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Optimization of Uav-Based Herbicidal Dose and Spray Volume for Weed Dynamics, Energy Efficiency and Carbon Footprint in Bread Wheat (Triticum Aestivum L.)

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OPTIMIZATION OF UAV-BASED HERBICIDAL DOSE AND SPRAY VOLUME FOR WEED DYNAMICS, ENERGY EFFICIENCY AND CARBON FOOTPRINT IN BREAD WHEAT (*TRITICUM AESTIVUM* L.)

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Abstract. The study was conducted at farmer's field, Jammu, India in *Rabi* seasons of 2024 and 2025 to optimize the drone applied herbicidal dose and spray fluid for weed dynamics, energy indices and carbon metrics in wheat crop (*Triticum aestivum* L.). The treatment consists of two quantity of herbicides (100% and 75% of recommended dose), three level of spray fluid with two method of application for drone (25, 37.5 and 50 l/ha) and for knapsack spray (500 l/ha). The results revealed that the application of 100% herbicide dose of Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha spray fluid through drone is considered as the most optimized treatment. This treatment had recorded the lower weed density (71.20-82.20%), dry matter (72.24-77.87%) and higher weed control efficiency over weedy check plot. It has also recorded higher grain yield (4.07 t/ha), net returns (80055 ₹/ha), benefit-cost ratio (2.64), higher energy productivity and carbon efficiency. Hence, it is concluded that the application of Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha spray fluid through drone gave higher weed control efficiency, energy productivity, carbon efficiency and net returns.
Keywords: *carbon efficiency, drone, energy indices, weed index*, *yield*

Introduction

Wheat (*Triticum aestivum* L.) is the one of the world's most cultivated cereal crop and a major source of food and livelihood for majority of the farmers. Globally wheat occupied 220.61 million hectares of cultivated land, with production of 789.49 million tonnes and productivity of 3.58 tonnes/ha, respectively (FAOSTAT, 2023). However, the crop production was highly infested by weeds which were compete with main crop for nutrients, sunlight and water leading to a significant yield loss if not properly managed (Chauhan et al.,2012). The traditional method such as hand weeding was not effective due to time consuming, inefficient and labour intensive. Among different weed control methods, the chemical method was most effective by suppress a broad spectrum of weeds and results in higher grain yield (Jabran et al.,2015). In recent years, the use of Agricultural drones has been one of the promising technology for the precision weed management. It helps in reduces chemical wastage, saves water, minimize environmental impact and improving operational efficiency (Huang et al.,2009). In this technology, optimizing the herbicide dose and spray volume is very important for effective weed control. As excessive dose of herbicide can harm the crop, degrades soil fertility, reduces quality of water and also increase increase input cost while the lower dose can reduce its efficacy which allows the weeds to compete with

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crop. In this context, the lower spray volume can cause uneven coverage, leaving unteated weeds and reduces herbicide efficacy whereas higher volume can cause chemical wastage, runoff and drift which harm the crop and environment. Thus, the optimizing of both herbicide dose and spray volume through drones improve the yield attributes, weed dynamics, energy use efficiency, carbon sustainability index and economics of wheat crop.

Material And Methods

Study site

The study was conducted at Farmer's field in village Phinder, RS Pura, Jammu, Jammu and Kashmir, India (32.60°N Latitude, 74.82°E Longitude, 332m above mean sea level) during the *Rabi* season of 2024 and 2025. The region's soil was sandy clay loam with slightly alkaline, low in organic carbon (4.34 g/kg), available nitrogen (232.73 kg/ha), medium available phosphorus (15.69 kg/ha) and potassium (161.28 kg/ha).

Treatments and field design

The study laid in Randomized Block Design (RBD) with three replications consist of ten treatments as shown in *Table 1*. The plot dimensions were 150 m^2 (10m x 15m) with a 3m buffer zone on each side of the plot. The variety of wheat was used 'JAUW-672' with spacing of 22.5 x 10 cm. The seed rate is 100 kg/ha with fertilizer application 120:60:40 kg/ha of N, P_2O_5 and K_2O as per the recommended package and practices. These treatments consist of 100% and 75% dose of herbicides, three level of spray fluid through drone and two method of sprayer application through drone (DS) and by knapsack (KS). The spray fluid of 25 l/ha, 37.5 l/ha and 50 l/ha applied through drone and spray fluid of 500 l/ha applied through knapsack sprayer. In these treatments, the pre-emergence (PE) apply at 2 days and post-emergence (PoE) at 25 days after sowing (DAS) of crop.

Table 1. *Treatment details of the experimental study*

S.no.	Treatment
T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF

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T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF
T_9	Weed free
T_{10}	Weedy check

Sprayer equipments

The drone used for herbicide application was hexacopter with four flat fan nozzles, has a tank capacity of 10 litres, performed application from a height of 3m above the ground, moved at a speed of 5m/s with spray width is 3m. However, the knapsack sprayer was mainly consist of 20 litres tank capacity, manually operated, having single flat fan nozzle.

Observations recorded

The observations recorded under yield attributes and yield were tillers/m^2, grains per spike, 1000-grain weight, grain yield, straw yield and harvest index. The parameters of energy indices and carbon metrics along with their formula were provided in *Table 2* which were taken from the findings of Devsenapathy et al.,2009. However, these both carbon and energy indices were calculated by mutiplying with their coefficients based on their input and output values were shown in *Table 3* and these coefficient values were taken from Hung et al., 2019. The economics were evaluated were taking the observations of cost of cultivation, gross returns, net returns and benefit-cost ratio. Among weed dynamics, the weed density was computed from the randomly selected four sites by setting a 1m x1m quadrant in each plot whereas the weed dry matter was determined by uprooting the weed together with their roots and then wash the weeds to remove soil particles from roots and other parts. Additionally, the weeds were oven-dried for 1.5-2 days at 60ºC . After complete oven drying, the weed dry matter of weeds were measured. The other different weed indices were also studied *viz.* weed control efficiency (WCE) (Mishra and Mishra, 1997), weed index (WI) (Raju, 1998) and Herbicide Efficiency Index (HEI) (Krishnamurthy et al.,1975), Weed Persistence Index and Crop Resistance Index with their formulas as listed below:

$$WCE\ (\%) = \frac{W_{pc} - W_{pt}}{W_{pc}} \times 100 \qquad \text{(Eq.1)}$$

where,
W_{pc} = Weed dry weight in control plot
W_{pt} = Weed dry weight in treated plot

$$WI\ (\%) = \frac{Y_{wf} - Y_t}{Y_{wf}} \times 100 \qquad \text{(Eq.2)}$$

where,

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Y_{wf} = Yield of weed free treatment
Y_t = Yield of treatment plot

$$HEI\ (\%) = \frac{Y_t - Y_{wc}}{Y_{wc}} \times \frac{W_{pc}}{W_{pt}} \quad \text{(Eq.3)}$$

where,
Y_{wc} = Yield of weed check plot
Y_t = Yield of treatment plot
W_{pc} = Weed dry weight in control plot
W_{pt} = Weed dry weight in treated plot

$$WPI\ (\%) = \frac{W_{pt}}{W_{pc}} \times \frac{W_{dc}}{W_{dt}} \quad \text{(Eq.4)}$$

where,
W_{dc} = Weed density in control plot
W_{dt} = Weed density in treated plot
W_{pc} = Weed dry weight in control plot
W_{pt} = Weed dry weight in treated plot

$$CRI\ (\%) = \frac{C_{dt}}{C_{dc}} \times \frac{W_{dc}}{W_{dt}} \quad \text{(Eq.5)}$$

where,

W_{dc} = Weed density in control plot
W_{dt} = Weed density in treated plot
C_{dc} = Crop dry weight in control plot
C_{dt} = Crop dry weight in treated plot

Statistical analysis

In statistical analysis, the field data was gathered and examined using the specific approach (Gomez and Gomez, 1984). The data collected during a two years period was subjected to statistically analyzed. Since the treatments effect were consistent across the years, the data were pooled and analyzed. To reduce the treatment and row effect, a least significant difference (LSD) of 5% level was computed for each of the parameter. In this the treatments mean were taken by applying the F-test on the basis of null hypothesis. Additionally, the weed density and weed dry matter were subjected to square root transformation *ie.* $\sqrt{x+1}$ for statistical analysis.

Table 2. *Calculation of various energy and carbon indices with their formulas*

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S. No.	Particular	Calculations
1.	Additional energy (MJ/ha)	Output energy of treated plot- Output energy of weedy check plot
2.	Energy intensiveness (MJ/₹)	Input energy (MJ/ha) / Cost of cultivation (₹/ha)
3.	Energy productivity (kg/MJ)	Economic yield (kg/ha) / Energy input (MJ/ha)
4.	Energy use efficiency (MJ)	Output energy (MJ/ha) / Input energy (MJ/ha)
5.	Net Carbon Gain (kg CO_2 eq/ha)	Carbon output (kg CO_2 eq/ha)- Carbon input (kg CO_2 eq/ha)
6.	Carbon Efficiency	Carbon output (kg CO_2 eq/ha) / Carbon input (kg CO_2 eq/ha)
7.	Carbon Sustainability Index	Net Carbon Gain (kg CO_2 eq/ha) / Carbon input (kg CO_2 eq/ha)
8.	Carbon Footprints (kg CO_2 eq/kg)	Carbon input (kg CO_2 eq/ha) / Economic yield (kg/ha)

Table 3. *Energy and carbon equivalents of various agricultural inputs and outputs*

S. No.	Particular	Unit	Energy equivalent (MJ/unit)	Carbon equivalents (kg CO_2/unit)	References
Inputs					
1.	Human labour	hr.	1.96	0.05	Hung et al., 2019
2.	Diesel	L	56.31	2.68	Hung et al., 2019
3.	Farm machinery	hr	62.70	4.45	Hung et al., 2019
4.	Electricity	kWh	11.93	0.82	Hung et al., 2019
5.	Water	m^3	1.02	0.17	Hung et al., 2019
6.	Nitrogen (N)	Kg	60.60	1.30	Hung et al., 2019
7.	Phosphorus (P_2O_5)	Kg	11.10	0.20	Hung et al., 2019
8.	Potassium (K_2O)	Kg	6.70	0.15	Hung et al., 2019
9.	Herbicides	Kg a.i.	254.45	10.00	Hung et al., 2019
10.	Paddy seed	Kg	14.70	0.40	Hung et al., 2019
Outputs					
11.	Grain yield	Kg	14.70	0.40	Hung et al., 2019
12.	Straw yield	Kg	12.50	0.40	Hung et al., 2019

Results and Discussion

Yield attributes and Yield

The results showed that the variable herbicidal dose and spray fluid through drone had significantly affect the yield attributes and yield of the crop. At harvest, the highest number of tillers (326.65/m^2), grains per spike (44.78), 1000-grain weight,

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grain (4.07 t/ha) and straw yield (5.90 t/ha) were recorded by the application of DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1) which was statistically at par with DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 37.5 l/ha SF (T_2) (*Table 4*). The superior yield attributes and yield obtained from this treatment may be attributed to better droplet concentration and uniform deposition on weeds which results in effective weed control, reduced crop weed competetion, improve resource availability and increase yield parameters (Jeevan et al., 2024).

Weed flora

The cropping field consist of different weed species in which *Phalaris minor* and *Avena ludoviciana* among grasses*, Cyperus rotundus* among sedges, *Chenopodium album, Rumex dentatus* and *Anagallis arvensis* among broad-leaved weeds were dominant whereas *Vicia sativa, Fumaria parviflora, Lathyrus aphaca* and *Medicago denticulata* were the other weeds were present.

Weed dynamics

Weed density and Weed dry matter

The weed density and weed dry matter was affected significantly by variable herbicide dose and spray fluid through drone at 30 and 60 DAS of crop in which the lower weed density (4.50, 4.06 m^2) and weed dry matter (3.82, 4.04 g/m^2) were recorded by the application of DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1) which was statistically at par with DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 37.5 l/ha SF (T_2). However, the heavy weed infestation was found in weedy check plot (*Table 5*). The better performance of this treatment may be due to better droplet distribution and uniform coverage on the targeted weeds which enhanced the herbicidal activity, leads to reduces the weed density and weed biomass (Kumari et al., 2018).

Weed control efficiency and Weed Index

Among the various treatments, the higher weed control efficiency at 30 days and 60 DAS (72.25, 77.87 %) and lowest weed index (2.63 %) was recorded by application of DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1) (Zhang et al., 2020) (*Table 5*).

Weed persistence index, Crop resistance index and Herbicide efficiency index

Among various treatments higher crop resistance index (6.24, 6.27%), herbicide efficiency index (2.64, 3.31%) and lower weed persistence index at both 30 and 60 DAS of crop was recorded in DS Pyroxasulfone @ 100g a.i./ha (PE) fb Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1) (*Table 6*). This was mainly due to uniform and effective weed control which reduce the crop-weed competition. The improved resource availability enhanced crop growth and vigour, which make crop

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Table 4. *Effect of drone based herbicide dose and spray volumes on yield attributes and yield in wheat crop (pooled values for two years)*

S.no.	Treatment	Tillers /m^2	Grains per spike	1000 grain weight (g)	Grain yield (t/ha)	Straw yield (t/ha)	Harvest index (%)
T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF	326.65	44.78	41.25	4.07	5.90	40.82
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF	323.55	43.50	40.80	4.04	5.67	41.61
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF	281.45	39.33	40.10	3.30	4.91	40.19
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF	300.25	41.10	40.35	3.70	5.31	41.07
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF	277.76	38.88	39.94	3.10	4.65	40.00
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF	272.34	38.35	39.85	2.75	4.35	38.73
T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF	305.57	42.80	40.75	3.80	5.45	41.08
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF	297.58	42.25	40.55	3.55	5.11	40.99
T_9	Weed free	332.47	45.85	41.75	4.18	6.10	40.66
T_{10}	Weedy check	241.45	34.44	39.20	2.35	4.25	35.61
SEd		8.47	1.06	0.46	0.12	0.15	0.72
CD (P= 0.05)		25.40	3.18	NS	0.35	0.44	NS

DS- Drone spray, KS- Knapsack spray, PE- Pre emergence, PoE- Post emergence, SF- Spray fluid

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Table 5. *Effect of drone based herbicide dose and spray volumes on weed density (number/m^2), dry matter (g/m^2), weed control efficiency (%) and weed index (%) in wheat crop (pooled values for two years)*

S.No.	Treatments	Weed density (no. /m^2)		Weed dry matter (g/m^2)		Weed Control Efficiency (%)		Weed Index (%)
		30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS	At harvest
T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF	4.50 (19.23)	4.06 (15.46)	3.82 (13.56)	4.04 (15.35)	72.25	77.87	2.63
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF	4.95 (23.47)	4.61 (20.23)	4.06 (15.47)	4.39 (18.27)	68.34	73.66	3.35
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF	6.30 (38.65)	6.06 (35.67)	4.99 (23.87)	5.64 (30.78)	51.15	55.63	21.05
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF	5.59 (30.23)	5.22 (26.28)	4.51 (19.34)	5.12 (25.23)	60.42	63.63	11.48
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF	6.58 (42.34)	6.31 (38.87)	5.15 (25.56)	5.87 (33.46)	47.69	51.77	25.84
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF	7.18 (50.49)	6.75 (44.56)	5.43 (28.47)	6.06 (35.67)	41.73	48.58	34.21
T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF	5.55 (29.78)	5.03 (24.35)	4.44 (18.67)	4.88 (22.86)	61.79	67.05	9.09
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF	6.05 (35.56)	5.60 (30.38)	4.73 (21.34)	5.42 (28.38)	56.32	59.09	15.07
T_9	Weed free	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	100.00	100.00	0.00
T_{10}	Weedy check	8.23 (66.78)	9.37 (86.89)	7.06 (48.86)	8.39 (69.37)	0.00	0.00	43.78
SEd		0.31	0.34	0.23	0.28	-	-	-
CD (P= 0.05)		0.92	1.03	0.65	0.84	-	-	-

The data were subjected to √x+1 transformation; Figures in the parenthesis are original values

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DS- Drone spray, KS- Knapsack spray, PE- Pre emergence, PoE- Post emergence, SF- Spray fluid, DAS- Days after sowing

Table 6. *Effect of drone based herbicide dose and spray volumes on weed persistence index (%), crop resistance index (%) and herbicide efficiency index (%) in wheat crop (pooled values for two years)*

S.No.	Treatments	Weed persistence index (%)		Crop resistance index (%)		Herbicide Efficiency Index (%)	
		30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS
T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF	0.96	1.24	6.24	6.27	2.64	3.31
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF	0.90	1.13	5.43	5.07	2.27	2.73
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF	0.84	1.08	2.87	2.60	0.83	0.91
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF	0.87	1.20	3.98	3.44	1.45	1.58
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF	0.83	1.08	2.52	2.27	0.61	0.66
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF	0.77	1.00	2.01	1.99	0.29	0.33
T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF	0.86	1.18	4.23	3.89	1.61	1.87
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF	0.82	1.17	3.46	2.94	1.17	1.25
T_9	Weed free	0.00	0.00	-	-	-	-
T_{10}	Weedy check	1.00	1.00	1.00	1.00	0.00	0.00
SEd		-	-	-	-	-	-
CD (P= 0.05)		-	-	-	-	-	-

DS- Drone spray, KS- Knapsack spray, PE- Pre emergence, PoE- Post emergence, SF- Spray fluid, DAS- Days after sowing

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to compete better and maintain higher productivity under reduced weed pressure (Chen et al., 2019)

Energy analysis

The variable dose of herbicides and spray fluid through drone showed a significant effect on the energy balance indices. The treatments sprayed with knapsack sprayer has required slightly higher input energy in comparison with drone application (*Table 7*). Among different treatments the higher output energy (168979 MJ/ha), energy productivity (0.310 kg/MJ) and energy use efficiency (12.86 MJ) was shown by DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1). This may be due to the fact that drone based herbicide application reduces the excess inputs such as water and labour compared to knapsack spraying. This reduces the input energy and increase the crop yield which increases the output energy, energy productivity and energy use efficiency.

Carbon metrics

The variable dose of herbicides and spray fluid through drone showed a significant effect on the carbon dynamics. The treatments sprayed with knapsack sprayer has required slightly higher carbon input in comparison with drone application (*Table 8*). Among various treatments the higher carbon output (3988 kg CO_2 eq/ha), carbon efficiency (8.75) and lower carbon footprint (0.112 kg CO_2 eq/kg) was shown by DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1). This may be attributed due to the fact that drone has less fuel consumption, lower labour requirement and efficient utilization of agricultural inputs. Also, the higher crop productivity under drone spraying also contributed to greater carbon output, net carbon gain and lower carbon footprint (Zhao et al., 2023).

Correlation studies

The crop dry matter and weed dry matter had a negative correlation with R^2 = 0.85. Due to the competetion for growing resources, the negative trend shows an increase in weed dry matter lower the crop dry matter. The strong relationship between these two variables is indicated by the higher value of R^2, which demonstrates that weed dry matter has a significant impact on crop dry matter (*Figure 1*). This result clearly showed that the effective weed management helps in lower weed dry matter is essential for enhancing crop growth and production

Similarly, the crop dry matter and herbicide efficiency index shows a positive relationship with value of R^2= 0.39. The positive linear relationship shows that with the increase in herbicide efficiency index there is a increase in crop dry matter. The higher value of R^2 indicates indicates that better control of weeds through herbicide application which promotes better crop growth and biomass accumulation (*Figure 2*). This demonstrates that different treatments with higher HEI directly contribute to increased crop dry matter production.

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Table 7. *Effect of drone based herbicide dose and spray volumes on energy analysis in wheat crop (pooled values for two years)*

Treatments		Input energy (MJ/ha)	Output energy (MJ /ha)	Additional energy (MJ/ha)	Energy intensiveness (MJ/₹)	Energy productivity (kg /MJ)	Energy use efficiency (MJ)
T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF	13141	167979	55809	0.43	0.310	12.86
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF	13144	164283	51113	0.43	0.307	12.50
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF	13148	139345	26175	0.43	0.251	10.60
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF	13132	152625	39455	0.44	0.282	11.62
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF	13135	131595	18425	0.44	0.236	10.02
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF	13139	120900	7730	0.43	0.209	9.20
T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF	15615	156685	43515	0.49	0.243	10.03
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF	15624	146720	33550	0.49	0.227	9.39
T_9	Weed free	17410	174296	61126	0.38	0.240	10.01
T_{10}	Weedy check	13110	113170	0	0.46	0.179	8.63

Common Input Energy in wheat crop= 13110 MJ/ha

DS- Drone spray, KS- Knapsack spray, PE- Pre emergence, PoE- Post emergence, SF- Spray fluid

Table 8. *Effect of drone based herbicide dose and spray volumes on carbon metrics in wheat crop (pooled values for two years)*

Treatments	Carbon Input (kg CO_2 eq/ha)	Carbon Output (kg CO_2 eq/ha)	Net Carbon Gain (kg CO_2 eq/ha)	Carbon Efficiency	Carbon Sustainability Index	Carbon Footprints (kg CO_2 eq/kg)

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T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF	456	3988	3532	8.75	7.75	0.112
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF	456	3884	3428	8.52	7.52	0.113
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF	457	3284	2827	7.19	6.19	0.138
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF	454	3604	3150	7.94	6.94	0.123
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF	456	3100	2644	6.80	5.80	0.147
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF	456	2840	2384	6.23	5.23	0.166
T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF	462	3700	3238	8.01	7.01	0.122
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF	460	3464	3004	7.53	6.53	0.130
T_9	Weed free	468	4112	3644	8.79	7.79	0.112
T_{10}	Weedy check	452	2640	2188	5.84	4.84	0.192

Common carbon input in wheat crop= 452 kg CO_2 eq/ha

DS- Drone spray, KS- Knapsack spray, PE- Pre emergence, PoE- Post emergence, SF- Spray fluid

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Relative economics

The relative economics evaluates the profitability of various treatments by comparing net returns with their input costs. Among different treatments, the application of DS Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha SF (T_1) with net returns (80055 ₹/ha) , benefit-cost ratio (2.64) (*Table 9*). This higher net returns and benefit-cost ratio through drone application was due to effective weed control and improved crop yield. The reduced weed competition enhaced the crop productivity, thereby increasing profitability. These results indicates the optimized drone spraying can improve economic efficiency in crop production (Kumar et al.,2024).

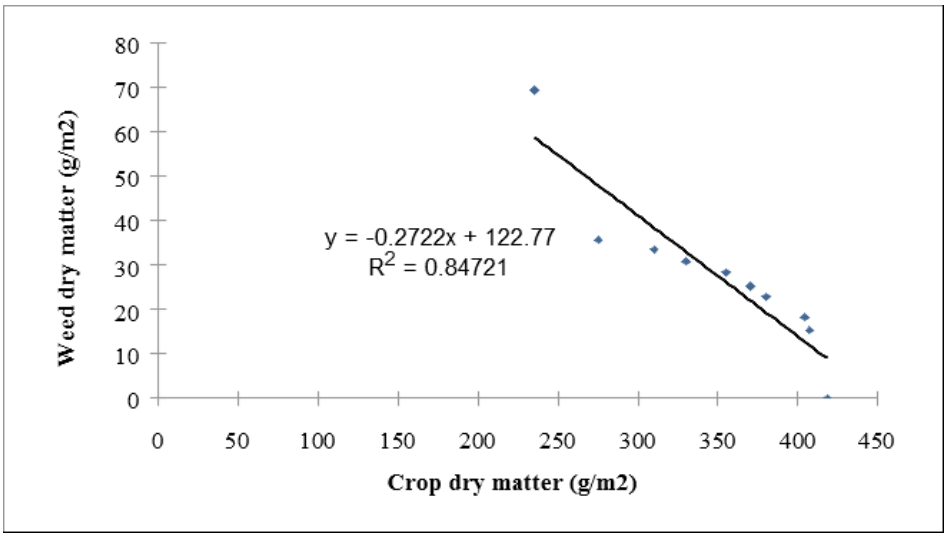


Figure 1. *The linear relationship between weed dry matter and crop dry matter*

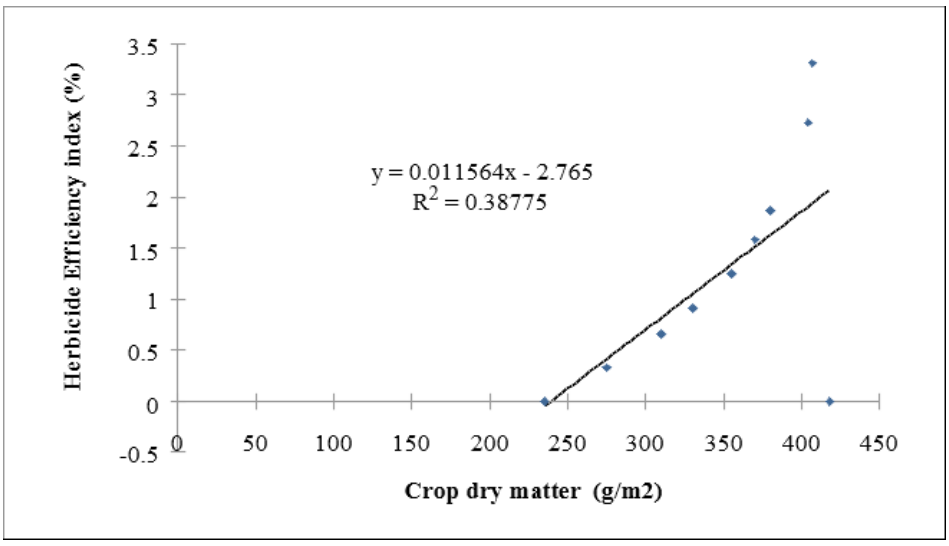


Figure 2. *The linear relationship between herbicide efficiency index and crop dry matter*

Table 9. *Effect of drone based herbicide dose and spray volumes on relative ecocnomics in wheat crop (pooled values for two years)*

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S.No.	Treatments	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	B:C ratio
T_1	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 25 l/ha SF	30340	110395	80055	2.64
T_2	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 37.5 l/ha SF	30570	109115	78545	2.57
T_3	DS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron+ Metsulfuron-methyl 32g a.i./ha (PoE) at 50 l/ha SF	30810	89825	59015	1.92
T_4	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 25 l/ha SF	29950	100225	70275	2.35
T_5	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 37.5 l/ha SF	30160	84475	54315	1.80
T_6	DS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 50 l/ha SF	30350	75500	45150	1.49
T_7	KS Pyroxasulfone 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 32g a.i./ha (PoE) at 500 l/ha SF	32147	102925	70778	2.20
T_8	KS Pyroxasulfone 75g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl 24g a.i./ha (PoE) at 500 l/ha SF	31950	96200	64250	2.01
T_9	Weed free	45750	113480	67730	1.48
T_{10}	Weedy check	28350	65850	37500	1.32

DS- Drone spray, KS- Knapsack spray, PE- Pre emergence, PoE- Post emergence, SF- Spray fluid

Conclusion

Henceforth, it can be concluded that based on two year study, the application of Drone spray Pyroxasulfone @ 100g a.i./ha (PE) *fb* Sulfosulfuron + Metsulfuron-methyl @ 32g a.i./ha (PoE) at 25 l/ha Spray fluid gave higher grain yield, crop resistance index, energy use efficiency, carbon efficiency, net returns and benefit-cost ratio.

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