PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.5980

eISSN 2348-1900

RESEARCH ARTICLE

Comparison of economics, energy budgeting and carbon footprint of unmanned aerial vehicle and knapsack-based weed management practices in dry direct-seeded rice

Aroulradj Karthickraja[1], Pasoubady Saravanane[1*], Poonguzhalan Ramadoss[1] & Nadaradjan Subbarayan[2]

[1]Department of Agronomy, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609603, Puducherry, India
[2]Department of Plant Breeding & Genetics, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609603, Puducherry, India

*Correspondence email - psaravanane@pajancoa.ac.in

Received: 19 October 2024; Accepted: 05 March 2025; Available online: Version 1.0: 25 June 2025

Cite this article: Aroulradj K, Pasoubady S, Poonguzhalan R, Nadaradjan S. Comparison of economics, energy budgeting and carbon footprint of unmanned aerial vehicle and knapsack-based weed management practices in dry direct-seeded rice. Plant Science Today (Early Access). https://doi.org/10.14719/pst.5980

Abstract

A field experiment assessed the knowledge gap in economic, energetics and carbon dynamics of Unmanned Aerial Vehicle and knapsack-based herbicide applications in dry direct-seeded rice. Twelve treatments were arranged in a randomized block design replicated thrice with varying UAV spray volumes (25, 50, 75 and 100 L ha^{-1}) and knapsack spray volume of 500 L ha^{-1} at 75 % HRD (pendimethalin + penoxsulam on 3 DAS at 468.8 g ha^{-1} *fb* bispyribac-sodium on 20 DAS at 18.8 g ha^{-1}) and 100 % HRD (pendimethalin + penoxsulam on 3 DAS at 625 g ha^{-1} *fb* bispyribac-sodium on 20 DAS at 25 g ha^{-1}), along with hand weeding twice and unweeded control. Results showed that UAV spray volume at 50 L ha^{-1} with 100 % HRD was significant over other weed management practices by higher grain yield (3866.0 kg ha^{-1}), higher NPK nutrient uptake (105.4, 21.7 and 130.8 kg ha^{-1}), higher B:C ratio (2.13), improved energy efficiency (11.58), higher energy profitability (10.58 kg MJ^{-1}), higher carbon sustainability index (18.4) and lower carbon emission (0.064 kg CO_2 eq. kg^{-1} yield). Therefore, UAV spray at 50 L ha^{-1} of pendimethalin + penoxsulam on 3 DAS at 625 g ha^{-1} *fb* bispyribac-sodium on 20 DAS at 25 g ha^{-1} (100 % HRD) is recommended for DDSR cultivating farmers in the coastal deltaic ecosystem of South India.

Keywords: carbon emission; dry direct-seeded rice; economic analysis; energy budgeting

Introduction

Rice (*Oryza sativa* L.) is a key staple crop, feeding billions worldwide. Traditional rice-growing methods, such as transplanting seedlings into flooded fields, require approximately 2500 - 3000 L of water to produce 1 kg of rice (1, 2). Manual transplanting increases labour costs by 25 - 30 %, increases energy due to fuel kg use in water pumping by machinery operation and emits higher greenhouse gas (GHG), mainly methane (1). Farmers increasingly adopt dry direct-seeded rice (DDSR) to overcome these challenges, where seeds are sown directly into the field without prior transplanting. This approach significantly conserves water by eliminating the need for continuous flooding by 30 - 50 %, reduces labour dependency, operational costs and minimizes energy consumption. Moreover, DDSR is crucial in lowering GHG emissions, mainly methane, making it a more sustainable alternative to traditional puddled transplanting. DDSR is emerging as a climate-smart solution for modern rice cultivation, enabling faster crop establishment and enhancing resource efficiency.

However, DDSR introduces challenges, particularly with weed management. Weeds compete with rice plants for nutrients, light and space, reducing yields if not controlled (3). Farmers traditionally used knapsack sprayers to apply herbicides manually, but this method is time-consuming, labour-intensive and may not provide uniform coverage. So, using Unmanned Aerial Vehicles (UAVs) for spraying herbicides has offered a better alternative, covering large areas faster, using less water and applying herbicides more precisely, leading to better weed control and higher yields (4). Many researchers suggest reducing herbicide doses in UAV applications to improve efficiency and reduce environmental impact (4, 5). However, more studies are needed in DDSR to fill this research gap.

Beyond weed control, it is essential to consider UAVs' cost, energy use and environmental impact compared to knapsack sprayers. While UAVs may improve weed control, evaluating their economic viability, energy efficiency and environmental sustainability is crucial. Most studies have focused on the immediate agronomic benefits like enhanced weed control, increased yield, economics and energetics, leaving a gap in understanding the broader sustainability aspects of carbon emission in coastal areas.

Economic indicators like net returns, benefit-cost ratio and return on investment assess the financial sustainability of UAV use (5). Energy efficiency and productivity evaluate energy consumption, while greenhouse gas emissions and carbon sequestration help determine UAV-based weed management's environmental impact (6). This research aims to study the knowledge gap and the objectives of the study by analyzing the economic returns, energy dynamics and carbon impact of UAV-based weed management compared to traditional methods in DDSR. This study will promote more sustainable and economically viable UAV-based weed management practices in DDSR by addressing these objectives.

Materials and methods

Experimental site and conditions

A field experiment was conducted during February - June 2023 at the eastern research farm of Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, Puducherry Union Territory (UT), India (10° 55′ N latitude and 79° 49′ E longitude, 4 m above mean sea level). The climate is tropical. During the cropping season, the mean minimum temperature was 24.1 °C and the mean maximum temperature was 32.9 °C. The soil at the experimental field was sandy clay loam with a neutral pH (6.61), low available nitrogen (141.1 kg ha^{-1}), high available phosphorus (31.8 kg ha^{-1}) and medium available potassium (188.8 kg ha^{-1}).

Experimental design and treatments

The experiment was conducted in a randomized block design (RBD) replicated thrice with 12 treatments to assess the effectiveness of economics, energy and carbon dynamics of UAV and knapsack sprayers in DDSR. The treatments from T_1 to T_8 involved UAV spray with different spray volumes and herbicide concentrations. T_1 and T_2 used a spray volume of 25 L ha^{-1}, with T_1 applying 75 % of the herbicide recommended dose (HRD) (pendimethalin + penoxsulam on 3 days after sowing (DAS) at 468.8 g ha^{-1} *bf* bispyribac-sodium on 20 DAS at 18.8 g ha^{-1}) and T_2 applying 100 % HRD (pendimethalin + penoxsulam on 3 DAS at 625 g ha^{-1} *fb* bispyribac-sodium on 20 DAS at 25 g ha^{-1}). T_3 and T_4 used a spray volume of 50 L ha^{-1}, with T_3 applying 75 % HRD and T_4 applying 100 % HRD. T_5 and T_6 used 75 L ha^{-1}, with T_5 applying 75 % HRD and T_6 applying 100 % HRD. T_7 and T_8 had a spray volume of 100 L ha^{-1}, with T_7 applying 75 % HRD and T_8 applying 100 % HRD. Treatments T_9 and T_{10} used a traditional manual knapsack sprayer with a recommended spray volume of 500 L ha^{-1}. T_9 applied 75 % HRD and T_{10} applied 100 % HRD. Then, T_{11} involved hand weeding twice at 20 and 40 DAS and T_{12} was left unweeded as the control.

Crop management

Rice cultivar 'ASD 16' (110 days duration) was sown at 75 kg ha^{-1} with a spacing of 15 cm × 10 cm in the 4th week of February 2024. Field preparation involved 2 tractor ploughings and a leveller to ensure uniform water distribution. The gross plot size was 12 m × 3.9 m. The crop was harvested in the fourth week of June from the net plot area of 11.6 m × 3.3 m. After threshing, cleaning and drying to 14 %, the grain yield was recorded and converted to kg ha^{-1} to satisfy the objectives.

Economics

After the harvest, an economic analysis was performed to evaluate the financial viability of each treatment. The cost of cultivation for each treatment was calculated by adding standard and treatment-specific costs. Gross return (GR) was estimated using market prices of rice grain (₹ 19.4 kg^{-1}) and straw (₹ 2.0 kg^{-1}). To evaluate the economic viability of the UAV-based treatments, key financial indicators such as gross return (GR), net return (NR), payback period (PP), net profit margin (NPM), benefit-cost ratio (BCR) and return on investment (ROI) were calculated using standard methodologies (5).

$$\text{GR}(₹\ ha^{-1}) = [\text{Grain yield }(kg\ ha^{-1}) \times \text{Cost of one kg grain}(₹\ kg^{-1})] + [\text{Straw yield }(kg\ ha^{-1}) \times \text{Cost of one kg straw }(₹\ kg^{-1})] \quad \text{(Eqn. 1)}$$

$$\text{NR}(₹\ ha^{-1}) = [\text{Gross return}(₹\ ha^{-1}) - \text{Cost of cultivation}(₹\ ha^{-1}) \quad \text{(Eqn. 2)}$$

$$\text{Payback period (years)} = \frac{\text{Cost of cultivation}(₹\ ha^{-1})}{\text{Net return }(₹\ ha^{-1})} \quad \text{(Eqn. 3)}$$

$$\text{Net profit margin} = \frac{\text{Net return}(₹\ ha^{-1})}{\text{Gross return }(₹\ ha^{-1})} \quad \text{(Eqn. 4)}$$

$$\text{Benefit cost ratio} = \frac{\text{Gross return }(₹\ ha^{-1})}{\text{Cost of cultivation}(₹\ ha^{-1})} \quad \text{(Eqn. 5)}$$

$$\text{ROI} = \frac{\text{Net return }(₹\ ha^{-1})}{\text{Cost of investment}(₹\ ha^{-1})} \times 100 \quad \text{(Eqn. 6)}$$

Energy budgeting

In addition to economic viability, the energy dynamics of the treatments are essential for understanding their sustainability. Energy budgeting for UAV-based weed management in DDSR was calculated using standard energy equivalents (Table 1) for different inputs and operations (7). Key inputs included labour, machinery, diesel, fertilizers, seeds and herbicides, while, grain and straw yield was considered as outputs. To assess the energy dynamics of the UAV-based treatment, key energy metrics such as energy output, net energy, energy use efficiency, energy productivity, energy intensiveness, energy profitability, specific energy and energy payback time were calculated. These energy indices were computed using the equations (8, 9).

Table 1. Energy equivalents of different energy inputs in DDDR

Sl. No.	Inputs	Units	Equivalent energy (MJ)
1.	Human labour		
i)	Adult man	h	1.96
ii)	Adult woman	h	1.57
2.	Diesel	L	56.31
3.	Farm machinery	kg	62.70
4.	Fertilizers		
i)	Nitrogen	kg	60.60
ii)	Phosphorus	kg	11.10
iii)	Potassium	kg	6.70
5.	Herbicides	kg	102.00
6.	Seeds and rice grain	kg	14.70
7.	Rice straw	kg	12.50

Energy output =

$$[\text{Grain yield (kg ha}^{-1}) \times \text{Equivalent yield of grain (kg)}] + [\text{Straw yield (kg ha}^{-1}) \times \text{Equivalent energy of straw (kg)}] \quad \text{(Eqn. 7)}$$

Net energy =

$$\text{Energy output (MJ ha}^{-1}\text{)} - \text{Energy input (MJ ha}^{-1}) \quad \text{(Eqn. 8)}$$

$$\text{Energy use efficiency (ratio)} = \frac{\text{Energy output (MJ ha}^{-1}}{\text{Energy input (MJ ha}^{-1})} \quad \text{(Eqn. 9)}$$

$$\text{Energy Productivity} = \frac{\text{Output (Grain yield) kg ha}^{-1}}{\text{Energy input (MJ ha}^{-1})} \quad \text{(Eqn. 10)}$$

$$\text{Energy intensiveness} = \frac{\text{Energy input (MJ ha}^{-1})}{\text{Total cost of cultivation (Rs. ha}^{-1}} \quad \text{(Eqn. 11)}$$

$$\text{Energy Profitability} = \frac{\text{Net energy output (MJ ha}^{-1})}{\text{Input energy (MJ ha}^{-1})} \quad \text{(Eqn. 12)}$$

$$\text{Specific energy MJ kg ha}^{-1} = \frac{\text{Energy input (MJ ha}^{-1})}{\text{Grain yield kg ha}^{-1}} \quad \text{(Eqn. 13)}$$

$$\text{Energy payback time (years)} = \frac{\text{Energy input (MJ ha}^{-1})}{\text{Net energy (MJ ha}^{-1})} \quad \text{(Eqn. 14)}$$

Carbon dynamics

An examination of carbon dynamics was performed to evaluate the environmental impact of each treatment. Greenhouse gas (GHG) emissions from various inputs were calculated using coefficients and expressed in CO_2-equivalents per hectare (10, 11). Carbon input was derived from total GHG emissions (Table 2), while carbon output was estimated from total biomass production. For UAV-based treatments, key indicators such as the carbon sustainability index, carbon efficiency ratio and carbon footprint per unit yield were calculated using the described methods (12).

Table 2. Carbon dynamics of different inputs used in a rice production system

Sl. No.	Particulars	Units	GHG coefficients (kg CO_2 eq. unit^{-1})
1.	Diesel	L	0.94
2.	Machinery	h	0.071
3.	Nitrogen	kg	1.3
4.	Phosphorus	kg	0.2
5.	Potassium	kg	0.15
6.	Herbicide	kg a.i.	6.3
7.	Straw	kg	0.44
8.	Seeds	kg	0.32
9.	Human labour	man day	0.23

$$\text{Carbon output} = \text{Grain yield} + \text{Straw yield} \times 0.44 \quad \text{(Eqn. 15)}$$

Carbon sustainability index =

$$\frac{\text{C output - C input}}{\text{C input}} \quad \text{(Eqn. 16)}$$

$$\text{Carbon efficiency ratio} = \frac{\text{C output}}{\text{C input}} \quad \text{(Eqn. 17)}$$

$$\text{Carbon footprints or estimated average GHG emissions kg CO}_2\text{ eq. kg}^{-1}\text{ grain} = \frac{\text{C input}}{\text{Grain yield}} \quad \text{(Eqn. 18)}$$

Statistical analysis

Analysis of variance (ANOVA) was performed on the grain yield, straw yield and NPK uptake to assess the effectiveness of weed management practices in DDSR, revealing significant differences among treatment means. Multiple comparisons were conducted using Duncan's Multiple Range Test (DMRT) and Tukey's test. The significance level was set at $P \leq 0.05$ and DMRT was used to categorize the means of different sprayers into distinct groups, which were analyzed using the R software platform (13, 14).

Results and Discussions

Yield and nutrient uptake of DDSR

The UAV and knapsack spray weed management practices in DDSR significantly impacted grain and straw yield (Table 3). The higher grain and straw yields were recorded in UAV spray of 50 L ha^{-1} with 100 % of HRD (T_4) (Fig. 1a), which yielded 3866.0 kg ha^{-1} and 7014.0 kg ha^{-1} and it was on par with T_2 (3655.0 kg ha^{-1} and 6731.0 kg ha^{-1}). This suggests that UAV-based treatments, mainly T_4 had effective weed control and better resource allocation through precise and uniform herbicide application, resulting in higher yields. Higher grain and straw yield production was due to better partitioning of photosynthates from source to sink due to reduced weed competition and improved crop growth that led to grain formation. A similar result was reported earlier (15). Another possible reason might be due to lower spray volume, which increased the herbicide concentration and enhanced weed control. According to another study, the lower spray volumes could boost the herbicide effectiveness due to higher concentrations (16). Increasing the spray volume to 75, 100 and 500 L ha^{-1} reduced grain and straw yield (2818.0 kg ha^{-1} - 3216.0 kg ha^{-1} and 6135.0 kg ha^{-1} - 6408.0 kg ha^{-1}) due to diluted herbicide concentrations (Fig. 1b). Similarly, scientists reported that diluted herbicides could negatively affect the yield due to reduced concentration (17). In contrast, lower grain and straw yield was observed in unweeded control (T_{12})(Fig. 1c) (1332.0 kg ha^{-1} and 3176.0 kg ha^{-1}), significantly lower than the other treatments due to poor weed control in T_{12}, leading to increased competition for nutrients, water and light made limited nutrient availability for crop growth.

The uptake of nitrogen (N), phosphorus (P) and potassium (K) was also significantly influenced by UAV and

Table 3. Yield and nutrient uptake of UAV and knapsack weed management options for DDSR

	Treatments	**Grain yield (kg ha^{-1})**	**Straw yield (kg ha^{-1})**	**Nitrogen (kg ha^{-1})**	**Phosphorous (kg ha^{-1})**	**Potassium (kg ha^{-1})**
T_1	UAV spray of 25 L ha^{-1} with 75 % of HRD	3387.0^{abcd}	6550.0^{ab}	95.0^{ab}	18.7^{abcde}	120.9^{ab}
T_2	UAV spray of 25 L ha^{-1} with 100 % of HRD	3655.0^{ab}	6731.0^{a}	96.4^{ab}	20.5^{abc}	119.7^{ab}
T_3	UAV spray of 50 L ha^{-1} with 75 % of HRD	3403.0^{abc}	6723.0^{a}	98.5^{ab}	21.4^{ab}	124.3^{ab}
T_4	UAV spray of 50 L ha^{-1} with 100 % of HRD	3866.0^{a}	7014.0^{a}	105.4^{a}	21.7^{a}	130.8^{a}
T_5	UAV spray of 75 L ha^{-1} with 75 % of HRD	2924.0^{cde}	6334.0^{b}	88.6^{abc}	17.6^{bcde}	84.3^{cd}
T_6	UAV spray of 75 L ha^{-1} with 100 % of HRD	3216.0b^{cde}	6408.0^{b}	92.4^{ab}	18.3^{abcde}	94.9^{cd}
T_7	UAV spray of 100 L ha^{-1} with 75 % of HRD	2827.0^{de}	6141.0^{b}	89.6^{abc}	17.0^{cde}	79.5^{d}
T_8	UAV spray of 100 L ha^{-1} with 100 % of HRD	3119.0^{bcde}	6355.0^{b}	94.4^{ab}	19.0^{abcd}	120.0^{ab}
T_9	Knapsack spray of 500 L ha^{-1} with 75 % of HRD	2818.0^{e}	6135.0^{b}	84.1^{bc}	16.5^{de}	76.3^{d}
T_{10}	Knapsack spray of 500 L ha^{-1} with 100 % of HRD	2916.0^{cde}	6310.0^{b}	93.3^{ab}	19.3^{abcd}	123.7^{ab}
T_{11}	Hand weeding twice at 20 and 40 DAS	2705.0^{e}	5929.0^{b}	88.4^{abc}	19.5^{abcd}	105.4^{bc}
T_{12}	Unweeded control	1332.0^{f}	3176.0^{c}	72.8^{c}	15.1^{e}	67.2^{d}
	S.Ed	156.1	353.08	5.33	1.09	5.99
	CD ($P \leq 0.05$)	323.7	732.3	11.1	2.3	12.4

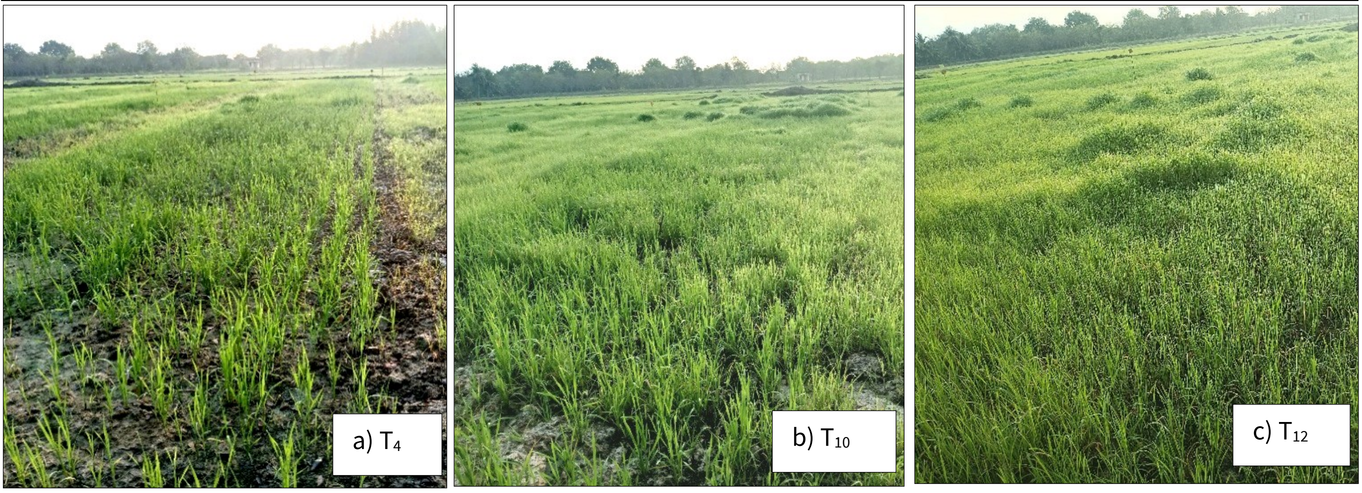

Fig. 1. Effect of different weed management treatments on crop growth in DDSR. (a) UAV spray (T_4), (b) Knapsack spray (T_{10}) and (c) Unweeded control (T_{12}).

knapsack spray weed management practices in DDSR (Table 3). The higher NPK uptake (105.4 kg ha^{-1}, 21.7 kg ha^{-1} and 130.8 kg ha^{-1} was found in the UAV spray of 50 L ha^{-1} with 100 % of HRD (T_4) and it was on par with UAV spray of 50 L ha^{-1} with 75 % HRD (T_3), 25 L ha^{-1} with 75 % HRD and 100% of HRD (T_1 and T_2), which showed 6 % to 8 % loss in NPK uptake. Increasing spray volume to 75, 100 and 500 L ha^{-1} showed 19.2 % loss in NPK uptake in DDSR. This indicated that UAV-based treatments, particularly T_4, enhanced nitrogen assimilation, phosphorus and potassium transformation due to reduced weed competition, allowing for better nutrient availability. Similarly, herbicide use significantly reduced the weed density and dry matter, increasing crop NPK uptake (18). In contrast, lower NPK uptake was observed in the unweeded control (T_{12}) (72.8 kg ha^{-1}, 15.1 kg ha^{-1} and 67.2 kg ha^{-1}), significantly lower than other treatments. This may again be due to poor weed control in T_{12}, leading to increased competition for nutrients, water and light, limited nutrient availability for crop growth.

Economic analysis of UAV and knapsack spray

The economic analysis of UAV and knapsack weed management options in DDSR revealed significant variations in profitability across treatments (Table 4). Among the treatments, UAV spray of 50 L ha^{-1} with 100 % HRD (T_4) recorded higher gross returns of ₹ 89028 and net returns of ₹ 47184, with a benefit-cost (B:C) ratio of 2.13. This treatment was more profitable due to its precision, resulting in better weed control and higher yields. The total cost of cultivation for T_4 was ₹ 41844, resulting in a return on investment of 4.8 and a net profit margin (NPM) of 53.0 %. This was aligned with the previous findings (15). The UAV spray of 25 L ha^{-1} with 100 % HRD (T_2) showed a slight decrease in gross returns (₹ 84369), net returns (₹ 43525), TCOC (₹ 40844), ROI (4.4) and NPM (51.6 %), compared to 50 L ha^{-1}, but still maintained economic viability due to higher herbicide concentration, which ensured effective weed control and profitability. However, increasing the UAV spray volume to 75 L ha^{-1} (T_5 and T_6) and 100 L ha^{-1} (T_7 and T_8) reduced the B:C ratio from 1.58 - 1.68. The TCOC for these treatments ranged from ₹ 41400 - ₹ 43844 and the ROI decreased from 2.5 - 3.3, with NPM ranging from 36.8 % - 43.0 %. This reduction was due to lower herbicide concentrations, which led to less effective weed control. This allowed weeds to compete with crops for nutrients, water and sunlight, reducing overall yield (18). Higher spray volumes in UAV applications increased battery consumption, requiring more frequent recharging, raising operational costs and higher technician labour cost. A scientist from a previous study reported that the higher spray volumes increased battery usage and technician costs (19). The knapsack spray of 500 L ha^{-1} (T_9 and T_{10}) had a lower B:C ratio (1.67), compared to T_4, mainly due to its labour-intensive process (Fig. 1b). The need for manual effort, frequent refilling and longer spraying time increased costs and

Table 4. Economic analysis of UAV and knapsack weed management options for DDSR

T	COC	TCOC	Gross returns	Net returns	ROI	PP	NPM	B:C ratio
T_1	34069	39400	78808	39408	4.0	1.00	50.0	2.00
T_2	34069	40844	84369	43525	4.4	0.94	51.6	2.07
T_3	34069	40400	79524	39124	4.0	1.03	49.2	1.97
T_4	34069	41844	89028	47184	4.8	0.89	53.0	2.13
T_5	34069	41400	69394	27994	2.8	1.48	40.3	1.68
T_6	34069	42844	75206	32362	3.3	1.32	43.0	1.76
T_7	34069	42400	67126	24726	2.5	1.71	36.8	1.58
T_8	34069	43844	73219	29375	3.0	1.49	40.1	1.67
T_9	34069	40104	66939	26835	4.2	1.49	40.1	1.67
T_{10}	34069	41548	69190	27642	4.3	1.50	40.0	1.67
T_{11}	34069	43069	64335	21266	3.3	2.03	33.1	1.49
T_{12}	34069	34069	32193	-1876	-0.3	-18.16	-5.8	0.94

T - Treatments; COC - Cost of cultivation; TCOC - Total cost of cultivation; ROI - Return on investment; PP - Payback period; NPM - Net profit margin T_1: UAV spray of 25 L ha^{-1} with 75 % of HRD; T_2: UAV spray of 25 L ha^{-1} with 100 % of HRD; T_3: UAV spray of 50 L ha^{-1} with 75 % of HRD; T_4: UAV spray of 50 L ha^{-1} with 100 % of HRD; T_5: UAV spray of 75 L ha^{-1} with 75 % of HRD; T_6: UAV spray of 75 L ha^{-1} with 100 % of HRD; T_7: UAV spray of 100 L ha^{-1} with 75 % of HRD; T_8: UAV spray of 100 L ha^{-1} with 100 % of HRD; T_9: Knapsack spray of 500 L ha^{-1} with 75 % of HRD; T_{10}: Knapsack spray of 500 L ha^{-1} with 100 % of HRD; T_{11}: Hand weeding twice at 20 and 40 DAS; T_{12}: Unweeded control.

decreased economic efficiency (20). The TCOC for T_9 and T_{10} was ₹ 40104 and ₹ 41548, respectively, with an ROI of 4.2 and 4.3 and an NPM of 40.1 % and 40.0 %. Hand weeding (T_{11}) resulted lower gross return (₹ 64335) and net returns (₹ 21266) compared to T_4. The TCOC was ₹ 43069, leading to a reduced ROI of 3.3 and an NPM of 33.1 %. This highlighted its inefficiency in modern DDSR practices where labour costs and time are critical factors. Another study has also reported that the higher cost of hand weeding alone reduced its financial viability (15, 20). The unweeded control (T_{12}) led to economic losses, with a gross return ₹ 32193 and a negative net return of ₹ -1876. The cost of cultivation was ₹ 34069, resulting in an ROI of -0.3 and an NPM of -5.8 %, confirming the economic disadvantage of not implementing weed management in DDSR (Fig. 1c) (21).

Energetics of UAV and knapsack spray

The energy analysis of UAV and knapsack spray in DDSR showed significant differences in efficiency among the treatments (Table 5). The UAV spray at 50 L ha^{-1} with 100 % HRD (T_4) was more efficient, with higher output energy (OE) of 144505 MJ ha^{-1} and net energy (NE) of 132022 MJ ha^{-1}, leading to 5.2 % increase in OE and a 10.7 % increase in NE as compared to the UAV spray at 25 L ha^{-1} with 100 % HRD (T_2). The IE for T_4 was 12483 MJ ha^{-1} and the EI was 0.30 MJ ₹$^{-1}$, indicating its ability to generate higher output relative to input energy. The energy use efficiency (EUE) of T_4 was also higher (11.58) by utilizing energy more effectively, which led to better weed control and higher yields. These results align with the previous findings (22). T_4 also had higher energy profitability (EPF) (10.58 kg MJ^{-1}), meaning it produced more grain yield per unit of energy (23). However, when the UAV spray volume increased to 75 L ha^{-1} (T_5 and T_6) and 100 L ha^{-1} (T_7 and T_8), the energy use efficiency dropped from 10.2 - 9.52 compared to T_4 (11.58). The specific energy (SE) increased from 3.88 MJ kg^{-1} in T_6 to 4.39 MJ kg^{-1} in T_7, indicating that increasing spray volumes led to energy wastage due to higher battery power and labour requirements (6). The energy payback time (EPT) in these treatments also increased slightly, 0.12 years in T_7, indicating a slower return on energy investment. The knapsack spray at 500 L ha^{-1} (T_9 and T_{10}) was less efficient than UAV treatments in all energetic aspects. For example, T_9 had an IE of 12413 MJ ha^{-1} and an EI of 0.31 MJ ₹$^{-1}$, resulting in NE of 105699 MJ ha^{-1}, which was 18.3 % lower than T_4. The EUE for T_9 was also lower (9.52), requiring more energy to achieve similar results. The SE was higher at 4.40 MJ kg^{-1}, further emphasizing its inefficiency. The longer EPT (0.12 years) and lower EPF suggest that knapsack spraying is more labour-intensive and energy-demanding than UAV-based methods. The manual labour involved in knapsack spraying leads to higher energy use and lower efficiency (24). Hand weeding (T_{11}) performed even worse, with a decrease in OE (113876 MJ ha^{-1}) compared to T_4. The EI was 0.29 MJ ₹$^{-1}$ and the SE was 4.63 MJ kg^{-1}, showing that hand weeding is less efficient in DDSR. The EUE was 9.09 and the EPT was 0.12 years, indicating that hand weeding is not energy-efficient. Hand weeding requires significant labour energy, leading to lower energy productivity (EPC of 0.22 kg MJ^{-1}) and a longer EPT, making it a less viable option for modern DDSR practices. The unweeded control (T_{12}) had poor energy performance, with a decrease in OE (59280 MJ ha^{-1}) and NE (47129 MJ ha^{-1}) compared to T_4. The IE was 12,151 MJ ha^{-1} and the EI was 0.36 MJ ₹$^{-1}$, higher among treatments, indicating poor energy conversion efficiency. The EPT was longer (0.26 years) and the EUE of 4.88 was lower among all treatments. The EPC of 0.11 kg MJ^{-1} further confirmed that uncontrolled weed growth significantly reduced energy efficiency in rice production. Similarly, it was observed higher energy intensiveness in unweeded plots and mentioned that excessive energy is required for minimal output in DDSR systems in an earlier report (5).

Carbon indicators of UAV and knapsack spray

The carbon analysis of UAV and knapsack sprayer in DDSR showed significant differences in carbon input, output and overall efficiency across treatments (Table 6). Among the various weed management practices, UAV sprays using 100 % HRD (T_2, T_4, T_6 and T_8) consistently had higher total carbon inputs (246.3 kg CO_2 eq. ha^{-1}), regardless of spray volume. Other treatments, such as UAV spray with 75 % HRD (T_1, T_3, T_5 and T_7) and knapsack spray ($T_9$and T_{10}), had slightly lower carbon inputs (from 245.3 - 245.4 kg CO_2 eq. ha^{-1}). This variation in carbon inputs is mainly due to differences in herbicide doses and the active ingredients used (10). Among the treatments,

Table 5. Energetics of UAV and knapsack weed management options for DDSR

T	OE (MJ ha^{-1})	IE (MJ ha^{-1})	NE (MJ ha^{-1})	EI (MJ Rs^{-1})	EPC (kg MJ^{-1})	EPF (kg MJ^{-1})	SE (MJ kg^{-1})	EPT (years)	EUE
T_1	131664	12413	119251	0.32	0.27	9.61	3.66	0.10	10.61
T_2	137866	12483	125383	0.31	0.29	10.04	3.42	0.10	11.04
T_3	134437	12413	122024	0.31	0.27	9.83	3.65	0.10	10.83
T_4	144505	12483	132022	0.30	0.31	10.58	3.23	0.09	11.58
T_5	122158	12413	109745	0.30	0.24	8.84	4.25	0.11	9.84
T_6	127375	12483	114892	0.29	0.26	9.20	3.88	0.11	10.20
T_7	118319	12413	105906	0.29	0.23	8.53	4.39	0.12	9.53
T_8	125287	12483	112804	0.28	0.25	9.04	4.00	0.11	10.04
T_9	118112	12413	105699	0.31	0.23	8.52	4.40	0.12	9.52
T_{10}	121740	12483	109257	0.30	0.23	8.75	4.28	0.11	9.75
T_{11}	113876	12528	101348	0.29	0.22	8.09	4.63	0.12	9.09
T_{12}	59280	12151	47129	0.36	0.11	3.88	9.12	0.26	4.88

T - Treatments; COC - Cost of cultivation; TCOC - Total cost of cultivation; ROI - Return on investment; PP - Payback period; NPM - Net profit margin T_1: UAV spray of 25 L ha^{-1} with 75 % of HRD; T_2: UAV spray of 25 L ha^{-1} with 100 % of HRD; T_3: UAV spray of 50 L ha^{-1} with 75 % of HRD; T_4: UAV spray of 50 L ha^{-1} with 100 % of HRD; T_5: UAV spray of 75 L ha^{-1} with 75 % of HRD; T_6: UAV spray of 75 L ha^{-1} with 100 % of HRD; T_7: UAV spray of 100 L ha^{-1} with 75 % of HRD; T_8: UAV spray of 100 L ha^{-1} with 100 % of HRD; T_9: Knapsack spray of 500 L ha^{-1} with 75 % of HRD; T_{10}: Knapsack spray of 500 L ha^{-1} with 100 % of HRD; T_{11}: Hand weeding twice at 20 and 40 DAS; T_{12}: Unweeded control.

Table 6. Carbon indicators of UAV and knapsack weed management options for DDSR

T	Carbon input (kg CO_2 eq. ha^{-1})	Carbon output (kg CO_2 eq. ha^{-1})	CSI	CER	Carbon footprint (kg CO_2 eq. kg^{-1} yield)
T_1	245.2	4372.3	16.8	17.8	0.072
T_2	246.3	4569.8	17.6	18.6	0.067
T_3	245.3	4468.6	17.2	18.2	0.072
T_4	246.3	4787.2	18.4	19.4	0.064
T_5	245.3	4073.5	15.6	16.6	0.084
T_6	246.3	4234.6	16.2	17.2	0.077
T_7	245.3	3945.9	15.1	16.1	0.087
T_8	246.3	4168.6	15.9	16.9	0.079
T_9	245.4	3939.3	15.1	16.1	0.087
T_{10}	246.4	4059.4	15.5	16.5	0.085
T_{11}	244.4	3799.0	14.5	15.5	0.090
T_{12}	242.0	1983.5	7.2	8.2	0.182

T – Treatments; COC – Cost of cultivation; TCOC – Total cost of cultivation; ROI – Return on investment; PP - Payback period; NPM – Net profit margin T_1: UAV spray of 25 L ha^{-1} with 75 % of HRD; T_2: UAV spray of 25 L ha^{-1} with 100 % of HRD; T_3: UAV spray of 50 L ha^{-1} with 75 % of HRD; T_4: UAV spray of 50 L ha^{-1} with 100 % of HRD; T_5: UAV spray of 75 L ha^{-1} with 75 % of HRD; T_6: UAV spray of 75 L ha^{-1} with 100 % of HRD; T_7: UAV spray of 100 L ha^{-1} with 75 % of HRD; T_8: UAV spray of 100 L ha^{-1} with 100 % of HRD; T_9: Knapsack spray of 500 L ha^{-1} with 75 % of HRD; T_{10}: Knapsack spray of 500 L ha^{-1} with 100 % of HRD; T_{11}: Hand weeding twice at 20 and 40 DAS; T_{12}: Unweeded control.

the UAV spray of 50 L ha^{-1} with 100 % HRD (T_4) showed higher carbon output at 4787.2 kg CO_2 eq. ha^{-1}, while maintaining a carbon input of 246.3 kg CO_2 eq. ha^{-1}. This led to a high carbon sustainability index (CSI) of 18.4 and a carbon efficiency ratio (CER) 19.4, indicating that this treatment was effectively converted to outputs. Similarly, in a previous study, it was stated that the higher CER represents the effectiveness of converting carbon inputs into useful outputs (25). Its a lower carbon footprint (CF) of 0.064 kg CO_2 eq. kg^{-1} yield shows that it uses carbon efficiently, with lower emissions per unit of yield. This efficiency is due to better weed control and higher crop yields, which maximize carbon output compared to the input. Similarly, effective weed management with UAV significantly reduces weed infestation, leading to higher yields and lower carbon footprints per unit of yield (26). In contrast, treatments with higher spray volumes showed lower carbon outputs in T_5 (4073.5 kg CO_2 eq. ha^{-1}) and T_7 (3945.9 kg CO_2 eq. ha^{-1}). These treatments had lower CSI (15.6 and 15.1) and CER (16.6 and 16.1) values. These findings suggest an increase in carbon emissions per unit of yield due to improper use of carbon inputs. Likewise, an earlier report mentioned that increasing spray volume without properly managing carbon inputs can increase carbon emissions (10). Knapsack spray of 500 L ha^{-1} (T_9 and T_{10}) showed reduced carbon outputs (4059.4 kg CO_2 eq. ha^{-1} and 3799.0 kg CO_2 eq. ha^{-1}) compared to T_4, resulting in higher carbon footprints (0.087 kg CO_2 eq. kg^{-1}yield and 0.085 kg CO_2 eq. kg^{-1} yield), showing that knapsack sprayers are less efficient in carbon management compared to UAV systems, due to their higher labour and energy demands (27). Hand weeding (T_{11}) produced less carbon output (3799.0 kg CO_2 eq. ha^{-1}) than T_4, with a CSI of 14.5 and a CER of 15.5. The CF was high (0.090 kg CO_2 eq. kg^{-1} yield), reflecting the energy-intensive nature of manual labour. The inefficiency of hand weeding is due to the significant human effort required to remove weeds, which increases time manually, energy use and labour costs. Unlike mechanized methods, which allow for efficient herbicide application over large areas, hand weeding requires repeated interventions, leading to higher energy expenditure per weed unit removed (10, 27). As a result, while hand weeding may be a viable option for small-scale farms, it is less practical for large-scale operations due to its labour demands and inefficiencies in energy use. The unweeded control (T_{12}) had lower carbon output (1983.5 kg CO_2 eq. ha^{-1}) than T_4, with low CSI and CER values of 7.2 and 8.2 respectively. It also had the highest carbon footprint among all treatments at 0.182 kg CO_2 eq. kg^{-1} yield, showing that uncontrolled weeds resulted in poor yields and inefficient carbon use. Similarly, it was reported higher carbon inefficiencies in unweeded plots, showing that weed management is crucial for improving carbon efficiency in DDSR (10, 28).

Conclusion

The study assessed UAV's partial budgeting, energy use and carbon sustainability and knapsack herbicide application in DDSR. The research revealed that UAV-based weed management mainly, UAV spray at 50 L ha^{-1} with 100 % HRD) (T_4), achieved higher grain yield (3866.0 kg ha^{-1}), higher NPK nutrient uptake (105.4 kg ha^{-1}, 21.7 kg ha^{-1} and 130.8 kg ha^{-1}), better B:C ratio (2.13), improved energy efficiency (11.58) and lower carbon emissions, with a carbon footprint of 0.064 kg CO_2 eq. kg^{-1} yield, making it the most efficient treatment. The findings enhanced grain yield, partial budgeting and environmental sustainability by optimizing resource use, reducing labour dependency and lowering carbon emissions. It can be concluded that UAV-based weed management is an approach for large-scale cultivation, particularly in labour-scarce areas, making it a more sustainable option in the southern coastal deltaic region.

Acknowledgements

The authors acknowledge the Dean, Professor and Head and all teaching staff of the Department of Agronomy, PAJANCOA and RI, for their invaluable assistance, comments and constructive suggestions on the research and manuscript. The author acknowledges the GKMS at PAJANCOA and RI for providing meteorological weather parameters.

Authors' contributions

AK carried out the field trial and research work. PS participated as the Chairman. PR and NS helped and participated in editing. 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. Gartaula H, Sapkota TB, Chhetri AK, Prasad G, Badstue L. Gendered impacts of greenhouse gas mitigation options for rice cultivation in India. Clim Change. 2020;163:1045–63. https://doi.org/10.1007/s10584-020-02941-w
2. Sivasakthi D, Saravanane P, Sridevi V, Coumaravel K. Effect of 2, 4-D dose and formulation for brown manuring on weed dynamics, yield and economics in wet seeded rice. Indian J Weed Sci. 2024;56 (2):124–27. https://doi.org/10.5958/0974-8164.2024.00021.1
3. Keerthi DE, Saravanane P, Poonguzhalan R, Nadaradjan S. Brown manuring for improved crop growth, yield and energetics of wet seeded rice (*Oryza sativa*) in the coastal deltaic ecosystem. Indian J Agron. 2024;69(1):87–90. https://doi.org/10.59797/ija.v69i1.5488
4. Karthickraja A, Saravanane P. Competitive ability of *Parthenium hysterophorus* with direct seeded rice and influence of parthenium flowering dynamics with meteorological factors. Plant Arch. 2025;25(1):2717–23. https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-1.376
5. Pooja K, Saravanane P, Sridevi V, Nadaradjan S, Vijayakumar S. Effect of cultivars and weed management practices on productivity, profitability and energetics of dry direct-seeded rice. Oryza- An Int J Rice. 2021;58(3):442–47. https://doi.org/10.35709/ory.2021.58.3.1
6. Paul RA, 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
7. Binning AS, Pathak BS, Panesar BS. Energy audit of crop production system. Research bulletin: School of Energy studies for agriculture, Ludhiana: P.A.U; 1984.
8. Vijayakumar S, Kumar D, Shivay YS, Sharma VK, Sharma DK, Saravanane P, et al. Energy budgeting of aerobic rice (*Oryza sativa*)- wheat (*Triticum aestivum*) cropping system as influenced by potassium fertilization. Indian J Agric Sci. 2019;89(11):1911–15. https://doi.org/10.56093/ijas.v89i11.95341
9. Basavalingaiah K, Ramesha YM, Paramesh V, Rajanna GA, Jat SL, Misra SD, et al. Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: A case study from puddled transplanted rice and direct-seeded rice system of Karnataka, India. Sustain. 2020;12(16):6439. https://doi.org/10.3390/su12166439
10. Lal R. Carbon emission from farm operations. Environ Intern. 2004;30(7):981–90. https://doi.org/10.1016/j.envint.2004.03.005
11. West TO, Marland G. Net carbon flux from agricultural ecosystems: methodology for full carbon cycle analyses. Environ Pollution. 2002;116(3):439–44. https://doi.org/10.1016/S0269-7491(01)00221-4
12. Chaudhary VP, Singh KK, Pratibha G, Bhattacharyya R, Shamim M, Srinivas I, Patel A. Energy conservation and greenhouse gas mitigation under different production systems in rice cultivation. Energy. 2017;130(1):307–17. https://doi.org/10.1016/j.energy.2017.04.131
13. Shafaei SM, Moghadami AN, Kamgar S. Analytical study of friction coefficients of pomegranate seed as essential parameters in design of post- harvest equipment. Inf Process Agric. 2016;3 (3):133–45. https://doi.org/10.1016/j.inpa.2016.05.003
14. Team RC. R: A language and environment for statistical computing. [Internet]. Vienna: R Foundation for Statistical. Computing; 2020 [cited 25 Jan 2025]. Available from: https://www.r-project.org/
15. Saravanane P. Effect of different weed management options on weed flora, rice grain yield and economics in dry direct-seeded rice. Ind J Weed Sci. 2020;52(2):102–06. https://doi.org/10.5958/0974-8164.2020.00019.2

16. Fulton GO, Furness GO. Low volume applications of herbicides sprayed on to soil, crop or pasture with a bluff plate sprayer. Plant Prot Q. 1988;3(1):108–11.
17. Kumar V, Kumari A, Price AJ, Bana RS, Singh V, Bamboriya SD. Impact of futuristic climate variables on weed biology and herbicidal efficacy: A review. Agron. 2023;13(2):559–73. https://doi.org/10.3390/agronomy13020559
18. Kaur S, Kaur R, Chauhan BS. Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. Crop Protect. 2018;103(1):65–72. https://doi.org/10.1016/j.cropro.2017.09.011
19. Chen P, Lan Y, Douzals JP, Ouyang F, Wang J, Xu W. Droplet distribution of unmanned aerial vehicle under several spray volumes and canopy heights in the cotton canopy. Int J Prec Agric Aviat. 2018;1(1):141–57. https://doi.org/10.33440/j.ijpaa.20200304.136
20. Kumar V, Mahajan G, Sheng Q, Chauhan BS. Weed management in wet direct-seeded rice (*Oryza sativa* L.): issues and opportunities. Adv Agron. 2023;179(1):91–133. https://doi.org/10.1016/bs.agron.2023.01.002
21. Karthickraja A, Saravanane P, Poonguzhalan R, Nadaradjan S. Comparison of UAV and knapsack herbicide application methods on weed spectrum, crop growth and yield in dry direct-seeded rice. Ind J Weed Sci. 2024;56(3):307–11. https://doi.org/10.5958/0974-8164.2024.00051.6
22. Singh MK, Pal SK, Thakur R, Verma UN. Energy input-output relationship of cropping systems. Indian J Agric Sci. 1997;67(6):262–64.
23. Lal B, Gautam P, Nayak AK, Panda BB, Bihari P, Tripathi R, et al. Energy and carbon budgeting of tillage for environmentally clean and resilient soil health of rice-maize cropping system. J Cleaner Prod. 2019;226(1):815–30. https://doi.org/10.1016/j.jclepro.2019.04.041
24. Ghosh D, Brahmachari K, Das A, Hassan MM, Mukherjee PK, Sarkar S, et al. Assessment of energy budgeting and its indicator for sustainable nutrient and weed management in a rice-maize-green gram cropping system. Agron. 2021;11(1):166. https://doi.org/10.3390/agronomy11010166
25. Yang W, Zhang N. Does the carbon emissions trading scheme improve carbon total factor productivity? Evidence from Chinese cities. Green Low-Carbon Econ. 2024;2(2):87–96. https://doi.org/10.47852/bonviewGLCE3202905
26. Malhi GS, Rana MC, Kumar S, Rehmani MIA, Hashem A, Allah AEF. Efficacy, energy budgeting and carbon footprints of weed management in blackgram (*Vigna mungo* L.). Sustain. 2021;13(23):13239. https://doi.org/10.3390/su132313239
27. Minofar B, Milcic N, Marousek J, Gavurova B, Marouskova A. Understanding the molecular mechanisms of interactions between biochar and denitrifiers in N_2O emissions reduction: pathway to more economical and sustainable fertilizers. Soil Tillage Res. 2025;248(1):106405. https://doi.org/10.1016/j.still.2024.106405
28. Marousek J, Marouskova A, Gavurova B, Minofar B. Techno-economic considerations on cement substitute obtained from waste refining. J Cleaner Prod. 2023;412(1):137326. https://doi.org/10.1016/j.jclepro.2023.137326

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.