplanted rice (5, 6). In terms of yield, both direct seeding and transplanting methods are comparable (7). However, direct-seeded rice is vulnerable to significant yield losses due to heavy weed infestation. Without effective weed management practices, yield losses in DSR can range from 20% to 100% in different agro-systems (8, 9). Therefore, effective weed management is crucial for profitable crop production (10).

Traditional methods of weed control, particularly manual herbicide spraying, are labour-intensive, time-consuming, and often result in inconsistent application efficiency (11). Additionally, manual pesticide application poses risks to workers due to exposure from spills, direct contact, and pesticide drift (12). To address these challenges, drone technology offers an alternative solution, providing timely and uniform herbicide application. This technology improves weed management outcomes while reducing labour costs and minimizing environmental impact (13, 14).

This study aims to evaluate the efficiency of drone-based herbicide application in comparison to conventional manual spraying method for weed control in WDSR fields. By analysing parameters such as weed density, weed dry weight, crop growth, and overall yield, the research seeks to highlights the potential benefits and limitations of drone technology in modern rice cultivation.

Materials and Methods

Plant materials

A field experiment was conducted at the Wetland Farm of Tamil Nadu Agricultural University, Coimbatore, during the *Navarai* season (January to April 2024). The experimental site is situated at 11˚00'N latitude and 76˚92'E longitude, with an altitude of 426.7 m above mean sea level (MSL). The soil at the site was clay loam, with a pH of 7.7 and an organic carbon content of 0.64%. During the cropping season, the average temperature was 28.7°C, with a high of 34.1°C and a low of 23.2°C. The season experienced an average relative humidity of 59.5%, a wind speed of 5.3 km/h, and a single rainy day, which recorded 7.9 mm of precipitation.

The experiment followed a strip-plot design, with three horizontal factors and six vertical factors, each replicated three times. The horizontal factor involved three seed rates (40, 50 and 60 kg ha^{-1}) sown using a drone seed spreader. The vertical treatments were:

W_1: Drone spraying of pre-emergence (PE) Pretilachlor @ 0.75 kg a.i. ha^{-1}, followed by (*fb*) early post-emergence EPOE Bispyribac sodium @ 25 g a.i. ha^{-1},

W_2: Drone spraying of Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1}, *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1},

W_3: Manual spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1}, *fb* early post-emergence EPOE Bispyribac sodium @ 25 g a.i. ha^{-1},

W_4: Manual spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1}, *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1},

W_5: Weed-free check,

W_6: Weedy check.

For drone herbicide application, a spray volume of 60 L ha^{-1} was used for pre-emergence herbicides and 40 L ha^{-1} for early post-emergence herbicides. Manual spraying involved a higher spray volume of 500 L ha^{-1}. An extended-range flat fan nozzle was used for drone spraying, while a standard flat fan nozzle was employed for the knapsack sprayer. The drone operated at a height of 1 m with a speed of 4 m/s, covering a swath width of 4 m. Pre-emergence herbicides were applied 8 days after sowing (DAS), and early post-emergence herbicides were applied at 25 DAS. The weed-free plot was maintained by regular manual hand weeding.

The experimental field was primarily infested with grass weeds such as *Echinochloa colona*, *Echinochloa crus-galli*, *Dinebra retroflexa*, *Leptochloa chinensis*, and *Paspalum* species. Among broadleaf weeds, *Ammannia baccifera*, *Bergia capensis*, and *Eclipta alba* were dominant. The major sedge weeds present included *Cyperus difformis* and *Cyperus rotundus*.

The rice variety used in the experiment was CO 55. Dry seeds were sown using a drone seed spreader via the broadcasting method at three different seed rates: 40, 50 and 60 kg ha^{-1}. A fertilizer dose of 150:50:50 kg/ha of $N:P_2O_5:K_2O$ was applied. Weed parameters, including weed density, weed dry weight, and weed control efficiency were observed at 45 and 60 DAS. Weed density was recorded in four randomly placed quadrants (0.5 m × 0.5 m) in each plot. Weed control efficiency was calculated using the previously described formula and the results were expressed as a percentage (15).

Yield parameters, including grain yield and straw yield, were measured from the net plot area and expressed in kg/ha at 14% moisture content. Economic indicators such as gross return, net return, and the benefit-cost ratio (BCR) were calculated based on the prevailing market prices of input and output. Energy equivalents for all inputs and outputs were taken from a study by previous researchers to study the energetics of weed management in rice (16). Energy indices were computed using the formulae given by (17, 18). Energy-use efficiency was determined as the ratio of output energy to input energy, while energy productivity was calculated by dividing grain yield by input energy, expressed in kg/MJ (18). The net energy was derived from the difference between energy output and input provided.

The data were statistically analysed according to the previously described method (19). Statistical significance was tested using the F-test, with a critical difference (CD) at a 0.05 probability level. Data related to weed density and weed dry weight were transformed using a square root transformation $\sqrt{(X+0.5)}$ before performing the statistical analysis. The correlation between weed dry weight, dry matter production, and grain yield was evaluated using Pearson linear correlation analysis (R Studio Version: 2024.04.2+764).

Results

Weed density, weed dry weight, and weed control efficiency

In the experimental plot, grasses exhibited the highest relative weed density at 41.3%, followed by broadleaf weeds at 33.6%, and sedges at 25.1%. The highest weed density (86.44 Weed/m^2) and weed dry weight (115.10 g/m^2) were observed in the unweeded plot. The application of pre-emergence herbicides followed by early post-emergence herbicides, using both drone and knapsack sprayer, effectively reduced weed density and dry weight (Table 1). Drone spraying of pretilachlor *fb* bispyribac sodium resulted in the better weed control, recording the lowest weed density (10.89 Weed/m^2), weed dry weight (13.92 g/m^2), and a higher weed control efficiency of 87.51%. The unweeded check, with a weed dry weight exceeding 105 g/m^2, experienced a grain yield reduction of approximately 47% compared to weed-free check.

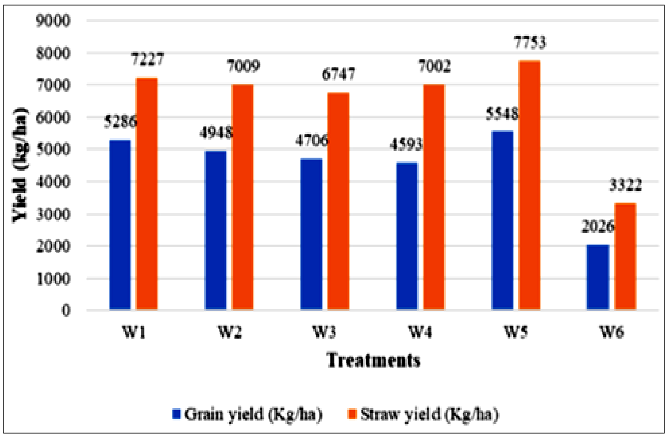

Fig. 1. Effect of different weed management practices on straw and grain yield of rice. **W$_1$:** Drone spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1}, **W$_2$:** Drone spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1}, **W$_3$:** Manual spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1}, **W$_4$:** Manual spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1}, **W$_5$:** Weed-free check, **W$_6$:** Weedy check

Table 1. Effect of seed rate and weed management practices on weed control of rice.

Treatments	Weed density (Weed/m^2)	Weed dry weight (g/m^2)	Weed control efficiency (%)
W1 (Drone spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1})	3.35^e (10.89)	3.77^e (13.92)	87.51
W2 (Drone spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1})	4.49^d (19.00)	4.95^d (24.29)	77.96
W3 (Manual spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1})	4.96^c (24.33)	5.59^c (31.11)	71.85
W4 (Manual spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1})	5.37^b (28.78)	6.06^b (36.79)	67.08
W5 (Weed-free check)	0.71^f (0.00)	0.71^f (0.00)	100.00
W6 (Unweeded check)	9.28^a (86.44)	10.69^a (115.10)	0.00
SEd	0.04	0.05	-
CD (p=0.5)	0.10	0.11	-

Figures in parenthesis are original values which were transformed into $\sqrt{(X+0.5)}$

Yield attributes

Different weed management practices significantly impacted both grain yield and straw yield (Fig. 1). The highest grain yield (5548 kg/ha) and straw yield (7753 kg/ha) were observed in the weed-free check, while the weedy check recorded the lowest yield, with grain yield at 2026 kg/ha and straw yield at 3322 kg/ha. Among herbicide treatments, grain yield ranged from 4593 kg/ha to 5286 kg/ha. Notably, the drone application of pretilachlor followed by bispyribac sodium achieved the highest grain yield (5286 kg/ha) and straw yield (7227 kg/ha).

Correlation study

A strong negative correlation was found between weed dry weight and crop dry matter production (-0.937) (Fig. 2). A similar trend was observed between weed dry weight and grain yield (-0.942), indicating that higher weed dry weight led to lower crop dry matter production and grain yield. Conversely, a strong positive correlation (0.969) existed between crop dry matter production and grain yield.

Energetics

Different weed management practices significantly influenced the energetics of rice cultivation (Table 2). The highest energy input (17897 MJ/ha), energy use efficiency (9.97), and energy productivity (0.31 kg/MJ) were observed in the weed-free plot. Among the herbicide application methods, drone spraying of pretilachlor *fb* bispyribac sodium recorded the highest energy use efficiency (9.53) and energy productivity (0.30 kg/MJ). Additionally, drone-based herbicide application resulted in lower input energy while demonstrating greater energy efficiency and productivity compared to manual spraying (Table 2).

Economics

The cost of herbicide application varied from 5180 to 6229 ₹/ha for drone application and from 5480 to 6529 ₹/ha for manual spraying, indicating a reduced cost for herbicide application (Fig. 3). The higher application charges for manual spraying are attributed to increased labour wages. The highest net returns and BCR were observed in the drone spraying of pretilachlor *fb* bispyribac sodium with values of 51631 ₹/ha and 2.17, respectively. Although the

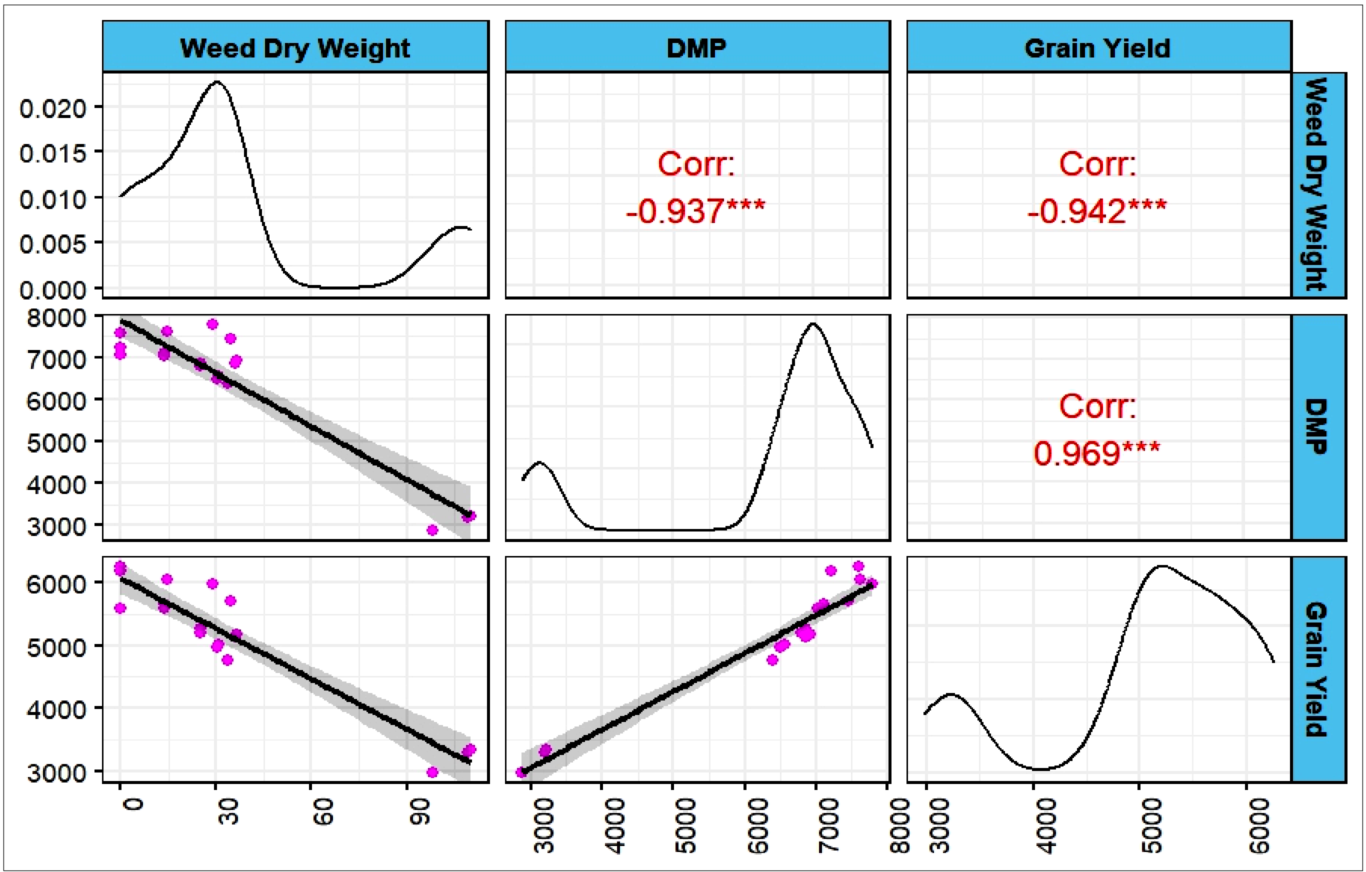

Fig. 2. Correlation between weed dry weight, dry matter production and grain yield (*** indicates corresponding values significant at p=0.01).

Table 2. Effect of different weed management practices on energetics of rice.

Treatments	Input energy (MJ/ha)	Output energy (MJ/ha)	Energy-use efficiency	Energy productivity (kg/MJ)
W1 (Drone spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1})	17648	168038	9.53	0.30
W2 (Drone spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1})	17714	160353	9.06	0.28
W3 (Manual spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1})	17806	153520	8.63	0.26
W4 (Manual spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1})	17873	155043	8.68	0.26
W5 (Weed-free check)	17897	178462	9.97	0.31
W6 (Unweeded check)	17445	71298	4.09	0.12

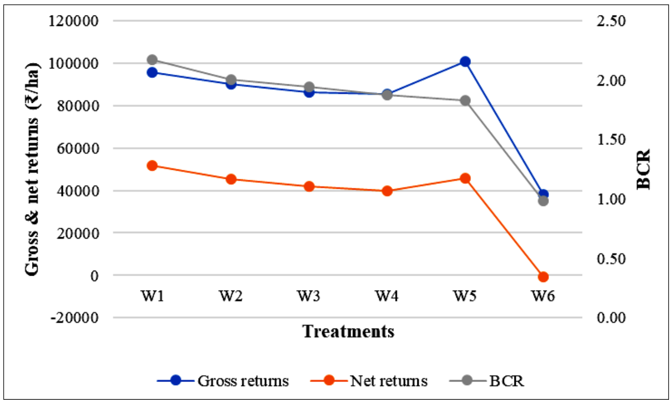

Fig. 3. Economic analysis of weed management practices. **W_1:** Drone spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1}, **W_2:** Drone spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1}, **W_3:** Manual spraying of PE Pretilachlor @ 0.75 kg a.i. ha^{-1} *fb* EPOE Bispyribac sodium @ 25 g a.i. ha^{-1}, **W_4:** Manual spraying of PE Pyrazosulfuron ethyl @ 20 g a.i. ha^{-1} *fb* EPOE Penoxsulam + Cyhalofop butyl @ 135 g a.i. ha^{-1}, **W_5:** Weed-free check, **W_6:** Weedy check

weed-free plot recorded the highest yield (5548 kg/ha) and gross returns (100923 ₹/ha) compared to the other weed management practices, it yielded lower net returns and BCR (45846 ₹/ha, 1.83) due to the higher costs of weeding. The lowest net return (-553 ₹/ha) and BCR (0.99) were found in the unweeded checks, attributable to poor grain and straw yield.

Discussion

The efficacy of pretilachlor in controlling a broad spectrum of weeds during the early stages of wet direct-seeded rice has been well-documented in previous studies (20, 21). Furthermore, another study demonstrated that the sequential application of pretilachlor followed by bispyribac sodium provides superior weed control in transplanted rice systems (22). This suggests that the combination of pretilachlor followed by bispyribac sodium offers enhanced weed suppression. However, the lower weed control efficiency observed with manual spraying can be attributed to inconsistent application of herbicides. Because rice seeds are broadcast across the field, certain patches remain inaccessible to labourers for manual spraying. In contrast, drone spraying provides more effective weed control, as herbicides are applied uniformly with wider coverage and greater droplet deposition, ensuring superior weed suppression (23, 24). The increased efficacy of drone spraying is further enhanced by the rotor downwash effect, which improves herbicide deposition on the abaxial surfaces of weed foliage (25, 26). This uniform coverage and improved deposition underscore the potential of drone spraying as a more efficient and effective weed management strategy in rice cultivation. Similar results have been reported in other studies (27, 28). Correlation studies revealed that weed dry weight negatively influenced crop dry matter production and yield, as weeds compete with crops for nutrients (28, 29).

The higher grain and straw yields observed with drone-based herbicide applications, compared to manual spraying, can be attributed to the superior weed control achieved through drone spraying (27). Drones are also more energy-efficient due to reduced spray volumes and labour requirements, which contribute to increased grain yields. Consequently, the higher energy output, combined with lower energy input, resulted in improved energy use efficiency and energy productivity (30). Additionally, the combination of drone spraying of pretilachlor followed by bispyribac sodium not only yielded higher grain outputs but also reduced cultivation costs, leading to greater net returns and an improved benefit-cost ratio (30).

Conclusion

The study conclusively demonstrated that drone spraying of PE pretilachlor followed by EPOE bispyribac sodium significantly reduces weed density and weed dry weight while achieving the highest grain and straw yields in wet direct-seeded rice (DSR). Additionally, this method recorded the maximum net return, benefit-cost ratio (BCR), and energy use efficiency compared to manual spraying. Therefore, the application of drone spraying of PE pretilachlor followed by EPOE bispyribac sodium is recommended for farmers seeking to enhance productivity and profitability in wet DSR cultivation.

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Authors' contributions

Conceptualization: VRA and SG; Methodology: VRA and SG; Resources: PG, DM and KR; Data :collection: VRA; Investigation: VRA and SG; Formal analysis: VRA and SGP; Writing-original draft: VRA and SG; Visualization: VRA and SGP; Supervision: SG, PG, DM and KR. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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