RESEARCH ARTICLE

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; herbicides; pretilachlor; unmanned aerial vehicles (UAVs); 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 at 0.75 kg active ingredient ha^{-1}, followed by early post-emergence EPOE Bispyribac sodium at 25 g active ingredient ha^{-1},

W_2: Drone spraying of Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1}, followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient ha^{-1},

W_3: Manual spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1}, followed by early post-emergence EPOE Bispyribac sodium at 25 g active ingredient ha^{-1},

W_4: Manual spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1}, followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient 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$_2$O$_5$:K$_2$O 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 earlier described formulae (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 followed by 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.
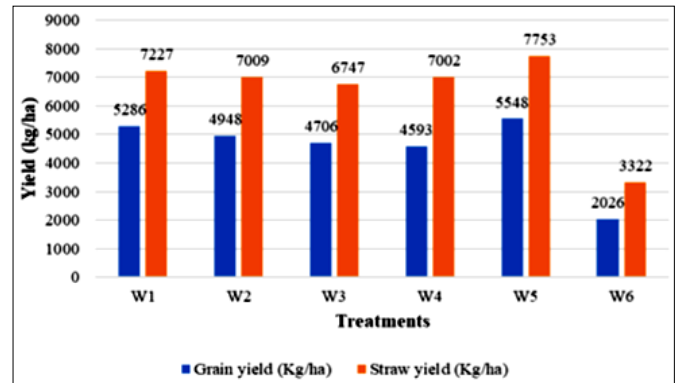

Fig. 1. Effect of different weed management practices on straw and grain yield of rice. W$_1$: Drone spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1} followed by EPOE Bispyribac sodium at 25 g active ingredient ha^{-1}, W$_2$: Drone spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient ha^{-1}, W$_3$: Manual spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1} followed by EPOE Bispyribac sodium at 25 g active ingredient ha^{-1}, W$_4$: Manual spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient 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 at 0.75 kg active ingredient ha^{-1} followed by EPOE	3.35[e] (10.89)	3.77[e] (13.92)	87.51
W2 (Drone spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient ha^{-1})	4.49[d] (19.00)	4.95[d] (24.29)	77.96
W3 (Manual spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1} followed by EPOE	4.96[c] (24.33)	5.59[c] (31.11)	71.85
W4 (Manual spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient 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 followed by 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 followed by bispyribac sodium with values of 51631 ₹/ha and 2.17, respectively. Although the 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
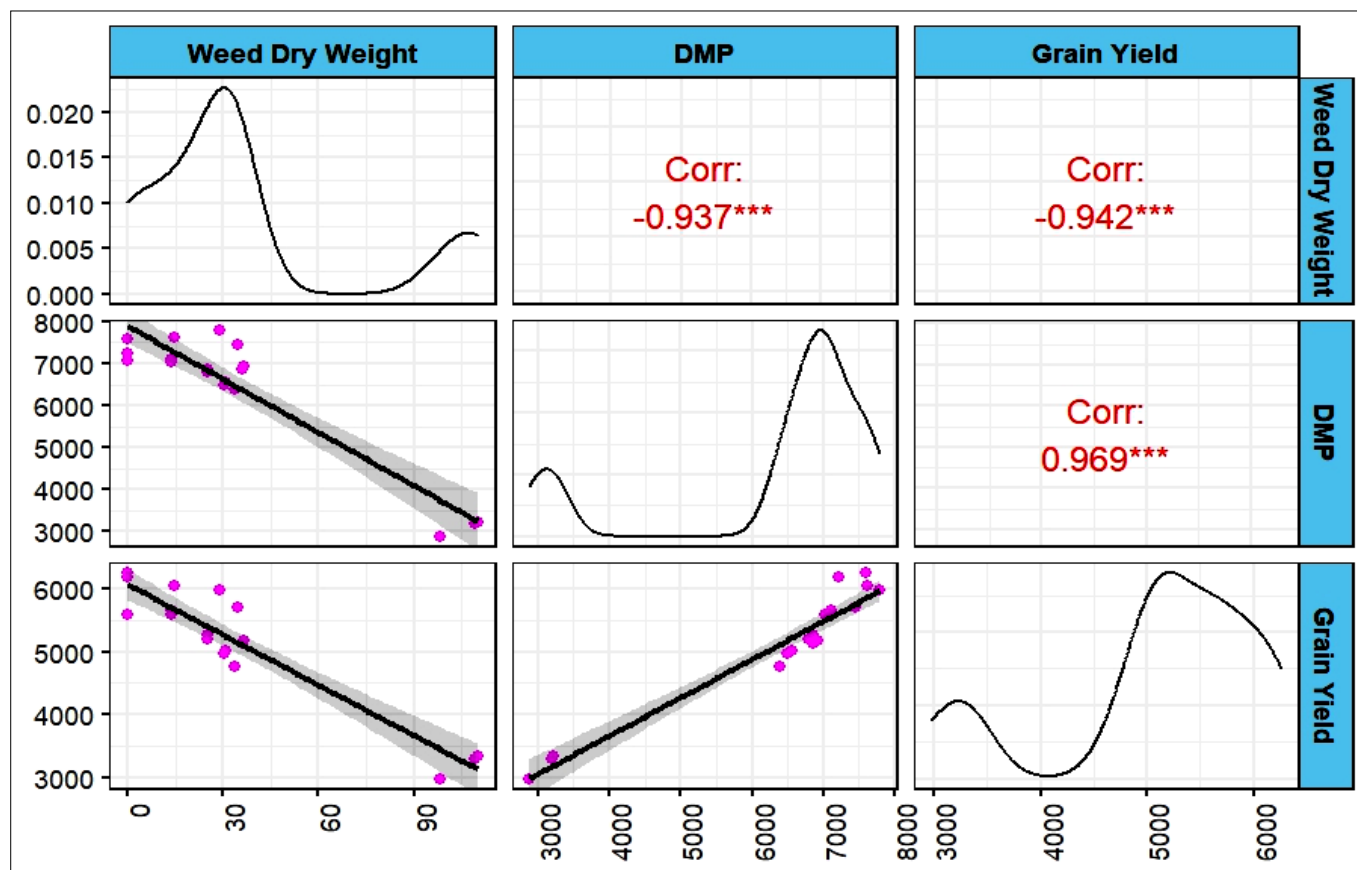
Fig. 2. Correlation between weed dry weight, dry matter production and grain yield (******* indicates corresponding values significant at p=0.01).

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 at 0.75 kg active ingredient ha^{-1} followed by EPOE Bispyribac sodium at 25 g active ingredient ha^{-1})	17648	168038	9.53	0.30
W2 (Drone spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient ha^{-1})	17714	160353	9.06	0.28
W3 (Manual spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1} followed by EPOE Bispyribac sodium at 25 g active ingredient ha^{-1})	17806	153520	8.63	0.26
W4 (Manual spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient 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
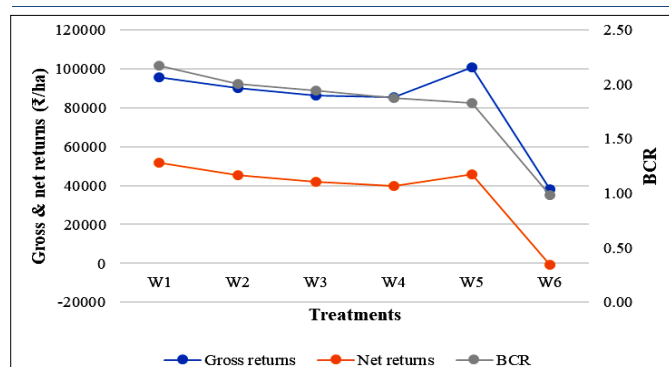
Fig. 3. Economic analysis of weed management practices. W$_1$: Drone spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1} followed by EPOE Bispyribac sodium at 25 g active ingredient ha^{-1}, W$_2$: Drone spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient ha^{-1}, W$_3$: Manual spraying of PE Pretilachlor at 0.75 kg active ingredient ha^{-1} followed by EPOE Bispyribac sodium at 25 g active ingredient ha^{-1}, W$_4$: Manual spraying of PE Pyrazosulfuron ethyl at 20 g active ingredient ha^{-1} followed by EPOE Penoxsulam + Cyhalofop butyl at 135 g active ingredient ha^{-1}, W$_5$: Weed-free check, W$_6$: Weedy check.

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 con-

trol 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.

Acknowledgements

Authors' contributions

VRA and SKG conceptualized the study, while VRA and SKG also developed the methodology. The resources were provided by PG, DM and KR. Data collection was conducted by VRA, followed by investigation efforts from both VRA and SKG. The formal analysis was carried out by VRA and SGP. The writing of the original draft involved contributions from VRA and SKG, with visualization tasks handled by VRA and SGP. Finally, supervision was provided by SKG, 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

References

1. Xu Y, Chu C, Yao S. The impact of high-temperature stress on rice: Challenges and solutions. Crop J. 2021;9(5):963-76. https://doi.org/10.1016/j.cj.2021.02.011

2. Fukagawa NK, Ziska LH. Rice: Importance for global nutrition. J Nutr Sci Vitaminol. 2019;65(Supplement):S2–S3. https://doi.org/10.3177/jnsv.65.S2

3. Fahad S, Adnan M, Noor M, Arif M, Alam M, Khan IA, et al. Chapter 1 - Major constraints for global rice production. In: Hasanuzzaman M, Fujita M, Nahar K, Biswas JK, editors. Advances in rice research for abiotic stress tolerance [Internet]. Woodhead Publishing; 2019 [cited 2024 Jul 14]. p. 1-22.

4. Prasad R, Shivay YS, Kumar D. Current status, challenges and opportunities in rice production. 2017 [cited 2024 Jul 14].

5. Susilawati HL, Setyanto P, Kartikawati R, Sutriadi MT. The opportunity of direct seeding to mitigate greenhouse gas emission from paddy rice field. IOP Conf Ser: Earth Environ Sci. 2019;393(1):012042.

6. Xu L, Li X, Wang X, Xiong D, Wang F. Comparing the grain yields of direct-seeded and transplanted rice: A meta-analysis. Agronomy. 2019;9(11):767. https://doi.org/10.3390/agronomy9110767

7. Farooq M, Siddique KHM, Rehman H, Aziz T, Lee DJ, Wahid A. Rice direct seeding: Experiences, challenges and opportunities. Soil Till Res. 2011;111(2):87-98. https://doi.org/10.1016/j.still.2010.10.008

8. Singh VP, Singh SP, Dhyani VC, Banga A, Kumar A, Satyawali K, et al. Weed management in direct-seeded rice. Ind Jour Weed Scie. 2016;48(3):233. https://doi.org/10.5958/0974-8164.2016.00059.9

9. Chamani Mohasses F, Mousavi Pakzad SM, Moatamed E, Entesari M, Bidadi H, Molaahmad Nalousi A, et al. Efficient genetic transformation of rice using *Agrobacterium* with a codon-optimized chromoprotein reporter gene (ChromoP) and introducing an optimized iPCR method for transgene integration site detection. PCTOC. 2023;156(1):1-14. https://doi.org/10.1007/s11240-023-02636-x

10. Das TK, Behera B, Nath CP, Ghosh S, Sen S, Raj R, et al. Herbicides use in crop production: An analysis of cost-benefit, non-target toxicities and environmental risks. Crop Prot. 2024;181:106691. https://doi.org/10.1016/j.cropro.2024.106691

11. Paul RAI, Arthanari PM, Pazhanivelan S, Kavitha R, Djanaguiraman M. UAV-based herbicide application for efficient weed management in direct-seeded rice. ASD [Internet]. 2023 [cited 2024 Apr 17].

12. Damalas CA, Koutroubas SD. Farmers' exposure to pesticides: Toxicity types and ways of prevention. Toxics. 2016;4(1):1. https://doi.org/10.3390/toxics4010001

13. Meesaragandla S, Jagtap MP, Khatri N, Madan H, Vadduri AA. Herbicide spraying and weed identification using drone technology in modern farms: A comprehensive review. RINENG. 2024;21:101870. https://doi.org/10.1016/j.rineng.2024.101870

14. Nobre FLDL, Santos RF, Herrera JL, Araújo ALD, Johann JA, Gurgacz F, et al. Use of drones in herbicide spot spraying: A systematic review. AWS. 2023;41:e020230014. https://doi.org/10.51694/AdvWeedSci/2023;41:00028

15. Mani VS, Gautam KC, Dass B, Singh YR. Integrated weed management for sustainable agriculture. In: Proceedings of 3rd All India Weed Control Seminar, Ind Jour Weed Scie. 1973.

16. Devasenapathy P, Senthilkumar G, Shanmugam PM. Energy management in crop production. IJA. 2009;54(1):80-90. https://doi.org/10.59797/ija.v54i1.4771

17. S Murthy RS, Elangovan S, Arunachalam P. Energy auditing in crop production. 2020; p. 137-88.

18. Singh R, Pande K, Sachan VK, Singh N, Sahu RP, Singh M. Productivity, profitability and energy consumption of potato based intercropping systems. Int J Veg Sci. 2015;22. https://doi.org/10.1080/19315260.2014.1003632

19. Gomez KA, Gomez AA. Statistical procedures for agricultural research [Internet]. John Wiley and Sons. 1984 [cited 2024 May 26].

20. Chauhan BS, Ngoc STT, Duong D, Ngoc PL. Effect of pretilachlor on weedy rice and other weeds in wet-seeded rice cultivation in South Vietnam. Plant Prod Sci. 2014;17(4):315-20. https://doi.org/10.1626/pps.17.315

21. Sahu R, Kumar D, Sahu J, Sharda K, Sohane R. Bio-efficacy of pre and post-emergence herbicides for control of complex weed flora in transplanted rice (*Oryza sativa* L.). Int J Chem Stud. 2020;8:2348-51. https://doi.org/10.22271/chemi.2020.v8.i2aj.9100

22. Kanaujiya PK, Singh R, Kumar P, Maurya NK, Kumar P, Kumar A, et al. Efficacy of various herbicide combinations on yield, its attributes and economics of transplanted rice in Indo Gangetic plain zone (*Oryza sativa* L.). Int J Chem Stud. 2021;9(2):519-22. https://doi.org/10.22271/chemi.2021.v9.i2h.11872

23. Ramesh T, Madhusree S, Rathika S, Meena S, Raja K. Drone based herbicide application in greengram (*Vigna radiata*). Indian J Agric Sci. 2024;94(3):329-32. https://doi.org/10.56093/ijas.v94i3.144541

24. Ray J. Exploring agriculture in the age of drones: A comprehensive review. Afr J Biol Sci. 2024;6:216-29.

25. Mehdizadeh M, Al-Taey D, Omidi A, Hadi A, Abbood Y, Askar S, et al. Advancing agriculture with machine learning: A new frontier in weed management. Front Agric Sci Eng. 2024. https://doi.org/10.15302/J-FASE-2024564

26. Martin D, Singh V, Latheef MA, Bagavathiannan M. Spray deposition on weeds (palmer amaranth and morning glory) from a remotely piloted aerial application system and backpack sprayer. Drones. 2020;4(3):59. https://doi.org/10.3390/drones4030059

27. Zhang K, Chen J, Wang C, Han L, Shang Z, Wang G, et al. Evaluation of herbicides aerially applied from a small unmanned aerial vehicle over wheat field. IJPAA. [Internet]. 2020 [cited 2024 Apr 16];3(1).

28. Tursun N, Datta A, Sakinmaz MS, Kantarci Z, Knezevic SZ, Chauhan BS. The critical period for weed control in three corn (*Zea mays* L.) types. Crop Protection. 2016;90:59-65. https://doi.org/10.1016/j.cropro.2016.08.019

29. Walia S, Banerjee T, Kumar R. Efficacy of weed management techniques on weed control, biomass yield and soil herbicide residue in transplanted wild marigold (*Tagetes minuta* L.) under high rainfall conditions of Western Himalaya. Agronomy. 2021;11(11):2119. https://doi.org/10.3390/agronomy11112119

30. Paul RAI, Arthanari PM, Pazhanivelan S, Kavitha R, Djanaguiraman M. Drone-based herbicide application for energy saving, higher weed control and economics in direct-seeded rice (*Oryza sativa*). Indian J Agric Sci. 2023;93(7):704-09. https://doi.org/10.56093/ijas.v93i7.137859