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Energy efficient weed control in high density planting rainfed cotton

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Abstract

An experiment utilizing a split-plot design was done to ascertain the optimal plant population and weed management strategies for enhancing yield, net income and energy efficiency in high-density rainfed cotton cultivation. The primary plot treatments comprised three spacing configurations: 100x10 cm, 150x50x10 cm and 175x50x10 cm. Six weed management approaches were evaluated as subplot treatments, with each treatment replicated three times throughout the 2023-24 rabi season. These practices included power weeding on 20 and 45 days after sowing (DAS), intercropping with black gram, hand weeding on 20 and 45 DAS, herbicide application of Metolachlor (pre-emergence) on 5 DAS, and a combination of Pyrithiobac sodium plus Quizalofop ethyl (post-emergence) on 20 DAS, along with weedy check and weed-free check.

The 100 x 10 cm spacing combined with power weeding proved superior, achieving higher yield parameters, greater yield, increased income (Rs. 67238/ha), a benefit-cost ratio of 2.27, energy productivity of 0.38 Kg/MJ, net energy productivity of 30334 MJ/ha, and an energy use efficiency of 4.0 in high-density planting. The narrow-row spacing (100x10 cm) with power weeding also optimized plant population and enhanced per-plant productivity. This configuration also supported proper soil tilling and aeration, enabling a higher uptake of inputs with minimum energy expenditure for weeding, leading to improved overall performance.

Keywords

economics; energy productivity; energy use efficiency; rainfed cotton; seed cotton; weed control efficiency

Introduction

Cotton is the world's leading fibre crop and a crucial natural resource, with an annual global economic impact of at least $600 billion. Beyond its role in fibre production, cotton has extensive applications across the value chain, from textiles to apparel and cottonseed products used in food and feed, further boosting its economic significance (1). Cotton is vital as a rainfed crop, supporting the livelihoods of rural communities (2). It is an essential cash crop in India, cultivated across approximately 11.8 million hectares, directly sustaining 5.8 million farmers and supporting millions more involved in related activities. However, despite its extensive cultivation, productivity remains a concern, with India's yield falling below the global average of 1,500 kg/ha. Approximately 60% of the raw material needs for India's textile industry are met by domestic cotton production (3).

On the other hand, the success of cotton cultivation mainly depends on soil fertility, climatic situations, varieties with high-yielding capacity and rainfall (4). The success of cotton cultivation in India largely depends on soil fertility, climate, high-yielding varieties and rainfall. Labour is the most significant cost factor in rainfed cotton farming in India, with tasks such as sowing, weeding, and harvesting comprising nearly 40% of the total production cost. Conventional cultivation, involving certain varieties, often requires 15-20 pickings, which increases labour costs (5). In contrast, varieties recommended for high-density planting involve 2-3 pickings, which reduce harvesting costs, though they can increase expenses associated with manual sowing and weeding.

In Tamil Nadu, approximately 70,000 hectares are dedicated to rainfed cotton cultivation, with key production districts including Virudhunagar, Ramanathapuram and Tirunelveli. Specifically, Ramanathapuram district allocates 16,000 hectares of rainfed cotton, depending on monsoon rainfall. The district receives an average annual rainfall of 716 mm, with 67% (478 mm) occurring during the Northeast Monsoon (NEM) season, exhibiting a dependable coefficient of variation (CV) of 28%. An additional 48 mm of rainfall during the winter season further supports successful rainfed cotton cultivation (6). Analysis of rainfall variability indicates that cultivating cotton during the 130 days within the NEM season allows for a successful harvest under rainfed conditions. To mitigate risks and achieve optimal yield, we used CO 17 - a short-duration, drought-tolerant cotton variety in our study. Despite challenges such as rainfall variability and pest management, advanced farming techniques offer significant opportunities to enhance productivity. For instance, high-density planting system (HDPS) offer considerable potential to boost productivity while optimizing water and resource use (7).

The yield of rainfed cotton remains low due to factors such as longer crop duration, limited water availability, high weed incidence and other abiotic stresses. Weed infestation, crop-weed competition, low water availability and reduced water-use efficiency are major limitations to achieve expected yields under rainfed conditions. Chemical weed management methods are often not feasible for small farmers due to the high cost of chemicals and the lack of available equipment for spraying (8). Additionally, cotton cultivation under rainfed conditions typically results in lower net income due to the high cost of production, as labour is required for all operations, from sowing to harvest. Therefore, management practices that effectively control weeds and make optimal use of limited water in rainfed conditions while reducing labour costs and increasing net income are essential for achieving optimal yields.

The High-Density Planting System (HDPS) has emerged as a promising technology for successful cotton cultivation under rainfed conditions in India, with significant potential to increase yields at feasible costs. HDPS, when paired with short-duration cotton varieties, enhances productivity by promoting efficient light interception, optimal leaf area development and early canopy closure-all of which contribute to effective weed control and improved yields. This approach employs narrow row spacing and a higher plant density per unit area, leading to increased leaf surface area, which captures more sunlight and reduces light penetration to the ground. A dense canopy achieves rapid closure, which offers several benefits: reduced soil water loss through transpiration, greater weed suppression, and an improved microclimate within the canopy. These factors collectively enhances photosynthesis, leading to higher yields through increased boll production, better boll development and improved fibre quality (9). High-density planting in cotton, combined with short-duration varieties with few or no monopodial branches, is an ideal practice to enhance water-use efficiency and reduce labour requirements for harvesting. Although high-density planting supports higher yields in a shorter time, it also presents challenges, such as increased production costs due to the need for more labour. Additional labour is required for regular sowing and weeding to minimize crop-weed competition during critical growth periods, ensuring optimal yield at high planting densities (10).

The present study aims to develop a comprehensive technology package that achieves optimal yields, enhances net income, reduces labour costs for sowing and weeding and improves energy efficiency through better mechanization practices under rainfed conditions.

Materials and Methods

Experimental site

The field experiment was conducted during the Rabi season of 2023-2024 (December to April) at the A-3 block of Panayadiendhal village (9.27'N, 78.69'E) in the Ramanathapuram district of Tamil Nadu, India, at an altitude of 115 ft above mean sea level.

The meteorological data recorded during the cropping period were as follows:

Soil parameters:

Mean annual rainfall of the area	:	716 mm
Amount of rainfall obtained during the cropping period	:	480 mm
Mean maximum temperature	:	32.2 ^{0}C
Mean minimum temperature	:	23.2 ^{0}C
Relative humidity	:	79 - 95 %
Mean evaporation	:	3.5 mm/day

Experimental design and treatments

Soil type	:	Clay loam soil
P^H	:	8.3
Electrical conductivity	:	4.5 (ds m^{-1})
Organic carbon	:	0.24 % (Low)
Available nitrogen (Kg/ha)	:	153(Low)
Available phosphorus (Kg/ha)	:	11(Medium)
Available potassium of (Kg/ha)		312(High)

The experiment was conducted over a total area of 0.2 hectares using a split-plot design, incorporating three types of spacings as main plot treatment: S_1-100x10 cm, S_2 -150x50x10 cm, S_3 -175x50x10 cm. The spacing adopted for manual dibbling by the researchers (3, 11) was also considered for mechanized seeding to develop a compendium technology for a mechanized high-density planting system in cotton cultivation to reduce cultivation costs by minimizing labour requirements.

The main plot treatment comprised six weed management approaches as subplot treatments, each replicated thrice. Power weeding was selected for its ability to control weeds and its potential to loosen the soil and improve moisture availability by harvesting rainwater. This method also addresses challenges such as labour shortages and high cultivation costs. Black gram intercropping was chosen for its smothering effect on weeds and potential to generate additional income. Hand weeding was included for comparative analysis with existing practices. Chemical control was employed to evaluate its effectiveness in weed management, but moisture availability during the chemical application is crucial, especially for pre-emergence herbicides. Therefore, rainfall significantly influences the success rate of chemical weed control. Both weedy and weed-free checks were included for comparative analysis and statistical evaluation of all parameters.

Experimental procedures

Field preparation

The experimental field was ploughed twice using a cultivator and once with a rotavator as part of the primary and secondary tillage operations, ensuring the soil was converted to a fine tilth condition.

Spacing and sowing

Sowing of de-linted cotton seeds was conducted at different spacings: (S_1) 100 x 10 cm, (S_2) 150 x 50 x 10 cm (paired row) and (S_3) 175 x 50 x 10 cm (paired row). A seed-cum-fertilizer drill with a width of 2.10 meters and nine delivery tubes, each spaced 25 cm apart, was used to facilitate seed flow. This drill features furrow openers that create narrow channels in the soil, allowing for the placement of seeds and fertilizers. After placement, the furrows are covered with soil by the leveling section at the back of the furrow openers.

In our experimental field, seeds were loaded into the seed box and the tractor was drawn at 2 km/h to achieve a 10 cm spacing between plants. To achieve the required spacing of 50, 100, 150 or 175 cm between crop rows, seeds were inserted alone into the requisite cups of the drill. For instance, to achieve 100 cm spacing between crop rows, the 1st, 5th and 9th tyne seed cups (with a tyne spacing of 25 cm) were allowed to release de-linted cotton seeds while the other cups were closed. Similarly, to achieve a 150 x 50 cm spacing between the crop rows, the 1st, 7th and 9th tyne seed cups were opened for seed flow while the remaining cups were closed.

Weeding operations

Treatment number	Treatments	Treatment details
W_1	Power weeding	Using a 7.5 HP petrol-powered power weeder at 20 and 45 DAS.
W_2	Intercropping with black gram	Using VBN-11 variety.
W_3	Hand weeding	Using hand hoe at 20 and 45 DAS.
W_4	Chemical control	Application of metolachlor as pre -emergence on 5 DAS and Pyrithiobac-sodium plus Quizalofop ethyl combination on 20 DAS as post-emergence.
W_5	Weedy check	Maintained without carrying out any weed control operation.
W_6	Weed free check	Maintained by carrying out frequent hand weeding on 15, 25, 35, 45 and 60 DAS

All these six weed management methods were implemented as treatments to identify the most suitable approach for rainfed cotton cultivation in terms of efficiency and cost.

Harvesting

The harvesting operation was performed using a hand-operated, battery-powered spindle picker machine. Manual cotton picking typically requires 20 labourers per hectare; however, labour availability has significantly decreased and labour costs have risen (Rs.800 per male and Rs.450 per female labour per day). Therefore, this research aims to develop a comprehensive mechanized technology for rainfed cotton cultivation, allowing the harvesting operation to be conducted with a spindle picker machine, which can be hired for Rs. 900/day. The recommended agronomic practice of cotton was followed, as outlined in the TNAU Crop Production Guide 2020.

Observations

The growth and yield parameters were observed from five plants selected at the centre of each plot. The various stages at which the growth parameters were measured included the vegetative stage (10 to 55 days), flowering stage (55 to 80 days), boll formation stage (80 to 120 days) and harvest stage (115 to 130 days). The actual days on which the growth parameters were recorded were at 30, 60, 90 and 120 DAS. Yield parameters were assessed during the boll formation stage (80 to 120 days) and the harvest stage (115 to 130 days). Specifically, boll weight, the number of bolls per plant and the number of bolls per square meter were observed at 85 DAS, while the seed cotton yield was measured at 125 DAS, following harvest.

Weed density was assessed using a quadrant placed randomly in each plot, and the weed control efficiency was calculated at 30, 45 and 60 DAS. Both weedy and weed-free checks were utilized to determine weed control efficiency. Collected weed samples were oven-dried at 80^0C for 48 hours until a constant weight was achieved. The harvesting operation was performed using a hand-operated manual picker and the lint yield was recorded from each plot and expressed in Kg/ha.

Weed control efficiency

Weed control efficiency (WCE) was calculated using the formula proposed by Mani (12):

$$\text{WCE (\%)} = \frac{\text{Dry weight of weeds in control plots - Dry weight of weeds in treated plots}}{\text{Dry weight of weeds in control plots}} \times 100 \quad \text{Eqn.01}$$

Energy calculation

Energy use efficiency and energy productivity were evaluated using the formula proposed by Devasenapathy (13). The values for all energy inputs and outputs were determined using established energy conversion coefficients.

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}} \quad \text{Eqn.02}$$

$$\text{Net Energy (MJ/ha)} = \text{Energy output (MJ/ha) - Energy input (MJ/ha)} \quad \text{Eqn.03}$$

$$\text{Energy Productivity (Kg/MJ)} = \frac{\text{Output (Kg)}}{\text{Energy input (MJ/ha)}} \quad \text{Eqn.04}$$

Economics

Net return, benefit-cost ratio and cost of cultivation were calculated based on the current market price of inputs and produce.

$$\text{Net return (Rs/ha)} = \text{Gross return (Rs/ha) - Cost of cultivation (Rs/ha)} \quad \text{Eqn.05}$$

$$\text{Benefit cost ratio (BCR)} = \frac{\text{Gross return (Rs/ha)}}{\text{Cost of cultivation (Rs/ha)}} \quad \text{Eqn.06}$$

Statistical analysis

Observations on various characteristics were statistically analyzed following the methodology adopted by Gomez (14). The collected data were compiled, tabulated and subjected to statistical analysis. A One-way ANOVA was performed using AGRES software to evaluate the treatment effect and statistical significance was determined at a critical difference with a probability level of p=0.05% (15).

Results

Weed species

The major weed species observed in the weedy check plot included *Trianthema portulocastrum, Chloris barbata, Astralagus dasyanthus, Cucumis priocarpus, Cyperus rotundus, Chrozophora rottleri, Poa annua, Abutilon palmeri* and *Paspalum quadrifarium*. Broad leaved weeds are significant crop competitors, as they consume limited resources such as soil moisture and nutrients under rainfed conditions. Consequently, these weeds adversely affect crop growth and development from the early stages, particularly during the critical period of crop-weed competition. This leads to a substantial reduction in yield if not managed effectively. The technologies implemented in this study will help control these weeds early, resulting in increased production and productivity.

Weed control efficiency

The spacing and weed management strategies, both separately and collectively, markedly affected the efficacy of weed control (Table 1). Among the main plot treatments, the highest percentage of weed control efficiency (72.3%) was recorded at a spacing of 100x10 cm (S_1). Among the subplot treatments, the weed-free check (W6) achieved the highest weed control efficiency at 95.0%, while weeding using a power weeder (W_1) followed closely with an efficiency of 88.5%. Combining the 100x10 cm spacing and the weed-free check recorded the highest overall weed control efficiency at 97.0%. The next highest weed control efficiency was observed for any spacing combined with the weed-free check. Moreover, integrating 100x10 cm spacing with power weeding improved weed control efficiency by 91.50%. This effectiveness can be attributed to the uprooting process facilitated by the power weeder, which reduces weed growth and minimizes crop-weed competition, allowing for better uptake of essential inputs. Moreover, when cotton plants are grown at a closer spacing of 100x10 cm, the denser canopy effectively covers the entire ground surface, limiting the germination and growth of weeds due to reduced light availability. In contrast, the cotton plants quickly cover the ground with closer spacing than the broader spacing or paired row systems of 150x50x10 cm and 175x50x10 cm. The lowest weed control efficiency was observed at the spacing of 175x50x10 cm (S_3) in combination with the weedy check (W_5) at 30 days after sowing (DAS) and this trend continued at 45 and 60 DAS.

Yield of Seed cotton (Kg/ha)

The spacing and weeding techniques significantly influenced seed cotton yield (Table 2). Among the main plot treatments, the highest seed cotton yield (1841 Kg/ha) was recorded at the spacing of 100x10 cm (S_1), while the lowest yield (1713 Kg/ha) was recorded at a spacing of 175x50x10cm (S_3). Among the subplot treatments, the highest yield of seed cotton (2118 Kg/ha) was noted in the weed-free check (W_6), whereas the lowest yield (1131 Kg/ha) occurred in the weedy check (W_5).

Combining 100x10 cm (S_1) with weed free check (W_6) achieved the highest overall yield of 2212 Kg/ha. Conversely, combining treatments involving the 175x50x10 cm spacing (S_3) with the weedy check (W_5) recorded the lowest yield at 1026 Kg/ha. Moreover, the treatment combination of 100x10 cm spacing (S_1) and weed management using a power weeder (W_1) yielded 2084 Kg/ha of seed cotton.

Table 1. Effect of treatment combinations of various spacing and weed management techniques on weed control efficiency at 30, 45 and 60 DAS

Main plot Treatment	***Sub plot treatments***						
	W_1	**W_2**	**W_3**	**W_4**	**W_5**	**W_6**	**Mean**
			WCE at 30 DAS				
S_1	91.5 (10.06)	76.1 (9.22)	84.7 (9.70)	84.9 (9.71)	0.0 (0.05)	97.0 (10.35)	**72.3**
S_2	88.1 (9.89)	73.7 (9.08)	83.7 (9.65)	83.1 (9.62)	0.0 (0.5)	95.2 (10.25)	**70.6**
S_3	86.10 (9.78)	70.9 (8.92)	80.6 (9.48)	79.0 (9.39)	0.0 (0.5)	92.9 (10.14)	**68.2**
Mean	**88.5**	**73.5**	**83**	**82.3**	**0.0**	**95.0**	**-**
			WCE at 45 DAS				
S_1	71.3 (8.95)	58.2 (8.13)	66.1 (8.63)	65.8 (8.61)	0.0 (0.5)	77.3 (9.29)	**56.4**
S_2	68.3 (8.77)	57.0 (8.05)	64.0 (8.50)	63.9 (8.49)	0.0 (0.5)	75.9 (9.21)	**54.8**
S_3	66.7 (8.67)	52.9 (7.77)	60.0 (8.25)	61.3 (8.33)	0.0(0.5)	72.3 (9.0)	**52.2**
Mean	**68.7**	**56.0**	**63.3**	**63.6**	**0.0**	**75.1**	-
			WCE at 60 DAS				
S_1	95.5 (10.2)	79.1 (9.3)	91.8 (10.0)	90.8 (10.0)	0.0 (0.5)	97.9 (10.3)	**75.8**
S_2	92.2 (10.1)	76.5 (9.2)	88.5 (9.9)	87.3 (9.8)	0.0 (0.5)	94.9 (10.2)	**73.2**
S_3	88.6(9.9)	73.2 (9.0)	85.8 (9.7)	85.2 (9.7)	0.0 (0.5)	93.3(10.1)	**71.01**
Mean	**92.1**	**76.2**	**88.7**	**87.7**	**0.0**	**95.3**	**-**

Not statistically analysed

Values represented in parenthesis are square root transformed values.

(S1) 100x10 cm, (S2) 150x50x10 cm, (S3) 175x50x10 cm, Weeding by power weeder with 75 cm width at 20 and 45 days after sowing (W1), intercropping of black gram along with sowing of cotton (W2), hand weeding two times at 20 and 45 days after sowing (W3), chemical weed management by the application of herbicide- metolachlor as pre-emergence on 5 DAS and Pyrithiobac sodium plus Quizalofop ethyl combination on 20 DAS as post-emergence(W4), weedy check was maintained without carrying out any weed control operation (W5), weed free check by carrying out frequent hand weeding on 15, 25, 35, 45 and 60 DAS (W6).

Table 2. Effect of treatment combinations of various spacing and weed management techniques on yield of seed cotton.

Main plot Treatment	***Sub plot treatments***						
	W_1	**W_2**	**W_3**	**W_4**	**W_5**	**W_6**	**Mean**
S_1	2084	1510	2054	1962	1224	2212	**1841**
S_2	2029	1481	2008	1912	1143	2120	**1782**
S_3	1991	1409	1963	1867	1026	2023	**1713**
Mean	**2034**	**1466**	**2008**	**1913**	**1131**	**2118**	
	S	**W**	**Interaction (SxW)**		**Interaction (WxS)**		
S. Ed	1.5	5.3	8.5		9.2		
CD (p=0.05)	4.2	10.9	17.7		18.9		

(S1) 100x10 cm, (S2) 150x50x10 cm, (S3) 175x50x10 cm, Weeding by power weeder with 75 cm width at 20 and 45 days after sowing (W1), intercropping of black gram along with sowing of cotton (W2), hand weeding two times at 20 and 45 days after sowing (W3), chemical weed management by the application of herbicide- metolachlor as pre-emergence on 5 DAS and Pyrithiobac sodium plus Quizalofop ethyl combination on 20 DAS as post-emergence(W4), weedy check was maintained without carrying out any weed control operation (W5), weed free check by carrying out frequent hand weeding on 15, 25, 35, 45 and 60 DAS (W6).

Energy parameters

Energy productivity

The highest level of energy productivity (0.27 kg/MJ) was recorded at a spacing of 100x10 cm (S_1) among the main plot treatments (Fig.1). Among the subplot treatments, the highest energy productivity (0.35 MJ/kg) was observed in the power weeded plots (0.33 MJ/kg), with the weed-free check (W_6) being the subsequent best treatment for achieving higher energy productivity.

Combining 100x10 cm spacing (S_1) with power weeding (W1) recorded the highest energy productivity at 0.38 kg/MJ. In contrast, the treatment combination of 175x50x10 cm spacing (S_3) with the weedy check (W_5) recorded the lowest energy productivity at 0.07 MJ/ha.

Net Energy

Net energy is the difference between input and output energy (16). All the technologies adopted in this study contribute to increased output energy and reduced input energy through the decreased labour involved, resulting in higher net energy. The treatment combination of narrow spacing (100x10 cm) and power weeding enhanced yield and achieved an output energy of 30,334 MJ/ha, corresponding to a 2,084 kg/ha yield. The reduction in input energy through power weeding led to a higher net energy of 28,825 MJ/ha.

The highest level of net energy (26,132 MJ/ha) among the main plot treatments was recorded at the 100x10 cm spacing (S_1) (Fig. 2). Among the subplot treatments, the highest net energy (28,825 MJ/ha) was observed in the power weeded plots (W_1). In comparison, the weed-free check (W_6) recorded the next best level of net energy at 28,437 MJ/ha.

The combination of 100x10 cm spacing (S_1) and power weeding (W_1) resulted in the highest net energy level of 30,334 MJ/ha. This can be attributed to the higher yield achieved with lower energy utilization. Conversely, the treatment combination of 175x50x10 cm spacing (S_3) with the weedy check (W_5) yielded the lowest net energy at 11,620 MJ/ha.

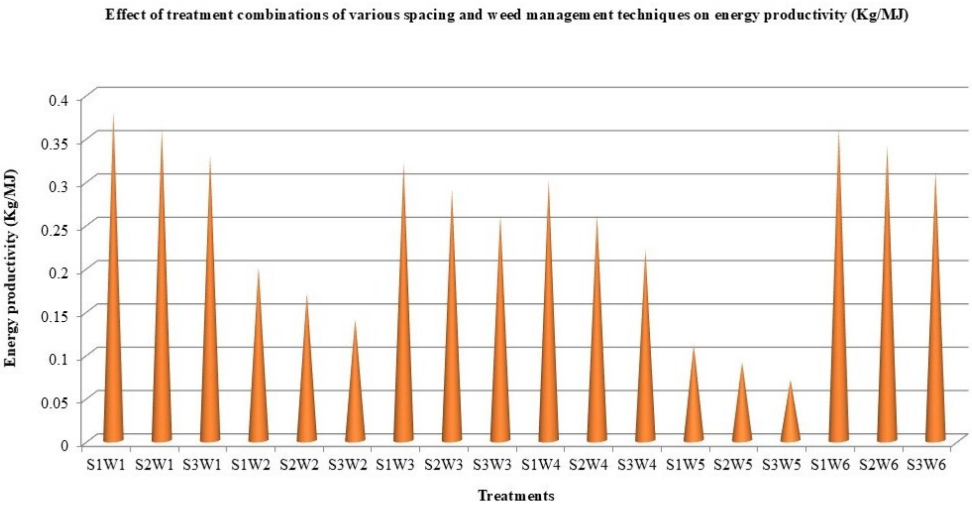

Fig. 1. Effect of treatment combinations of various spacing and weed management techniques on energy productivity (Kg/MJ)

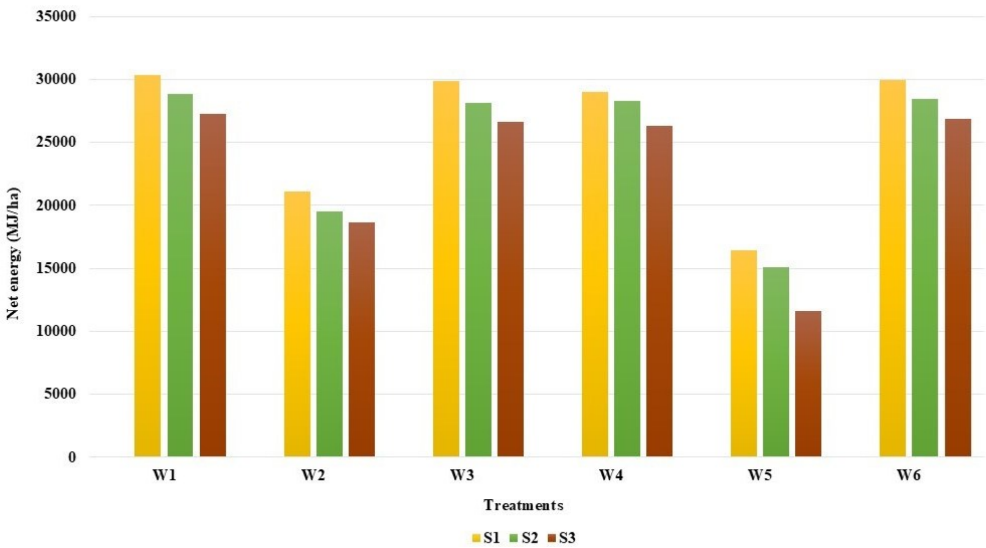

Fig. 2. Effect of treatment combinations of various spacing and weed management techniques on net energy (MJ/ha)

Energy use efficiency

The highest energy use efficiency (3.27) was observed at the spacing of 100x10 cm (S_1). In contrast, the lowest energy use efficiency (2.60) was recorded at the spacing of 175x50 cm among the main plot treatments (Fig. 3). Among the subplot treatments, the highest energy use efficiency (3.53) was achieved with power weeding (W_1). In contrast, the lowest energy use efficiency (1.75) was noted in the weedy check (W_5).

The treatment combination of 100x10 cm spacing (S_1) and power weeding (W_1) recorded the highest energy use efficiency (4.01). In contrast, the combination of 175x50 x10 cm spacing (S_3) and the weedy check (W_5) yielded the lowest energy use efficiency (1.30%).

Economics

The highest net income (Rs. 67,328/ha) and benefit-cost ratio (BCR) of 2.28 were achieved with the treatment combination of 100x10 cm spacing and weed management through power weeding (Table 3). This success can be attributed to reduced cultivation costs through effective energy utilization, facilitating better weed control and leading to higher gross returns from increased yields. Each additional weeding requires more labour, contributing to overall cultivation costs.

The highest cultivation cost (Rs. 90,802/ha) was observed in the treatment combination of 175x50x10 cm spacing along with the weed-free check. This is likely due to the greater labour required to keep the field completely free of weeds at frequent intervals.

The increased weed control efficiency in the weed-free check necessitates higher energy input and consequently, higher cultivation costs. In contrast, the power weeder promotes crop growth and improves yield and yield parameters with minimal energy requirements.

Technologies that enhance yield, net income, BCR, energy use efficiency and net productivity are crucial. Sowing using a seed-cum-fertilizer drill at a spacing of 100x10 cm, along with power weeding and other agronomic practices, is considered an energy-efficient weed management strategy under a high-density planting system for rainfed cotton, reducing the reliance on labour for sowing and weeding.

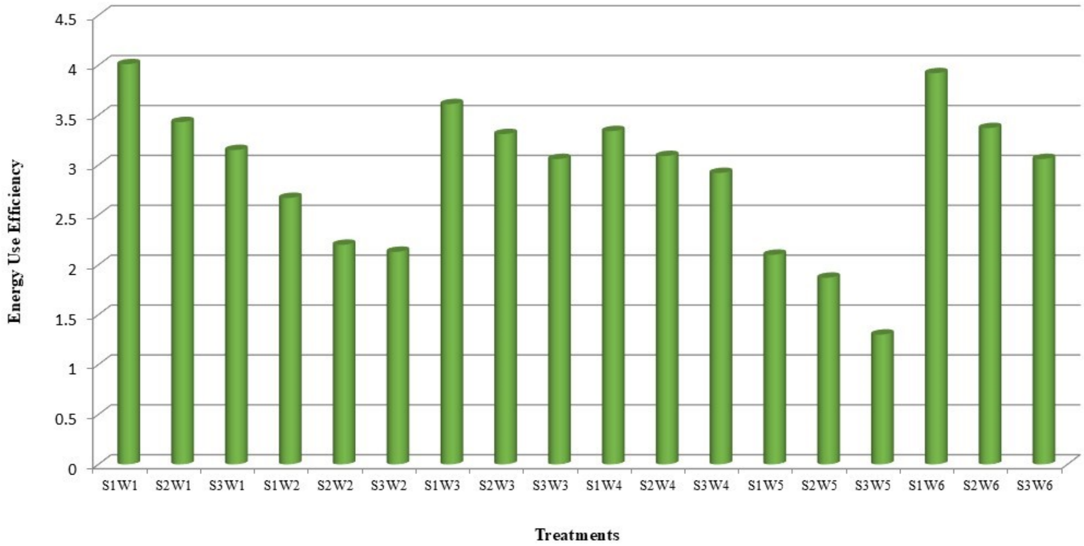

Fig. 3. Effect of treatment combinations of various spacing and weed management techniques on energy use efficiency

Table 3. Effect of treatment combination of various spacing and weed management techniques on economics of rain fed high density planting cotton

Treatments	Cost of cultivation (Rs./ha)	Gross return (Rs./ha)	Net return (Rs./ha)	B:C ratio
S_1 W_1	52762	120000	67238	2.27
S_1 W_2	61452	126800	65348	2.06
S_1 W_3	66802	112800	45998	1.68
S_1 W_4	61612	103200	41588	1.67
S_1 W_5	50802	69600	18798	1.37
S_1 W_6	90802	129000	38198	1.42
S_2 W_1	52762	117000	64238	2.21
S_2 W_2	61452	126800	58658	1.95
S_2 W_3	66802	105000	38198	1.57
S_2 W_4	61612	97800	36188	1.58
S_2 W_5	50802	65400	14598	1.28
S_2 W_6	90802	123000	48198	1.64
S_3 W_1	52762	110400	60638	2.14
S_3 W_2	61452	126800	53558	1.87
S_3 W_3	66802	99000	32198	1.48
S_3 W_4	61612	90000	28388	1.46
S_3 W_5	50802	61200	10398	1.20
S_3 W_6	90802	113400	38598	1.51

(S1) 100x10 cm, (S2) 150x50x10 cm, (S3) 175x50x10 cm, Weeding by power weeder with 75 cm width at 20 and 45 days after sowing (W1), intercropping of black gram along with sowing of cotton (W2), hand weeding two times at 20 and 45 days after sowing (W3), chemical weed management by the application of herbicide- metolachlor as pre-emergence on 5 DAS and Pyrithiobac sodium plus Quizalofop ethyl combination on 20 DAS as post-emergence(W4), weedy check was maintained without carrying out any weed control operation (W5), weed free check by carrying out frequent hand weeding on 15, 25, 35, 45 and 60 DAS (W6).

Discussion

Cotton is particularly vulnerable to infestations by grasses, sedges and broad leaved weeds, which can diminish yields by as much as 30%. Depending on the kind and density of the weeds, cotton yield losses may vary from 50% to 85% (17). Weeds primarily compete for nutrients, moisture and sunlight, especially during the early stages of crop growth (18). Rainfed cotton heavily relies on limited water resources and the issue is exacerbated by weeds that consume a significant amount of soil moisture, depriving the crop of essential hydration. Nutrient competition is also critical; weeds typically absorb more nutrients, particularly nitrogen and phosphorus, adversely affecting cotton growth.

Additionally, weeds can shade cotton plants, reducing the rate of photosynthesis. Competition for space can lead to overcrowding, inhibiting root expansion in the soil and further lowering yields. In high-density planting system, early weed control is crucial for suppressing their growth in later stages (19). Various research demonstrates the significant impact of weeds on cotton yield due to competition for resources. For example, a study by Jabran (20) showed that unchecked weeds lead to a 60% loss in cotton yield, particularly during the initial growth stages when cotton is most vulnerable to competition for light, water and nutrients. Weeds such as *Trianthema portulocastrum* and *Cynodon dactylon* have been noted for their aggressive competition for water and nitrogen sources. The critical period of weed control is the minimum time frame during which a crop must be kept weed-free to avoid significant yield loss. Weed interference occurring prior to or following this period often does not lead to yield reductions beyond 5%. For the cotton variety CO 17, the critical period of weed control is between 20 and 60 days after sowing. Therefore, maintaining a weed-free field during this time frame is essential for achieving maximum yield.

Plant height was greater under the hand weeding operation, which was conducted three times at 20, 40 and 60 days after sowing (DAS). This method was significantly more effective than the herbicide treatment with pyrithiobac-sodium at a rate of 62.5 g/ha, followed by quizalofop ethyl at 50.0 g/ha. Additionally, herbicides such as flumioxazin, pyrithiobac and trifloxysulfuron-sodium have also demonstrated increased effectiveness for weed management in cotton (21).

On the other hand, herbicide-resistant weeds can be effectively managed through mechanical methods, eliminating concerns about herbicide residue (22). Mechanical practices in cotton cultivation, such as power weeding, effectively manage herbicide-resistant weeds without harming the environment (23). The continuous use of chemicals can damage the ecosystem and contribute to the development of herbicide-resistant weeds; however, using a power weeder does not lead to the emergence of such resistance and represents a sustainable weed management practice (24). Power weeders are engine-operated machines that require low power for bed preparation. They are both handy and compact, classified as medium-duty machines (25). These weeders have a weeding efficiency of 93%, surpassing the 80% efficiency of dry land weeders, which results in less labour time and effort, conserving fuel during the weeding process (26). Using power weeders effectively reduces grasses, sedges and broad leaved weeds at all crop growth stages, thereby enhancing cotton's vigor and growth. Mechanical weeding with weeders is highly effective in dry and wetland conditions.

Furthermore, it helps maintain a loose soil surface by creating soil mulch, which promotes proper growth and increases seed cotton yields. However, power weeders have high initial investment costs, which can be intimidating and may discourage small and marginal farmers from adopting this technology. Additionally, power weeders function effectively and safely only when farmers and farm workers are adequately trained, which requires significant time and resources for education and skill development. These financial and educational barriers can significantly impact the widespread adoption of power weeders in cotton farming, even though higher weed control efficiency is a recognized benefit (27).

Spindle picker machines utilize rotating spindles to contact the ripened cotton fibres, achieving physical adherence of the fibre to the spindles (28). Intercropping with black gram suppresses the vegetative growth of cotton for up to 90 days. When black gram is intercropped, it extends the fruiting duration but also reduces the number of sympodial branches per plant, the number of fruiting points per plant and the weight of the bolls (29).

The leaf area index (LAI) and dry matter production (DMP) were higher in a sole cotton system. However, the DMP decreased at all stages of cotton growth when intercropped. This decline in DMP was linked to reduced plant height and LAI associated with intercropping (30). Despite the economic benefits of intercropping, which yielded black gram at 750 kg/ha and ensured productivity and sustainable farming, the DMP of cotton declined throughout all growth stages due to intercropping (31). Higher seed cotton yields and other yield parameters were recorded with hand weeding conducted twice, compared to chemical weed control methods. Hand weeding operations performed at 20, 40 and 60 days after sowing (DAS) significantly enhanced plant height, dry matter accumulation, boll numbers per plant, yield of seed cotton per plant and seed cotton per hectare (32). The highest energy productivity was achieved through increased yield and reduced energy requirements for production. The energy requirement of a power weeder is lower than that needed to maintain a weed-free field. Producing 4,750 kg of cotton per hectare requires 29,138.11 MJ of energy, with 75.5% of this energy sourced from fuel and fertilizers, resulting in an energy productivity of 0.163 kg/MJ (33).

Efficient use of energy sources is crucial for lowering operating costs and reducing emissions of air pollutants and greenhouse gases. Energy indicators such as net energy, productivity and intensity were higher with closer spacing, likely due to improved seed cotton yield (34). With rising concerns over fuel costs and energy conservation, it has become increasingly crucial for cotton farmers worldwide to understand and calculate their fuel and energy consumption. By being aware of their fuel, electricity and energy use, farmers can optimize and select the most efficient farming practices (35). The primary challenge for those engaged in rainfed cotton cultivation is the widening gap between increasing input costs, such as labour, fertilizers, pesticides and seeds and declining income from their produce. Securing a satisfactory profit margin is imperative to mitigate these escalating worries in the agricultural sector. This can be achieved by aligning crop prices with cultivation costs, as established in this study (36).

Conclusion

This study concludes that using a power weeder offers the highest weed control efficiency under rainfed conditions and is also an economically viable option for managing weeds and achieving optimal yields in rainfed cotton cultivation. The power weeder maximizes weed control and improves soil tilth between crop growth periods, aiding in moisture conservation and enhancing crop yield. Hand weeding provides the next best level of weed control, followed by chemical control. While Metolachlor effectively controls weeds during cotton's initial growth phase, its efficacy depends on soil moisture availability due to its residual nature. Overall, weed control achieved through chemical methods is lower than power and hand weeding. Adopting a spacing of 100 x 10 cm and using the power weeder at 20 and 45 days DAS can significantly increase yields for the farming community, contributing to sustainable agricultural production under rainfed conditions.

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Authors' contributions

JS executed the field research and prepared the manuscript. SV formulated the research proposal, guided the student and assisted in manuscript editing. TR provided guidance on agronomic aspects for conducting the research, while SS contributed expertise on soil management. BS assisted with statistical analysis and data interpretation.

Compliance with ethical standards

Conflict of interest: The authors declare that we have no conflict of interest.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used none of AI Technology. All the authors reviewed and edited the content as required and take full responsibility for the publication's content.

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