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RESEARCH ARTICLE

Weed suppression and yield response of high-density cotton to herbicides and spray fluid volumes through drone spraying

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Abstract

Drone application of herbicides is an emerging concept in weed management. For drone spraying, spray volume needs to be optimized to improve its efficacy. The present study was conducted at Tamil Nadu Agricultural University, Coimbatore, during *summer*, 2024 to optimize spray volumes for drone spraying of herbicides in high-density cotton. The study was designed in a strip-plot with 3 horizontal plots (herbicides: H_1 - PE application of pendimethalin 1kg/ha followed by hand weeding at 25DAS, H_2 - PE application of pendimethalin 1kg/ha followed by EPoE application of quizalafop-ethyl 50 g/ha + pyrithiobac-sodium 62.5 g/ha and H_3 - EPoE application of quizalafop-ethyl 50 g/ha + pyrithiobac-sodium 62.5 g/ha), 5 vertical plots (spray volumes: S_1 - 30 L/ha, S_2 - 35 L/ha, S_3 - 40 L/ha, S_4 - 45 L/ha, S_5 - 50 L/ha) and replicated thrice. A weed-free check and an unweeded check were maintained separately. Regarding herbicides, pendimethalin followed by quizalafop-ethyl + pyrithiobac-sodium and pendimethalin followed by hand weeding, recorded lower total weed density and dry weight and higher drymatter production of cotton and seed cotton yield. Application of herbicides with 45 L/ha and 50 L/ha recorded lower total weed density and dry weight, higher drymatter production of cotton and seed cotton yield. The results revealed that the drone spraying of pendimethalin 1.0 kg ha^{-1} as pre-emergence followed by EPoE application of quizalafop ethyl 50g/ha + pyrithiobac sodium 62.5 g/ha with spray volume of 45 L/ha was found to be effective in combating the weeds in high-density cotton.

Keywords: drone; high-density cotton; spray volume optimization; weed density and dry weight; yield

Introduction

Cotton is one of the world's important cash crops. Due to its fiber quality, it is recognized as a vital crop in the global fabric sector (1). It is also known as the “king of fiber” and “white gold”. It is grown nearly in 80 countries across the world. Among them, 10 countries account for around 80% of cotton production, of which six are from Asia (China, India, Pakistan, Uzbekistan, Turkey and Turkmenistan). In India, cotton is grown on 12.69 million ha, accounting for 32.52 million bales of production with a productivity of 436 kg ha^{-1} (2). The leading producers are Maharashtra, Gujarat and Telangana. According to the International Cotton Advisory Committee's estimate, for one ton of cotton production, approximately 5 to 6 people can get employment throughout the year (3).

Weeds are the major yield-limiting factor of cotton, which competes for water, space, light, nutrients and CO_2 available, resulting in a deficit of nutrients and reduced yield (4). To improve the crop yield, weeds should be managed during the critical weed period. Physical, mechanical, cultural and chemical methods are commonly used to manage the weeds. The effective weed management was associated with the mechanical and chemical weed management methods (5, 6).

With increasing urbanization and rapid population growth, the net cultivable area and per capita availability of water resources are limited (7). In chemical weed management, 500 L ha^{-1} of water is used to spray the herbicide using a knapsack sprayer. Also, manual spraying of herbicides includes high cost, labour drudgery, availability of labour during peak periods and huge time consumption (8, 9). To cope with these issues automation in herbicide application *viz.*, drone spraying is a possible option.

An unmanned aircraft system (UAS) / drone is an aircraft that is remotely operated using a receiver (10). Nowadays, a drone is a boon technology in agriculture and is effectively employed in spraying operations, crop monitoring, yield estimation and water quality monitoring to reduce labour drudgery and spraying time (11). Under the changing climate, water is a vital resource that should be used very precisely. We need to reduce the spray volume of the herbicide without affecting its efficiency. Various studies reported that a very small quantity of spray fluid is enough for agricultural drones to manage the weeds. Chen (12) used 15 and 22.5 L ha^{-1} spray fluid in wheat and recorded that the reduced spray volume did not affect weed control efficiency. While Jeevan (13) used 25 - 50 L ha^{-1} in paddy. The efficacy of the herbicide remains unchanged with drone and manual knapsack applications. Paul (14) and Pranaswi (15) conducted a field study and recorded that the unmanned aerial vehicle (UAV) didn't reduce the efficacy of herbicides in rice and wheat, respectively. Abd Ghani (16) found that the effectiveness of UAV-sprayed systemic post-emergence herbicides is comparable with conventional methods. However, the quantity of spray fluid required for herbicide spraying with the drone is still to be optimized in cotton. To fill this research gap, the current experiment was planned to optimize the spray volume of water required for the drone to spray the herbicides in cotton.

Materials and Methods

Experimental details

The experimental field is sited at field number 36 E, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore (11°00'56" N, 76°56'17" E with an elevation of 453 m AMSL) during the *summer*, 2024 to figure out the optimum spray volume of herbicides using drones in cotton. The experiment was laidout in a strip-plot design with 3 horizontal plots (herbicide combinations) and 5 vertical plots (spray fluid volumes). In addition to that, a weed-free and an unweeded check were maintained. All the plots were replicated thrice. Cotton (variety: CO-17) seeds were obtained from the Regional Research Station, Aruppukottai. The gross plot of 90 m^2 (3.6×25 m) and the net plot of 44.5 m^2 (1.8×24.7 m) were employed for this study. Seeds were manually dibbled in the ridges with 90×15 cm spacing to maintain high-density planting.

Treatment details

The pre-emergence (PE) and early post-emergence (EPoE) herbicides were sprayed with a battery-operated hexacopter drone. The drone's specifications are listed in Table 1. Horizontal plot treatments were H_1 - PE application of pendimethalin 1.0 kg ha^{-1}, followed by (*fb*) hand weeding at 25 DAS, H_2 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} and H_3 - EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} alone, while vertical plot treatments included different spray volumes *viz.*, S_1 - 30 L ha^{-1}, S_2 - 35 L ha^{-1}, S_3 - 40 L ha^{-1}, S_4 - 45 L ha^{-1} and S_5 - 50 L ha^{-1}. The spray volumes were attained by calibrating the velocity and operating pressure of the battery-operated drone (Table 2).

Observations recorded

Observations on weeds

Weed flora: The major weeds observed in the experimental site were *Trianthema portulacastrum, Boerhavia diffusa, Amaranthus viridis, Dinebra retrofelxa, Chloris barbata, Cynodon dactylon, Dactyloctenium aegyptium and Echinochloa colona* (Fig. 1). Broadleaf and grass weeds were observed in the field and the sedges were not observed.

Weed density: During the research program, data on weed parameters, including density of grass weeds, sedge weeds and broadleaf weeds, total weed density and total weed dry weight, were recorded at 20 and 40 days after sowing. The number of weeds present in a square meter area was counted by randomly placing a quadrant in four places. The weed species present inside the quadrant were grouped as grasses, broadleaf weeds and total weeds at 20 and 40 DAS and expressed as nos. m^{-2}.

Total weed dry weight: The weed species present inside the quadrant were carefully removed without root damage. The roots were rinsed in water to remove soil debris. The weed samples were kept in the shade for drying up to 2 to 3 days. Then the samples were kept in a hot air oven at 70°C until reaching a constant weight. After reaching a constant weight, the total weed dry weight was measured and expressed in g m^{-2}.

Observations on crop

Drymatter production

Three plants were randomly collected from the gross plot area and the roots were washed to remove the soil debris. The samples were kept in the shade for 2 to 3 days. Then the samples were kept in a hot air oven at 70°C until reaching a constant weight. The drymatter production was recorded and expressed in kg ha^{-1}.

Table 1. Specifications of the hexacopter drone (battery-operated)

Particulars	Specification
Model	E610P
Power source	Li-po battery
Spray fluid tank volume	10 litres
Weight	6.9 kg
Movement speed	0 to 8 m s^{-1}
Weight holding capacity	26 kg
Nozzle type	Flat-fan
Number of nozzles	4
Discharge rate	0 to 3.2 l min^{-1}
Flying height	1 to 20 m
Size	
• Folded condition (L×W×H)	955 × 860 × 660 mm
• Unfolded condition (L×W×H)	2050 × 1830 × 660 mm
Nozzle pressure	3.4 kg cm^{-2}
Spray width	3 to 5 m
Hovering time without spray fluid	30 mins
Spraying time	20 mins
Horizontal hovering accuracy	± 1.5 m
Vertical hovering accuracy	± 0.5 m
Time taken to charge	90 mins
Remote controller range	1.5 km
Resistance to wind	4 m s^{-1}
Resistance to gust	5 m s^{-1}

Table 2. Details of the velocity and operating pressure of the drone used to calibrate the spray volumes

Treatment	Spray volume (L ha^{-1})	Velocity (m s^{-1})	Operating pressure (%)
S_1	30	4	60
S_2	35	4	100
S_3	40	3	70
S_4	45	3	80
S_5	50	3	100

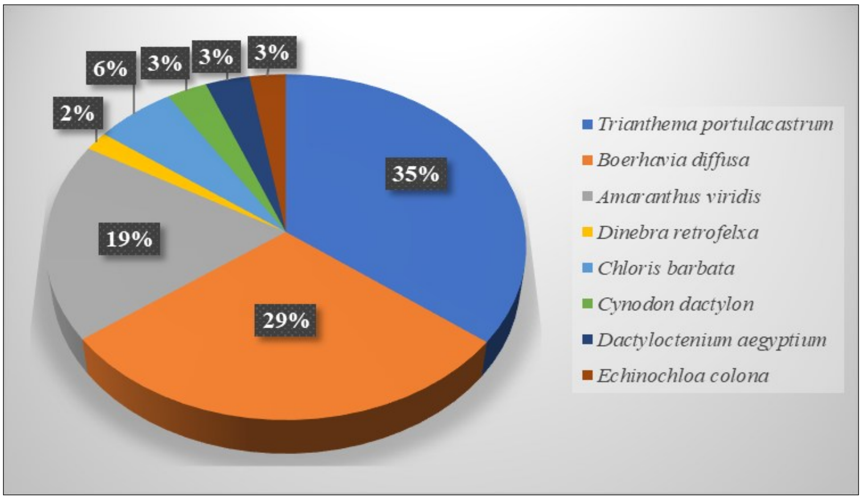

Fig. 1. Weed flora present in the experimental field.

Seed cotton yield

After the bolls bursting, the seed cotton was manually collected from the net plot area and the weight was recorded after drying and expressed in kg ha^{-1}.

Statistical analysis

All the data were statistically analysed using RStudio (Version 2025.05.0+496, 2009-2025, Posit software, PBC) as suggested by Gomez and Gomez (17). The weed-free and unweeded checks were compared using the unpaired t-test with unequal variance. Statistical significance was tested at a 5% level of significance ($p < 0.05$). The non-significant data were marked as 'NS'. The data on weed density and weed dry weight were subjected to a square root transformation before the statistical analysis.

Results and Discussion

Density of grass weeds (No. m^{-2})

The different herbicide combinations significantly influenced the grass weed density in HDPS cotton (Table 3, 4). The lowest grass weed density (0.00 and 0.00 No. m^{-2}) was registered in the weed-free plot at both 20 and 40 DAS, respectively. The unweeded check recorded with a higher grass weed density (29.00 and 55.67 No. m^{-2}) at 20 and 40 DAS, respectively. Pre-emergence (PE) application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1}+ pyrithiobac sodium 62.5 g ha^{-1} recorded significantly lower grass weed density (1.00 and 0.60 No. m^{-2}) at both 20 and 40 DAS, respectively and was comparable (1.20 No. m^{-2}) with PE application of pendimethalin 1.0 kg ha^{-1} *fb* a hand weeding at 25 DAS. Early post-emergence (EPoE) application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1}alone recorded a higher density of grasses (26.67 and 0.93 No. m^{-2}) at 20 and 40 DAS, respectively. Chaudhary (18) found that the pre-emergence application of pendimethalin suppresses the grasses at earlier stages.

Among the different spray fluid volumes, drone application of herbicides at 50 L ha^{-1} recorded a significantly lower grass weed density (8.89 and 0.56 No. m^{-2}) at 20 and 40 DAS, respectively. It was comparable (9.22 and 0.56 No. m^{-2}) to the spray volume of 45 L ha^{-1} at both stages, respectively. Higher grass weed density (10.22 and 1.11 No. m^{-2}) was recorded in the spray volume of 30 L ha^{-1}at all stages. The reduced spray volume might have resulted in the reduced coverage of herbicides. Poor coverage of herbicides could result in reduced efficacy of the herbicides and higher weed density (19).

The interaction effect showed that the lowest grass weed density (0.33 No. m^{-2}) was found with the PE application of pendimethalin 1.0 kg ha^{-1}, *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} at 50 L ha^{-1} at 20 DAS. However, it was comparable (0.33 No. m^{-2}) with the PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1}+ pyrithiobac sodium 62.5 g ha^{-1} at 45 L ha^{-1}during 40 DAS. Higher grass weed density (1.33 No. m^{-2}) was addressed in the EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} at 30 L ha^{-1} at 40 DAS.

Density of broadleaf weeds (No. m^{-2})

The broadleaf weed density was significantly influenced by herbicide combinations and spray fluid volumes (Table 3, 5). The weed-free and unweeded checks were recorded with the lowest (0.00 and 0.00 No. m^{-2}) and the highest (78.00 and 94.33 No. m^{-2}) broadleaf weed density at both 20 and 40 DAS, respectively. Pre-emergence application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} recorded significantly lower density (27.87 and 7.73 No. m^{-2}) of broadleaf weeds at 20 and 40 DAS, respectively. It was comparable (29.80 No. m^{-2}) to the PE application of pendimethalin 1.0 kg ha^{-1} *fb* hand weeding, at 20 DAS. The higher broadleaf weed density (74.27 and 23.13 No. m^{-2}) was observed with EPoE application of quizalafop ethyl 50 g ha^{-1}+ pyrithiobac sodium 62.5 g ha^{-1}alone at both 20 and 40 DAS, respectively. Application of the early post-emergence herbicide alone may reduce its performance than the sequential application of herbicides and other weed management practices (20).

Among the spray volumes, lower broadleaf weed density (39.11 and 11.11 No. m^{-2}) was recorded with 50 L ha^{-1} spray volume at 20 and 40 DAS, respectively. However, it was comparable with the spray volume of 45 L ha^{-1} (41.00 and 12.11 No. m^{-2}). A significantly higher broad-leaved weed density (49.22 and 20.00 No. m^{-2}) was registered with the spray volume of 30 L ha^{-1} at both 20 and 40 DAS, respectively. The reduced spray volume might have resulted in the reduced coverage of herbicides. Poor coverage of herbicides will lead to reduced efficacy of the herbicides and higher weed density. This work aligns with Singh (19).

Considering the interaction effect, lower broadleaf weed density (22.67 and 2.67 No. m^{-2}) was registered with the PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} at 50 L ha^{-1} at both 20 and 40 DAS, respectively. Early post-emergence

Table 3. Effect of different herbicides and spray fluid volumes on density of grass and broadleaf weeds (No. m^{-2}) in cotton

		Grass weed density (No. m^{-2})		Broadleaf weed density (No. m^{-2})	
		20 DAS	40 DAS	20 DAS	40 DAS
Herbicide combinations					
H_1		1.30 (1.20)	1.14 (0.80)	5.47 (29.80)	3.88 (14.67)
H_2		1.19 (1.00)	1.04 (0.60)	5.32 (27.87)	2.78 (7.73)
H_3		5.20 (26.67)	1.19 (0.93)	8.65 (74.27)	4.83 (23.13)
S. Ed.		0.04	0.01	0.07	0.07
C.D. (P = 0.05)		0.11	0.03	0.20	0.18
Spray fluid volume					
S_1		2.74 (10.22)	1.27 (1.11)	6.91 (49.22)	4.44 (20.00)
S_2		2.73 (10.22)	1.18 (0.89)	6.85 (48.22)	4.22 (18.00)
S_3		2.55 (9.56)	1.13 (0.78)	6.33 (42.33)	3.83 (14.67)
S_4		2.48 (9.22)	1.02 (0.56)	6.22 (41.00)	3.43 (12.11)
S_5		2.31 (8.89)	1.02 (0.56)	6.06 (39.11)	3.23 (11.1)
S. Ed.		0.10	0.03	0.16	0.16
C.D. (P = 0.05)		0.23	0.07	0.36	0.36
Check plot					
Weed-free		0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
Unweeded		5.43 (29.00)	7.49 (55.67)	8.86 (78.00)	9.74 (94.33)
Interaction effect					
H×S	**S. Ed.**	0.17	0.03	0.17	0.18
	C.D. (P = 0.05)	NS	0.07	0.39	0.40
S×H	**S. Ed.**	0.18	0.04	0.22	0.22
	C.D. (P = 0.05)	NS	0.09	0.48	0.48

(*original values are given in the parentheses, which were transferred into $\sqrt{x+0.5}$)

H_1 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* Hand weeding;

H_2 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

H_3 - EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

S_1 - 30 L ha^{-1}; S_2 - 35 L ha^{-1}; S_3 - 40 L ha^{-1}; S_4 - 45 L ha^{-1}; S_5 - 50 L ha^{-1}

Table 4. Interaction effect of different herbicides and spray fluid volumes on grass weed density (No. m^{-2}) in cotton at 40 DAS

Grass density at 40DAS (No. m^{-2})						
Treatments	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**Mean**
H_1	1.22 (1.00)	1.22 (1.00)	1.08 (0.67)	1.08 (0.67)	1.08 (0.67)	1.14 (0.80)
H_2	1.22 (1.00)	1.08 (0.67)	1.08 (0.67)	0.91 (0.33)	0.91 (0.33)	1.04 (0.60)
H_3	1.35 (1.33)	1.22 (1.00)	1.22 (1.00)	1.08 (0.67)	1.08 (0.67)	1.19 (0.93)
Mean	1.27 (1.11)	1.18 (0.89)	1.13 (0.78)	1.02 (0.56)	1.02 (0.56)	
			H	**S**	**H×S**	**S×H**
Weed-free	**Unweeded**	**S. Ed.**	0.01	0.03	0.03	0.04
0.71 (0.0)	7.49 (55.67)	**CD (P = 0.05)**	0.03	0.07	0.07	0.09

(*original values are given in the parentheses, which were transferred into $\sqrt{x+0.5}$)

H_1 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* Hand weeding;

H_2 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

H_3 - EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

S_1 - 30 L ha^{-1}; S_2 - 35 L ha^{-1}; S_3 - 40 L ha^{-1}; S_4 - 45 L ha^{-1}; S_5 - 50 L ha^{-1}

Table 5. Interaction effect of different herbicides and spray fluid volumes on broadleaf weed density (No. m^{-2}) in cotton at 20 and 40 DAS

Broadleaf weed density at 20DAS (No. m^{-2})							Broadleaf weed density at 40DAS (No. m^{-2})						
Treatments	S_1	S_2	S_3	S_4	S_5	Mean	Treatments	S_1	S_2	S_3	S_4	S_5	Mean
H_1	6.26 (38.67)	6.23 (38.33)	4.98 (24.33)	4.95 (24.00)	4.92 (23.67)	5.47 (29.80)	H_1	4.33 (18.33)	3.89 (14.67)	3.85 (14.33)	3.71 (13.33)	3.63 (12.67)	3.88 (14.67)
H_2	5.70 (32.00)	5.58 (30.67)	5.31 (27.67)	5.18 (26.33)	4.81 (22.67)	5.32 (27.7)	H_2	3.49 (11.67)	3.44 (11.33)	3.02 (8.67)	2.20 (4.33)	1.78 (2.67)	2.78 (7.73)
H_3	8.80 (77.00)	8.73 (75.67)	8.69 (75.00)	8.55 (72.67)	8.46 (71.00)	8.65 (74.27)	H_3	5.51 (30.00)	5.33 (28.00)	4.63 (21.00)	4.37 (18.67)	4.29 (18.00)	4.83 (23.13)
Mean	6.92 (49.22)	6.85 (48.22)	6.33 (42.33)	6.23 (41.00)	6.06 (39.11)		Mean	4.44 (20.00)	4.22 (18.00)	3.83 (14.67)	3.43 (12.11)	3.23 (11.11)	
			H	S	H×S	S×H				H	S	H×S	S×H
Weed-free	Unweeded	S. Ed.	0.07	0.16	0.17	0.22	Weed-free	Unweeded	S. Ed.	0.07	0.16	0.18	0.22
0.71 (0.0)	8.86 (78.00)	CD (P = 0.05)	0.20	0.37	0.39	0.48	0.71 (0.0)	9.74 (94.33)	CD (P = 0.05)	0.18	0.36	0.40	0.48

(*original values are given in the parentheses, which were transferred into $\sqrt{x+0.5})$

H_1 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* Hand weeding;

H_2 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

H_3 - EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

S_1 - 30 L ha^{-1}; S_2 - 35 L ha^{-1}; S_3 - 40 L ha^{-1}; S_4 - 45 L ha^{-1}; S_5 - 50 L ha^{-1}

application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} at 30 L ha^{-1}spray volume resulted in higher broadleaf weed density (77.00 and 30.00 No. m^{-2}) at both 20 and 40 DAS, respectively.

Total weed density (No. m^{-2})

Total weed density was significantly influenced by different herbicide combinations and spray fluid volumes in high-density planting system (HDPS) of cotton (Table 6, 7). The weed-free check recorded the lowest total weed density (0.00 No. m^{-2}) at all the stages. The highest total weed density recorded in the unweeded check (107.00 and 150.00 No. m^{-2}) at 20 and 40 DAS, respectively. PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} registered with lower (28.87 and 8.33 No. m^{-2}) total weed density at both 20 and 40 DAS, respectively. During 20 DAS, it was comparable (31.00 No. m^{-2}) to PE application of pendimethalin 1.0 kg ha^{-1} *fb* hand weeding at 25 DAS. EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} registered with higher total weed density (100.93 and 24.07 No. m^{-2}) at 20 and 40 DAS, respectively. The sequential application of herbicide in the high-density cotton contributed to lower weed density in the treatments of pre-emergence herbicide *fb* application of early post-emergence herbicides and pre-emergence herbicide *fb* hand weeding (21).

Among different spray fluid volumes, 50 L ha^{-1}registered with lower total weed density (48.00 and 11.67 No. m^{-2}) at 20 and 40 DAS, respectively. It was comparable with the spray fluid volume of 45 L ha^{-1} (50.22 and 12.67 No. m^{-2}) at 20 and 40 DAS, respectively. A significantly higher total weed density (59.44 and 21.11 No. m^{-2}) was observed in the spray volume of 30 L ha^{-1} at 20 and 40 DAS, respectively. The higher volume of herbicides leads to better coverage of the herbicides over the weed flora. This work aligns with Singh (19).

Regarding the interaction effect, PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} at 50 L ha^{-1} recorded lower total weed density (22.67 and 3.00 No. m^{-2}) at 20 and 40 DAS, respectively. EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} with 30 L/ha spray volume had found with higher total weed density (104.33 and 31.33 No. m^{-2}) at all stages.

Total weed dry weight (g m^{-2})

The herbicide combinations and spray fluid volumes significantly influenced the total weed dry weight under HDPS cotton (Table 6). The weed-free plot recorded the lowest total weed dry weight (0.00 and 0.00 g m^{-2}) and the unweeded check recorded with the highest total weed dry weight (24.67 and 102.84 g m^{-2}) at 20 and 40 DAS, respectively. Among the herbicide treatments, PE application of pendimethalin 1.0 kg ha^{-1} and EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} recorded significantly lower weed dry weight (5.32 and 8.29 g m^{-2}) at 20 and 40 DAS, respectively. It was followed by the PE application of pendimethalin 1.0 kg ha^{-1} + hand weeding at 25 DAS (6.16 and 11.48g m^{-2}) at 20 and 40 DAS, respectively. EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} alone recorded significantly higher weed dry weight (20.82 and 42.13 g m^{-2}) at both 20 and 40 DAS, respectively. The higher total weed density in the application of early post-emergence herbicide alone might have resulted in higher weed dry weight (20).

Considering the spray volumes, 50 L ha^{-1} spray volume recorded lower total weed dry weight (9.67 and 19.51 g m^{-2}) at 20 and DAS, respectively. It was comparable with 45 L ha^{-1} (9.90 g m^{-2}) during 20 DAS. Meanwhile, higher weed dry weight (11.97 and 21.97 g m^{-2}) was recorded in the spray volume of 30 L ha^{-1} at 20 and 40 DAS, respectively. Lower weed dry weight might be due to the better deposition and absorption of herbicides in the higher spray volumes (22).

Observation on the growth and yield of cotton

Drymatter production (kg ha^{-1})

The herbicide combinations and spray fluid volumes significantly influenced the drymatter production of cotton at the harvest stage (Fig. 2). The weed-free check recorded higher drymatter production (5583 kg ha^{-1}) of cotton at harvest stage. The weed-free check produced 31% increased drymatter over the unweeded check (3856 kg ha^{-1}). Among the herbicide combinations, PE

Table 6. Effect of different herbicides and spray fluid volumes on total weed density (No. m^{-2}) and total weed dry weight (g m^{-2}) in cotton

		Total weed density (No. m^{-2})		Total weed dry weight (g m^{-2})	
		20 DAS	**40 DAS**	**20 DAS**	**40 DAS**
Herbicide combinations					
H_1		5.57 (31.00)	3.99 (15.47)	2.58 (6.16)	3.46 (11.48)
H_2		5.40 (28.87)	2.89 (8.33)	2.40 (5.32)	2.96 (8.29)
H_3		10.07 (100.93)	4.93 (24.07)	4.61 (20.82)	6.53 (42.13)
S. Ed.		0.06	0.07	0.06	0.03
C.D. (P = 0.05)		0.17	0.19	0.17	0.07
Spray fluid volume					
S_1		7.48 (59.44)	4.57 (21.11)	3.37 (11.97)	4.44 (21.97)
S_2		7.42 (58.44)	4.33 (18.89)	3.31 (11.50)	4.40 (21.51)
S_3		6.86 (51.89)	3.94 (15.44)	3.21 (10.80)	4.28 (20.20)
S_4		6.74 (50.22)	3.51 (12.67)	3.07 (9.90)	4.26 (19.97)
S_5		6.56 (48.00)	3.32 (11.67)	3.03 (9.67)	4.21 (19.51)
S. Ed.		0.12	0.16	0.08	0.05
C.D. (P = 0.05)		0.28	0.37	0.18	0.12
Check plot					
Weed-free		0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
Unweeded		10.37 (107.00)	12.27 (150.00)	5.02 (24.67)	10.17 (102.84)
Interaction effect					
H×S	**S. Ed.**	0.16	0.18	0.17	0.10
	C.D. (P = 0.05)	0.35	0.40	NS	NS
S×H	**S. Ed.**	0.18	0.22	0.17	0.10
	C.D. (P = 0.05)	0.40	0.49	NS	NS

(*original values are given in the parentheses, which were transferred into $\sqrt{x+0.5}$)

H_1 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* Hand weeding;

H_2 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

H_3 - EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

S_1 - 30 L ha^{-1}; S_2 - 35 L ha^{-1}; S_3 - 40 L ha^{-1}; S_4 - 45 L ha^{-1}; S_5 - 50 L ha^{-1}

Table 7. Interaction effect of different herbicides and spray fluid volumes on total weed density (No. m^{-2}) in cotton at 20 and 40 DAS

Total weed density at 20 DAS (No. m^{-2})							Total weed density at 40 DAS (No. m^{-2})						
Treatments	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**Mean**	**Treatments**	**S_1**	**S_2**	**S_3**	**S_4**	**S_5**	**Mean**
H_1	6.39 (40.33)	6.36 (40.00)	5.08 (25.33)	5.05 (25.00)	4.98 (24.33)	5.57 (31.00)	**H_1**	4.45 (19.33)	4.02 (15.67)	3.94 (15.00)	3.81 (14.00)	3.72 (13.33)	3.99 (15.47)
H_2	5.85 (33.67)	5.73 (32.33)	5.40 (28.67)	5.24 (27.00)	4.81 (22.67)	5.41 (28.87)	**H_2**	3.63 (12.67)	3.54 (12.00)	3.14 (9.33)	2.27 (4.67)	1.87 (3.00)	2.89 (8.33)
H_3	10.24 (104.33)	10.17 (103.00)	10.11 (101.67)	9.96 (98.67)	9.87 (97.00)	10.07 (100.93)	**H_3**	5.64 (31.33)	5.43 (29.00)	4.74 (22.00)	4.45 (19.33)	4.38 (18.67)	4.93 (24.07)
Mean	7.49 (59.44)	7.42 (58.44)	6.86 (51.89)	6.75 (50.22)	6.95 (47.8)		**Mean**	4.57 (21.11)	4.33 (18.89)	3.94 (15.44)	3.51 (12.67)	3.32 (11.67)	
			H	**S**	**H×S**	**S×H**				**H**	**S**	**H×S**	**S×H**
Weed-free	**Unweeded**	**S. Ed.**	0.06	0.12	0.16	0.18	**Weed-free**	**Unweeded**	**S. Ed.**	0.07	0.16	0.18	0.22
0.71 (0.00)	10.37 (107.00)	**CD (P = 0.05)**	0.17	0.28	0.35	0.40	0.71 (0.00)	12.27 (150.00)	**CD (P = 0.05)**	0.19	0.37	0.40	0.49

(*original values are given in the parentheses, which were transferred into $\sqrt{x+0.5}$)

H_1 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* Hand weeding;

H_2 - PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

H_3 - EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1};

S_1 - 30 L ha^{-1}; S_2 - 35 L ha^{-1}; S_3 - 40 L ha^{-1}; S_4 - 45 L ha^{-1}; S_5 - 50 L ha^{-1}

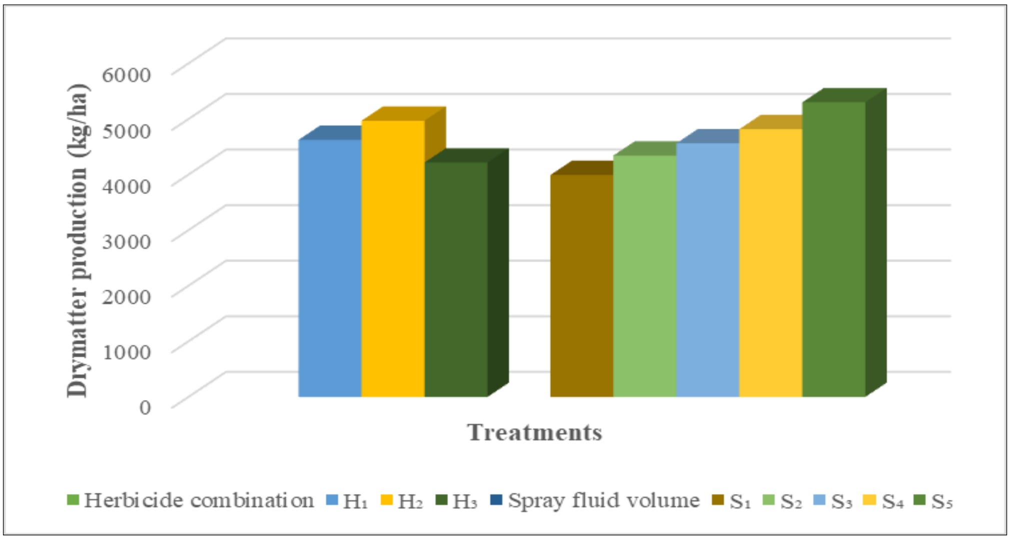

Fig. 2. Effect of herbicide combinations and spray fluid volumes on drymatter production of cotton at harvest stage (kg ha^{-1}).

application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} recorded higher drymatter production (4970 kg ha^{-1}) of cotton, it was comparable to the PE application of pendimethalin 1.0 kg ha^{-1} *fb* hand weeding at 25 DAS (4626 kg ha^{-1}). The effective weed management practice might have attributed to the increased efficiency of photosynthesis and partitioning of the assimilates (23).

Among the spray volumes, 50 L ha^{-1} spray volume recorded statistically higher drymatter production (5301 kg ha^{-1}) of cotton at harvest. It was comparable (4819 and 4564 kg ha^{-1}) with the spray volume of 45 and 40 L ha^{-1}, respectively. Efficient weed control and reduced weed competition in the higher spray volume of herbicides might have contributed to higher drymatter production in cotton (24).

With regard to the interaction effect, PE application of pendimethalin 1.0 kg ha^{-1} and EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} with 50 L ha^{-1} spray volume recorded higher drymatter production (5498 kg ha^{-1}) at the harvest stage. A significantly lower drymatter production (3757 kg ha^{-1}) was registered in the EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} with 30 L ha^{-1}.

Seed cotton yield (kg ha^{-1})

The herbicide combinations and spray fluid volumes significantly influenced the seed cotton yield (Fig. 3). The weed-free check recorded with significantly higher seed cotton yield (2365 kg ha^{-1}) over all the plots. When compared with weed-free check, a 29% seed cotton yield reduction was noticed in the unweeded check (1672 kg ha^{-1}). Among the herbicides, PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} produced significantly higher seed cotton yield (2161 kg ha^{-1}), it was followed by PE application of pendimethalin 1.0 kg ha^{-1} *fb* hand weeding (1982 kg ha^{-1}). The effective weed management might have attributed to the increased efficiency of photosynthesis and partitioning of the assimilates and resulted in a higher yield of cotton (23).

Among the spray volumes, spray fluid quantity 50 L ha^{-1} recorded statistically higher seed cotton yield (2223 kg ha^{-1}). It was comparable to the spray volume of 45 L ha^{-1} (2069 kg ha^{-1}). Lower seed cotton yield was recorded with the spray volume of 30 L ha^{-1}. The reduced weed competition in the higher spray volume of herbicides might have contributed to higher yield (24).

The interaction effect among the herbicide combinations and spray fluid volume was found to be non-significant.

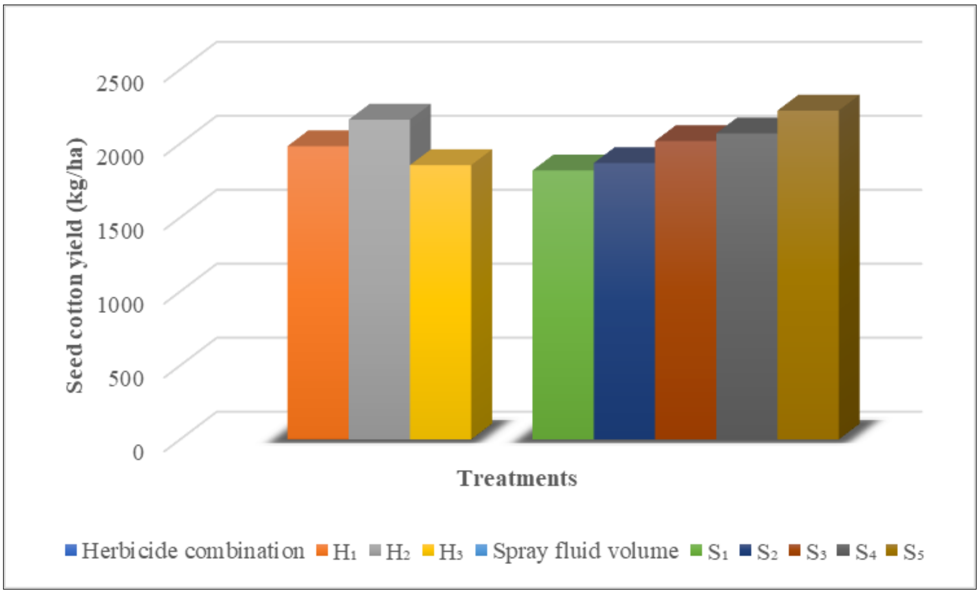

Fig. 3. Effect of herbicide combinations and spray fluid volumes on seed cotton yield (kg ha^{-1}).

Conclusion

The results indicated that, among the herbicide treatments, PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1} recorded lower total density and dry weight of weeds and higher drymatter production and seed cotton yield. The spray fluid volume of 50 L ha^{-1} produced higher drymatter and seed cotton yield with lower density and dry weight of weeds. However, it was comparable with 45 L ha^{-1} spray fluid volume.

The above results recorded that the PE application of pendimethalin 1.0 kg ha^{-1} *fb* EPoE application of quizalafop ethyl 50 g ha^{-1} + pyrithiobac sodium 62.5 g ha^{-1}, with the spray fluid volume of 45 L ha^{-1} can effectively control the weeds with a higher yield of cotton.

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Authors' contributions

APA conducted the experiment, data collection, data analysis and wrote the original draft. SR was responsible for conceptualization, supervision and manuscript editing. SP, RK[1], RR, RK[2] and MMRAF contributed to supervision and editing. All authors read and approved the final manuscript [RK[1]- R Kavitha; RK[2]- R Kumaraperumal].

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflicts of interest to declare.

Ethical issues: None

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