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RESEARCH ARTICLE

Energy efficiency and economic analysis of mechanized vs conventional cotton production system: A comparative study under rainfed vertisols of Tamil Nadu

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Abstract

Energy efficiency plays a pivotal role in optimizing input use and improving the sustainability of agricultural practices, especially in energy-intensive crops like cotton. Due to its high economic importance, cotton cultivation has been in the need of the hour in developing mechanized cultivation practices aimed at improving production efficiency. This study evaluated energy consumption and performed an economic analysis of mechanized versus conventional cotton production under rainfed vertisols in Tamil Nadu. Among the various inputs, fertilizer application consumed the most energy in both systems, followed by labor energy differences between the 2 methods. Mechanized cultivation drastically reduced labor energy requirements (174.2 MJ/ha) compared to manual methods (2215.6 MJ/ha), highlighting the potential for labor savings. Mechanized cultivation also showed more efficient use of non-renewable energy sources, whereas conventional methods relied more on renewable energy inputs, highlighting the trade-offs between the 2 systems. Mechanized cultivation significantly reduced production costs (Rs. 74290/ha) compared to conventional methods (Rs. 140440/ha), largely due to a 47.8 % reduction in labor costs, demonstrating its economic viability. This study suggests that improving the energy efficiency of mechanized cotton production should prioritize efficient fertilizer use and reducing diesel fuel consumption through enhanced machinery performance.

Keywords

cotton; mechanization; economics; energy; efficiency

Introduction

Cotton is the most significant natural fiber crop produced globally, cultivated on 33.48 million hectares with an annual production of 113.11 million bales (73.7 million tons). The top cotton-producing nations, including China, India, the USA, Brazil and Pakistan, contribute 75.4 % of global cotton production. Among these leading producers, India plays a vital role, cultivating cotton across 13.48 million ha and producing 36.5 million bales, which accounts for 32 % of global production (1). Though cotton cultivation significantly contributes to India's agricultural economy, it is resource-intensive requiring large amounts of synthetic fertilizers, chemical pesticides and both human and machine labor. Traditionally, manual harvesting accounts for 60 % of labor (about 1560 man-h/ha) and 35 % of cultivation costs, is being replaced by mechanical harvesting, reducing production costs by 8-10 % and increasing farmers' income. However, rising production costs and labor shortages highlight the need for new technologies suited for mechanization. The shift toward mechanization in cotton farming has significantly increased energy consumption, particularly in fossil fuel usage. For instance, mechanical operations such as tillage, planting and harvesting rely heavily on diesel-powered machinery. Studies have shown that the fuel consumption for cotton mechanization can account for up to 60-80 L/ha, contributing to an overall increase in carbon emissions. This contrasts sharply with traditional methods, where labor-intensive practices consumed far less fossil energy.

Energy is a fundamental input for sustaining agricultural production and analyzing its efficiency is crucial for optimizing farming practices. Each input has a unique efficiency influenced by environmental conditions and agronomic practices. Thus, assessing the input use efficiency of farming practices is critical in modern Indian agriculture. Energy auditing and budgeting have emerged as essential tools for identifying high energy-consuming inputs and providing insights into optimizing resource use (2). Current trends in energy budgeting focus not only on reducing energy consumption but also on exploring alternatives such as renewable energy sources. This approach enables farmers to enhance energy efficiency, lower costs and adopt more sustainable practices, contributing to the long-term sustainability of cotton production (3, 4). In agriculture, 2 primary forms of energy are involved: direct and indirect. "Direct energy" refers to the energy used directly on the farm for various activities, while "indirect energy" encompasses the energy associated with the production, packaging and delivery of inputs like fertilizers, chemicals and machinery to the farm (5).

Despite the importance of energy efficiency in agriculture, few studies have specifically examined the energy input-output dynamics of cotton production. A study assessing the energy balance of cotton cultivation in Turkey found that producing 4750 kg of cotton/ha requires 29138.11 MJ of energy, with 75.5 % of this coming from fuel and fertilizers (6). Another study explored energy consumption patterns in cotton production, identifying that the majority of energy comes from indirect (60 %) and non-renewable resources (71 %) (7). These studies emphasize the importance of improving energy use efficiency and propose strategies for preserving natural resources, including optimizing production structures, enhancing farm management practices and adopting new technologies (8).

To develop effective policy measures that help cotton farms enhance productivity through improved efficiency, it is beneficial to measure economic, technical and allocative efficiency at the farm level and identify the factors influencing these efficiencies (9). Given high energy demands by cotton cultivation and its environmental impact, there is a growing need for research aimed at improving energy efficiency in its production. Developing eco-friendly, cost-effective technologies, resilient genetic varieties and improved agronomic practices are essential for sustainably enhancing cotton production while addressing both economic and environmental concerns. Analyzing energy consumption in cotton mechanization is crucial for ensuring sustainable practices and reducing reliance on fossil fuels. In this study, the energy requirements of inputs and outputs in cotton production were examined and the calculations were made for energy use efficiency, energy productivity, net energy, specific energy, direct energy, indirect energy, renewable energy and non-renewable energy. This study aims to analyze energy consumption in cotton mechanization, focusing on both economic and environmental impacts.

Materials and Methods

Experimentation Details

Two field experiments were conducted at Tamil Nadu Agricultural University, Cotton Research Station, Veppanthattai (latitude 11°34’ N, longitude 78°48’ E), during the summer and winter seasons of 2023-24. The experiments followed a split-split plot design with 3 factors and each experiment was replicated 3 times. This design was chosen to study the effects and interactions of cotton varieties, plant spacings and growth regulators, minimizing variability and resource use while allowing for detailed analysis of each factor and their combinations. The main plots included three cotton varieties (V_1- CO 17, V_2- VPT 2, V_3- Suraksha), the sub-plots involved 4 plant spacings (S_1 - 90 x 15 cm, S_2 - 70 x 15 cm, S_3 - 90 x 10 cm, S_4 - 70 x 10 cm) and the sub-sub plots had 2 plant growth regulators (G_1- mepiquat chloride at 150 ppm, G_2- mepiquat chloride + cyclanilide at 400 ppm). The growth regulators were applied at the square initiation and boll formation stages.

Crop Management

Soil and Climate: The experimental field consisted of black cotton soil (Peelamedu series/vertisols), characterized as slightly alkaline clay loam with low organic carbon (5.2 and 4.2 g/kg) and nitrogen (177.5 and 170.4 kg/ha) and medium phosphorus (24.9 and 22.8 kg/ha) and potassium levels (185.0 and 190.7 kg/ha) during both summer and winter respectively. The summer season experiment conducted from March to July, received 259 mm of rainfall over 15 rainy days, with temperatures ranging from 26.2 °C to 39.2 °C and mean humidity levels of 67.5 % in the morning and 62.8 % in the afternoon. The winter season experiment, conducted from August to January, received 405 mm of rainfall over 34 rainy days, with temperatures between 23.1 °C and 39.0 °C and higher humidity, averaging 81.2 % in the morning and 66.5 % in the afternoon.

Field Preparation and Sowing: The experimental field was thoroughly prepared using tractor-drawn disc harrows to break the hard pan soil, followed by a cultivator and a rotavator to break clods and level the soil uniformly. Before the final ploughing, well-decomposed farmyard manure at 12.5 t/ha was evenly applied. A recommended fertilizer dose of 100:50:50 kg/ha NPK was

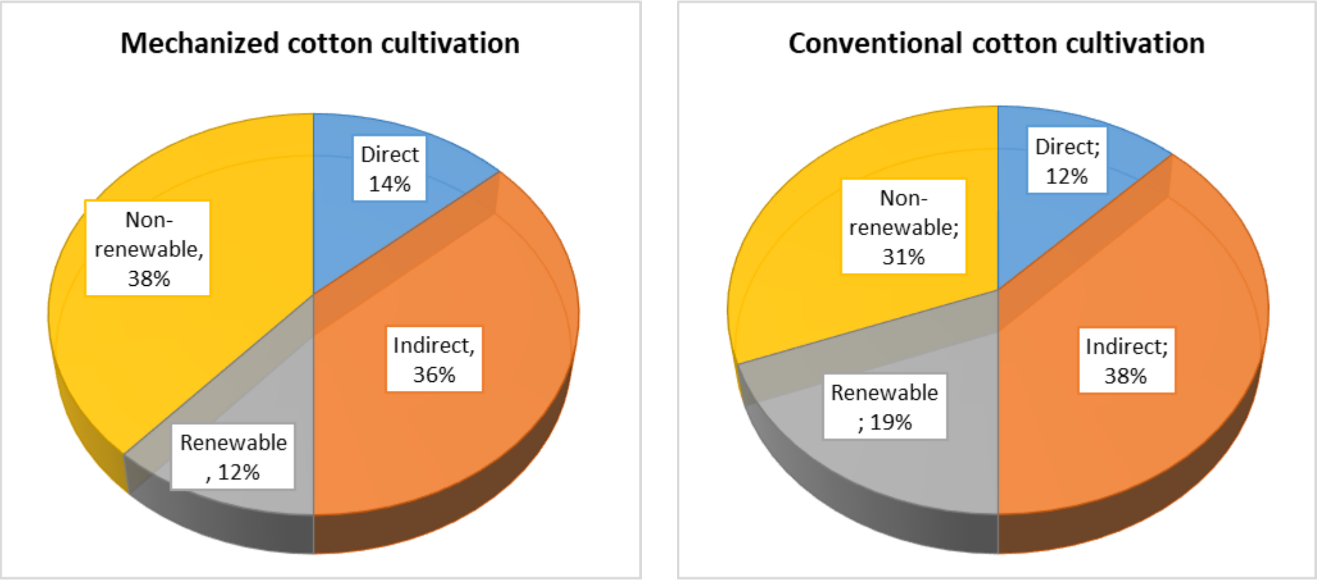
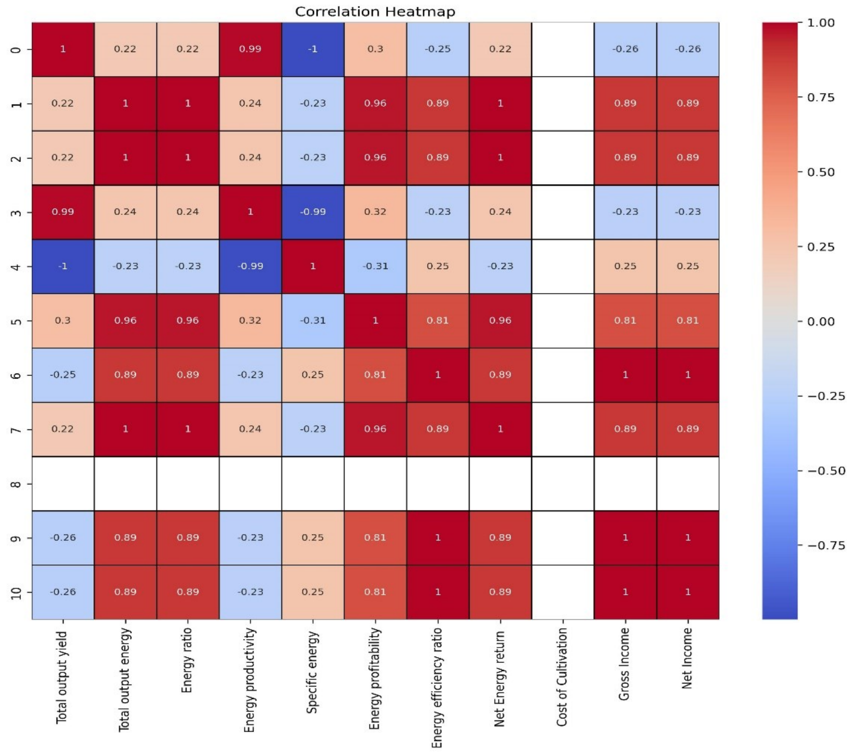


Fig. 1. Direct, indirect, renewable and non-renewable energy sources of mechanized and conventional cotton cultivation



	Total output yield	Total output energy	Energy ratio	Energy productivity	Specific energy	Energy profitability	Energy efficiency ratio	Net Energy return	Cost of Cultivation	Gross Income	Net Income
0	1	0.22	0.22	0.99	-1	0.3	-0.25	0.22		-0.26	-0.26
1	0.22	1	1	0.24	-0.23	0.96	0.89	1		0.89	0.89
2	0.22	1	1	0.24	-0.23	0.96	0.89	1		0.89	0.89
3	0.99	0.24	0.24	1	-0.99	0.32	-0.23	0.24		-0.23	-0.23
4	-1	-0.23	-0.23	-0.99	1	-0.31	0.25	-0.23		0.25	0.25
5	0.3	0.96	0.96	0.32	-0.31	1	0.81	0.96		0.81	0.81
6	-0.25	0.89	0.89	-0.23	0.25	0.81	1	0.89		1	1
7	0.22	1	1	0.24	-0.23	0.96	0.89	1		0.89	0.89
8											
9	-0.26	0.89	0.89	-0.23	0.25	0.81	1	0.89		1	1
10	-0.26	0.89	0.89	-0.23	0.25	0.81	1	0.89		1	1

Fig. 2. Interpretation of Pearson Correlation Analysis of variables along with correlation matrix and heatmap.

applied in split doses, as a basal application before sowing and a top dressing at the square initiation stage. Delinted cotton seeds (10 kg/ha) were sown using a pneumatic precision planter.

Weed Management and Irrigation: To control early weed growth such as annual grasses and broadleaf weeds, Pendimethalin 30 % EC (3.3 L/ha) was applied as a pre-emergence herbicide at 3 DAS using a battery-operated knapsack sprayer. Power weeding was performed at 25 and 45 DAS, with the power weeder adjusted to suit the row spacing of 70 cm and 90 cm. Life irrigation was supplemented by rain hose irrigation at 3 DAS, with additional irrigation provided 4 times during the winter season and 6 times during the summer season.

Canopy Management and Plant Protection: Canopy management in cotton plays an important role in optimizing light interception, promoting better photosynthesis, balancing vegetative and reproductive growth and enhancing boll retention and yield. It also ensures uniform plant height and structure, facilitating efficient mechanical harvesting. Canopy structure can be managed by growth retardants such as Mepiquat Chloride (150 ppm) and a combination of Mepiquat Chloride with Cyclanilide (400 ppm) were sprayed at 45 DAS and 65 DAS to improve plant architecture for mechanical harvesting. At 45 and 65 DAS, Acephate 75 % SP (2 g/L of water), Imidacloprid 17.8 % SL (4 mL/L) and Fipronil 5 % SC (3 mL/L) were applied using a tractor-mounted boom sprayer to control sucking pests in cotton. These pesticides were chosen for their complementary modes of action, targeting nervous systems of pest through systemic and contact activity, providing broad-spectrum control and minimizing resistance development.

Harvesting: To facilitate mechanical cotton picking, defoliants (Thiadiuron 36 % SC + Diuron 18 % SC) were sprayed at 500 mL/ha during the physiological maturity stage to ensure synchronized defoliation and boll opening. A spindle-type cotton picker was used for mechanical harvesting and the harvested cotton was then transported to ginning factories for processing (Fig. 3).

Energy budgeting

In addition to field experiments, various energy efficiency parameters were evaluated to analyze the relationship between energy consumption, total output and production/ha in mechanized cotton production systems. The parameters calculated included energy ratio, specific energy, energy productivity, energy intensiveness and net energy yield, using the following equations (10, 11):

Fig. 3. Comparison of conventional cotton cultivation vs mechanized cotton cultivation.

Metric Name	Linear Formula and interpretation
Energy Ratio: Indicates whether the energy output exceeds the energy input	Energy Ratio = Energy Output (MJ/ha) / Energy Input (MJ/ha) Interpretation: A ratio greater than 1 signifies a positive energy balance.
Specific Energy: Determines the amount of energy required to produce 1 kg of output.	Specific Energy = Energy Input (MJ/ha) / Output (kg/ha) Interpretation: Lower values indicate higher energy efficiency.
Energy Productivity: Assesses how effectively energy input is converted into agricultural or production output.	Energy Productivity = Output (kg/ha) / Energy Input (MJ/ha) Interpretation: Higher values represent better energy utilization.
Energy Profitability: Evaluates the net energy gain in relation to the energy invested.	Energy Profitability = Net Energy (MJ/ha) / Energy Input (MJ/ha) Interpretation: Values greater than 0 indicate a profitable energy balance.
Energy Efficiency Ratio: Focuses on the energy efficiency related to the primary product being produced.	Energy Efficiency Ratio = Energy Output of Main Product (MJ/ha) / Energy Input (MJ/ha) Interpretation: A higher ratio means the main product is produced more efficiently concerning energy use.
Net Energy: Calculates the actual energy gain after accounting for all energy inputs.	Net Energy = Energy Output (MJ/ha) - Energy Input (MJ/ha) Interpretation: Positive net energy means energy output exceeds energy input, indicating efficiency.

The energy ratio between output and input is a key metric used to evaluate energy use efficiency. To estimate the energy ratio, energy inputs from sources such as human labor, machinery, diesel fuel, fertilizers, pesticides and seeds are calculated, along with the energy output derived from crop yield (12). Energy output from the by-product (stalk) is estimated by multiplying the amount of by-product by its corresponding energy equivalent. Total input and output energy are calculated by summing the energy equivalents of all inputs (Table 1) (13, 14). Specific energy (MJ/kg) is the amount of energy invested to produce a unit of the product. Energy productivity, defined as the quantity of product produced per unit of input energy (kg/MJ), is the inverse of specific energy. This metric provides insight into how efficiently energy is utilized within a production system to generate a particular product. Indirect energy includes the energy embodied in seeds, chemical fertilizers, herbicides, pesticides, fungicides, farmyard manure and machinery, while direct energy covers human labor, diesel, electricity and water for irrigation used in cotton production. Non-renewable energy sources include diesel, electricity, chemical fertilizers, herbicides, pesticides, fungicides and machinery, while renewable energy consists of human labor, farmyard manure, seeds and water for irrigation.

The output-input analysis was also used to evaluate the economic benefits of cotton production/ha, following a process similar to energy balance analysis (15). The cost of cotton production was categorized into fixed and variable costs. Fixed costs included land value, water value and basic infrastructure, while variable costs covered current expenses such as chemicals, fuel, human labor and electricity. The economic output was determined by the fiber and seed yield of the cotton, with all prices reflecting market rates from 2024. The economic analysis focused on several key financial metrics, calculated using the following equations (16):

Total cost of production = variable cost of production (Rs./ha) + fixed cost of production (Rs./ha)

Gross return = cotton yield (kg/ha) × cotton price (Rs./ha)

Net return = gross value of production (Rs./ha) - total cost of production (Rs./ha)

Benefit to cost ratio = gross value of production (Rs./ha) / total cost of production (Rs./ha)

Table 1. Energy equivalents of inputs and outputs used in the study.

Inputs	Unit	Energy equivalent (MJ/unit)
Human power		
Adult man	Hours	1.96
Adult women	Hours	1.57
Machinery		
Tractor	Hours	10.94
Power tiller	Hours	3.24
Cultivator	Hours	3.14
Rotavator	Hours	10.28
Self-propelled combine harvester	Hours	171.00
Diesel	Litres	56.31
Battery operated power sprayer	Hours	0.50
Electricity	KWh	11.93
Fertilizers		
Nitrogen (N)	kg	60.6
Phosphorus (P_2O_5)	kg	11.1
Potassium (K_2O)	kg	6.70
Farm yard manure	kg	0.3
Chemicals		
Herbicides	kg	238.30
Pesticides	Litres	101.20
Defoliants	Litres	101.20
Plant growth regulator	Litres	101.20
Irrigation water	m^3	0.63
Output (Main)		
Kapas/seed cotton	kg	11.8
Straw yield (cotton)	kg	2.25

Statistical analysis

The collected data were subjected to statistical analysis of variance (ANOVA) using AGRES software on a Windows platform. Duncan's Multiple Range test (DMRT) is a post hoc test to measure specific differences between pairs of means. This procedure calculates mean values at a 5 % significance level, which serves as the threshold for determining significant versus non-significant differences between treatment means. Additionally, correlation heat map was conducted using SPSS version 21.

Results and Discussion

Energy analysis

Energy requirements for mechanized and conventional cotton cultivation are summarized in Tables 2 and 3, highlighting key operations such as field preparation, fertilizer application and harvesting (17). The energy inputs include cotton seeds, fertilizers (e.g., urea, single super phosphate, muriate of potash), machinery (cultivators, rotavators, pneumatic precision planters, power tillers, battery-operated sprayers and spindle-type cotton pickers), fuel (diesel and electricity), pesticides, herbicides, plant growth regulators and defoliants. The quantity of cotton seed sown remains constant for both mechanized and conventional methods. While mechanized cultivation required 9.08 % more energy overall, this increase was primarily driven by the greater use of machinery and fuel for harvesting and field preparation, suggesting that mechanization shifts the energy burden from labor to fuel consumption. In mechanized cultivation, the majority of energy (62.3 %) was expended on fertilizers and their application, followed by harvesting (12.0 %) and field preparation (10.2 %). Similarly, in conventional cultivation, fertilizer application consumed the most energy (10586.1 MJ/ha), with field preparation also being a significant factor (11.2 %). Fertilizer application accounted for over 60 % of total energy input in both methods due to the high energy requirements for production and transportation (18).

In mechanized cotton cultivation, machinery consumed 891.3 MJ/ha (5.2 % of total input energy), with fuel usage accounting for 4371.5 MJ/ha (25.7 %) and labor usage at 174.2 MJ/ha (1.0 %). Under the conventional method, machinery consumed 172.4 MJ/ha (1.12 %), fuel usage was 1554.5 MJ/ha (10.1 %) and labor usage was significantly higher at 2215.6 MJ/ha (14.3 %). The greater reliance on diesel fuel in mechanized systems raises concerns about environmental sustainability, particularly in terms of greenhouse gas emissions and fossil fuel dependence. While energy consumption for field preparation and fertilizer application was similar in both methods, mechanized cultivation required more energy for sowing and weeding due to higher machinery and fuel usage (19). Conversely, the conventional method relied heavily on human labor for these operations.

Mechanized cultivation also consumed a larger amount of diesel (4371.5 MJ/ha) compared to the conventional method (1554.5 MJ/ha). Despite this, labor energy in conventional cultivation was much higher at 2215.6 MJ/ha (14.3 %), whereas mechanized cultivation required only 174.2 MJ/ha (1.0 %). The reduced need for manual labor in mechanized systems significantly lowers labor costs, making it more energy-efficient and cost-effective. This efficiency allows for more timely completion of operations, reducing the risk of delays during peak periods like sowing and weeding, which can lead to reduced yields in conventional systems due to labor shortages (20).

Table 2. Energy requirement for different operations in mechanized and conventional cotton cultivation.

Inputs	Mechanized cotton cultivation		Conventional cotton cultivation	
	Energy (MJ/ha)	**%**	**Energy (MJ/ha)**	**%**
Field preparation	1728.6	10.2	1728.6	11.2
Fertilizer application	10586.1	62.3	10586.1	68.5
Seed sowing	745.5	4.4	306.4	2.0
Weeding and thinning	1217.8	7.2	949.2	6.1
Irrigation	0.0	0.0	0.0	0.0
Chemicals application	687.9	4.0	629.8	4.1
Harvesting	2035.2	12.0	1256.0	8.1
Total energy	**17001.1**	**100.0**	**15456.0**	**100.0**

Table 3. Input wise energy required for cotton cultivation.

Inputs	Mechanized cotton cultivation		Conventional cotton cultivation	
	Energy (MJ/ha)	**%**	**Energy (MJ/ha)**	**%**
Seeds	118.0	0.7	118.0	0.76
Fertilizers	10550.0	62.1	10550.0	68.26
Machinery	891.3	5.2	172.4	1.12
Fuel	4371.5	25.7	1554.5	10.06
Pesticides	455.4	2.7	455.4	2.95
Herbicides	238.3	1.4	238.3	1.54
PGRs + Defoliants*	202.4*	1.1	151.8	0.98
Human	174.2	1.0	2215.6	14.33
Total energy	**17001.1**	**100.0**	**15456.0**	**100.0**

Energy requirements for various machine operations are detailed in Table 4. The self-propelled combine harvester (spindle-type cotton picker) consumed the most energy at 2035.2 MJ/ha (38.2 %). Field operations followed, with the cultivator using 11.8 % and the rotavator 20.7 %, together accounting for 32.5 % of total energy consumption. The sowing machine required 627.5 MJ/ha (11.8 %), while the power tiller consumed 896.7 MJ/ha (16.8 %). Fuel energy consumption was highest for the cotton picker at 1689.3 MJ/ha, followed by the rotavator at 985.4 MJ/ha, the power tiller at 844.7 MJ/ha and the cultivator at 563.1 MJ/ha. The pneumatic precision planter used the least fuel energy, consuming only 281.6 MJ/ha. Overall, machine energy was particularly high for sowing and harvesting operations, totaling 342 MJ/ha out of the 891.3 MJ/ha total machine energy. Harvesting alone required 1689.3 MJ/ha in fuel energy, which represented 17.9 % of the total energy used by all machinery. This breakdown illustrates that harvesting is the most energy-intensive operation in mechanized cotton cultivation, particularly in terms of fuel consumption (21). The high energy demands of machinery like the cotton picker signifies the efficiency challenges associated with mechanized farming, particularly when balancing the benefits of reduced labor with the significant energy costs of running such equipment.

The yield components and their energy equivalents, including kapas yield and stalk yield, for both mechanized and conventional methods are presented in Table 5. The Suraksha variety, sown at a spacing of 90 × 15 cm and treated with mepiquat chloride and cyclanilide at 400 ppm during square initiation and boll development stages, produced higher seed cotton and stalk yields. This higher yield was associated with a greater energy equivalent output. Specifically, under mechanized cultivation, the Suraksha variety produced a total energy equivalent of 37566.7 MJ/ha, which was 4.2 % higher than the output from the conventional method.

Analysis of different energy parameters for both methods, detailed in Table 6, revealed that the conventional method consumed 1545.1 MJ/ha less energy than mechanized cultivation. The energy ratio and energy productivity were also higher in the conventional method, indicating greater energy use efficiency. Specific energy, which refers to the amount of energy required to produce 1 kg of seed cotton, was found to be higher in mechanized cultivation due to its greater input energy requirements. Consequently, the net energy return was higher in the conventional method, suggesting that mechanized cultivation consumes more input energy resources, including fuel and fertilizers to achieve its output (22).

Moreover, the distribution of direct, indirect, renewable and non-renewable energy sources differed between the 2 methods. In mechanized cultivation, the shares were 14 % direct, 36 % indirect, 12 % renewable and 38 % non-renewable energy, while in conventional cultivation, they were 12 %, 38 %, 19 % and 31 % respectively. The higher reliance on external inputs,

Table 4. Energy requirement for different machine operations.

Type of operation	Machines	Machine energy (MJ/ha)	Fuel energy (MJ/ha)	Human energy (MJ/ha)	Total energy (MJ/ha)	%
Field preparation	Cultivator	56.3	563.1	7.8	627.3	11.8
	Rotavator	106.1	985.4	9.8	1101.3	20.7
Sowing	Pneumatic precision planter	342.0	281.6	3.9	627.5	11.8
Weed management	Power tiller	32.4	844.7	19.6	896.7	16.8
Chemical spraying	Battery operated sprayer	12.5	7.5	17.7	37.7	0.7
Harvesting	Spindle type cotton picker	342.0	1689.3	3.9	2035.2	38.2
Total energy		**891.3**	**4371.5**	**62.7**	**5325.6**	**100**

Table 5. Yield components and their energy equivalent yield.

Treatments	Seed cotton yield (SCY) (kg/ha)		Stalk yield (SY) (kg/ha)		Energy equivalent of SCY (MJ/ha)		Energy equivalent of SY (MJ/ha)		Total output yield (kg/ha)		Energy equivalent of total output yield (MJ/ha)	
	MC	CC	MC	CC	MC	CC	MC	CC	MC	CC	MC	CC
Compact cotton varieties												
CO 17	2256	2178	3990	3805	26620.8	25700.4	8977.5	8561.2	6246	5983	35598.3	34261.6
VPT 2	2167	2171	3476	3299	25570.6	25617.8	7821.0	7422.7	5643	5470	33391.6	33040.5
Suraksha	2415	2348	4031	3676	28497.0	27706.4	9069.7	8271.0	6446	6024	37566.7	35977.4
Plant spacing (cm)												
90 x 15 cm	2421	2405	3461	3124	28567.8	28379.0	7787.2	7029.0	5882	5529	36355.0	35408.0
70 x 15 cm	2310	2260	3853	3499	27258.0	26668.0	8669.2	7872.7	6163	5759	35927.2	34540.7
90 x 10 cm	2303	2255	3774	3649	27175.4	26609.0	8491.5	8210.2	6077	5904	35666.9	34819.2
70 x 10 cm	2084	2010	4240	4102	24591.2	23718.0	9540.0	9229.5	6324	6112	34131.2	32947.5
Plant growth regulator												
MC at 150 ppm	2184	2151	4066	3822	25771.2	25381.8	9148.5	8599.5	6250	5973	34919.7	33981.3
MC + C at 400 ppm	2375	2314	3598	3365	28025.0	27305.2	8095.5	7571.2	5973	5679	36120.5	34876.4

(MC= Mechanized cotton cultivation; CC= Conventional cotton cultivation)

(MC- Mepiquat chloride; C- Cyclanilide)

Table 6. Energy terms calculated for comparing both mechanical and conventional cotton cultivation from different compact cotton varieties, plant spacing and growth regulators.

Treatments	Energy ratio		Energy productivity (MJ/ha)		Specific energy (MJ/ha)		Energy profitability		Energy efficiency ratio		Net Energy return (MJ/ha)	
	MC	CC	MC	CC	MC	CC	MC	CC	MC	CC	MC	CC
Compact cotton varieties												
CO 17	2.09	2.22	0.37	0.39	2.72	2.58	1.09	1.22	1.57	1.66	18597	18805
VPT 2	1.96	2.14	0.33	0.35	3.01	2.83	0.96	1.03	1.50	1.66	16390	17584
Suraksha	2.21	2.33	0.38	0.39	2.64	2.57	1.21	1.21	1.68	1.79	20565	20521
Plant spacing (cm)												
90 x 15 cm	2.14	2.29	0.35	0.36	2.89	2.80	1.14	1.17	1.68	1.84	19354	19952
70 x 15 cm	2.11	2.23	0.36	0.37	2.76	2.68	1.11	1.12	1.60	1.73	18926	19084
90 x 10 cm	2.10	2.25	0.36	0.38	2.80	2.62	1.10	1.14	1.60	1.72	18665	19363
70 x 10 cm	2.01	2.13	0.37	0.40	2.69	2.53	1.01	1.03	1.45	1.53	17130	17491
Plant growth regulator												
MC at 150 ppm	2.05	2.20	0.37	0.39	2.72	2.59	1.05	1.09	1.52	1.64	17918	18525
MC + C at 400 ppm	2.12	2.26	0.35	0.37	2.85	2.72	1.12	1.14	1.65	1.77	19119	19420

(MC= Mechanized cotton cultivation; CC= Conventional cotton cultivation)

(MC- Mepiquat chloride; C- Cyclanilide)

particularly fertilizers, contributed to the increased use of non-renewable energy in mechanized cultivation. Fertilizers, particularly nitrogen, were the largest contributors to energy inputs, followed by phosphorus. While fertilizer application enhances crop growth and development (23), it also decreases resource use efficiency, leading to potential negative environmental impacts. Therefore, it is crucial to reduce energy inputs, particularly from fertilizers and fuel, to mitigate environmental degradation (24).

Cost analysis

Mechanized cultivation offers significant cost savings by reducing labor costs through the use of efficient machinery. The cost breakdown for cotton cultivation inputs is detailed in Table 7. Both conventional and mechanized methods incur similar costs for seeds (Rs. 2000/ha), fertilizers (Rs. 16857/ha) and chemicals such as herbicides and pesticides (Rs. 1783/ha). However, the costs associated with machinery and human labor differs substantially between the 2 methods. In mechanized cultivation, machinery costs amount to Rs. 35300/ha, while labor costs are Rs. 15490/ha. Conversely, in the conventional method, machinery costs are much lower at Rs. 9200/ha, but labor costs are significantly higher at Rs. 108740/ha. This analysis shows that in mechanized cultivation, machinery is the largest expense, accounting for 47.5 % of the total cost, followed by fertilizers (22.7 %) and labor (20.9%). The conventional method's dependence on labor, which constitutes 77.5 % of the total cost, highlights its vulnerability to labor shortages, which can further increase costs and delay critical farming operations (25). While machinery costs account for a large portion of expenses in mechanized systems, they offer long-term savings by reducing reliance on manual labor, making mechanized farming more financially sustainable over multiple growing seasons.

Table 7. Input wise cost required for cotton cultivation.

Inputs	Mechanized cotton cultivation		Conventional cotton cultivation	
	Cost (Rs./ha)	%	Cost (Rs./ha)	%
Seeds	2000.0	2.7	2000.0	1.4
Fertilizers	16857.1	22.7	16857.1	12.0
Machinery	35300.0	47.5	9200.0	6.6
Pesticides	1150.0	1.5	1150.0	0.8
Herbicides	633.0	0.9	633.0	0.4
PGRs + Defoliants*	2860.0*	3.8*	1860.0	1.3
Human	15490.0	20.9	108740.0	77.5
Total cost	**74290.1**	**100.0**	**140440.1**	**100.0**

The reduction in labor costs (Rs. 93250/ha) and overall production costs (Rs. 66150/ha) in mechanized cultivation demonstrates its potential to enhance profitability by minimizing labor-intensive operations. Table 8 highlights that in mechanized cotton cultivation, the highest costs are associated with fertilizers and their application (Rs. 19377/ha, contributing 26.1 % of total costs), followed by harvesting (25.8 %). In the conventional method, the most significant expense is harvesting, which costs Rs. 67200/ha and constitutes 47.8 % of the total cost, with weeding and thinning operations accounting for 21.1 %. Mechanized harvesting, which saves Rs. 38000/ha compared to conventional methods, also improves operational efficiency by completing harvesting more quickly, reducing the risk of yield loss due to delayed harvesting. This analysis demonstrates the financial efficiency and potential for cost reduction when mechanized practices are adopted in cotton cultivation (26). The total cost of production for mechanized cotton cultivation was Rs. 74290/ha, which is 47.8 % lower than the Rs. 140440/ha required for conventional cultivation, resulting in a cost difference of Rs. 66150/ha (Table 9). Although the gross income from the Suraksha variety was 10.7 % higher under conventional practices compared to

Table 8. Cost of production for different operations in mechanized and conventional cotton cultivation.

Inputs	Mechanized cotton cultivation		Conventional cotton cultivation	
	Cost (Rs./ha)	%	Cost (Rs./ha)	%
Field preparation	9200.0	12.4	9200.0	6.6
Fertilizer application	19377.1	26.1	19377.1	13.8
Seed sowing	5400.0	7.3	8300.0	5.9
Weeding and thinning	12103.0	16.3	29603.0	21.1
Chemicals application	9010.0	12.1	6760.0	4.8
Harvesting	19200.0	25.8	67200.0	47.8
Total cost	**74290.1**	**100.0**	**140440.1**	**100.0**

Table 9. Effect of treatments on economics of mechanized vs conventional cotton cultivation.

Treatments	Cost of Cultivation (Rs.)			Gross Income (Rs.)			Net Income (Rs.)			B:C ratio		
	MC	CC	% change	MC	CC	% change	MC	CC	% change	MC	CC	% change
						Compact cotton varieties						
CO 17	74290	140440	-47.8	148896	165528	-10.0	75606	25088	66.8	2.03	1.18	41.9
VPT 2	74290	140440	-47.8	143022	164996	-13.3	69732	24556	64.8	1.95	1.17	40.0
Suraksha	74290	140440	-47.8	159390	178448	-10.7	86100	38008	55.9	2.17	1.27	41.5
						Plant spacing (cm)						
90 x 15 cm	74290	140440	-47.8	159786	182780	-12.6	86496	42340	51.0	2.18	1.30	40.4
70 x 15 cm	74290	140440	-47.8	152460	171760	-11.2	79170	31320	60.4	2.08	1.22	41.3
90 x 10 cm	74290	140440	-47.8	151998	171380	-11.3	78708	30940	60.7	2.07	1.22	41.1
70 x 10 cm	74290	140440	-47.8	137544	152760	-10.0	64254	12320	80.8	1.88	1.09	42.0
						Plant growth regulator						
MC at 150 ppm	74290	140440	-47.8	144144	163476	-11.8	70854	23036	67.5	1.97	1.16	41.1
MC + C at 400 ppm	74290	140440	-47.8	156750	175864	-10.9	83460	35424	57.6	2.14	1.25	41.6

(MC= Mechanized cotton cultivation; CC= Conventional cotton cultivation)

(MC- Mepiquat chloride; C- Cyclanilide)

mechanized cultivation, this was primarily due to the higher market price of handpicked cotton (27). Mechanized cotton typically sells for a lower price because it often contains more trash and has lower fiber quality compared to conventionally harvested cotton (28). Although mechanized cotton tends to sell for a lower price due to reduced fiber quality, the significant reduction in production costs more than compensates, leading to higher net income and a better benefit-cost ratio. As a result, mechanized cultivation proves to be more profitable overall when compared to conventional methods, despite the lower market price for machine-harvested cotton.

While mechanized cotton farming offers immediate cost savings by reducing labor expenses and increasing operational efficiency, its long-term benefits significantly enhance farming sustainability. By reducing reliance on manual labor, mechanization mitigates the risks posed by labor shortages and fluctuating labor markets, ensuring timely planting and harvesting, which leads to more consistent yields and lowers the risk of crop loss. Over time, the upfront investment in machinery spreads across multiple seasons, lowering per-season costs and improving profitability. Mechanization also supports the adoption of precision agriculture techniques, allowing for targeted resource management, such as efficient fertilization and pest control, which reduces input waste and increases productivity. Furthermore, with the right equipment, mechanization can improve soil health through reduced compaction and promote better land management. From an environmental perspective, when mechanized farming coupled with sustainable practices, can lead to more efficient use of resources and open the door to renewable energy solutions, further reducing the environmental footprint. Additionally, the shift toward mechanization can reallocate labor to more skilled roles, fostering economic growth in rural communities and increasing resilience against climate and market fluctuations. However, mechanization not only boosts short-term profitability but also builds a resilient, financially stable and environmentally sustainable cotton farming system in the long run.

Interpretation of Pearson Correlation Analysis of variables along with correlation matrix and heatmap

The study examined the genotypic correlations between various traits related to energy use in cultivation (Fig. 2). The analysis revealed that total output yield had a positive and significant relationship with energy productivity (0.991**), but a positive yet non-significant correlation with energy profitability (0.297 NS), total output energy (0.219 NS), net energy return (0.219 NS) and the energy ratio (0.218 NS). Total output yield showed a significant and negative correlation with cost of cultivation and specific energy (-0.999**), while non-significant negative correlations were found for gross income (-0.257 NS), net income (-0.257 NS) and the energy efficiency ratio (-0.254 NS). For total output energy, the study revealed a positive and significant association with energy ratio (1.0**), net energy return (1.0**), energy profitability (0.961**), energy efficiency ratio (0.888**), gross income (0.887**) and net income (0.887**). Although a positive correlation with energy productivity (0.237 NS) was observed, it was statistically non-significant. However, a significant and negative correlation was noted with cost of cultivation, while non-significant negative correlations were found for specific energy (-0.226 NS). Energy ratio exhibited positive and significant associations with total output energy (1.0**), net energy return (1.0**), energy profitability (0.961**), energy efficiency ratio (0.888**), gross income (0.887**) and net income (0.887**). A non-significant positive correlation with energy productivity (0.237 NS) was observed, similarly significant negative correlation with cost of cultivation and a non-significant negative correlation with specific energy (-0.225 NS). Energy productivity showed non-significant positive correlations with energy profitability (0.324 NS), total output energy (0.237 NS), energy ratio (0.237 NS) and net energy return (0.237 NS). In contrast, it exhibited a significant negative correlation with cost of cultivation and specific energy (-0.991**), alongside non-significant negative correlations for gross income (-0.235 NS), net income (-0.235 NS) and the energy efficiency ratio (-0.232 NS). Specific energy had a positive but non-significant correlation with gross income (0.25 NS), net income (0.25 NS) and the energy efficiency ratio (0.247 NS). However, it displayed significant negative correlations with cost of cultivation and energy productivity (-0.991**) and non-significant negative correlations with energy profitability (-0.308 NS), total output energy (-0.226 NS), net energy return (-0.226 NS) and the energy ratio (-0.225 ns). For energy profitability, the study revealed positive and significant associations with total output energy (0.961**), energy ratio (0.961**), net energy return (0.961**), energy efficiency ratio (0.813**), gross income (0.811**) and net income (0.811**), while a non-significant positive correlation was found with energy productivity (0.324 NS). A significant negative correlation was observed with cost of cultivation and a non-significant negative correlation with specific energy (-0.308 NS). Energy efficiency ratio had a positive and significant relationship with gross income (1.0**), net income (1.0**), total output energy (0.888**), energy ratio (0.888**), net energy return (0.888**) and energy profitability (0.813**), with a non-significant positive correlation with specific energy (0.247 NS). Additionally, exhibited a significant negative correlation with cost of cultivation and non-significant negative correlations for energy productivity (-0.232 NS). Net energy return was positively and significantly associated with total output energy (1.0**), energy ratio (1.0**), energy profitability (0.961**), energy efficiency ratio (0.888**), gross income (0.887**) and net income (0.887**), with a non-significant positive correlation with energy productivity (0.237 ns). Conversely, it showed a significant negative correlation with cost of cultivation and a non-significant negative correlation with specific energy (-0.226 NS). The study also found that cost of cultivation had a significant negative correlation with total output energy, energy ratio, energy productivity, specific energy, energy profitability, energy efficiency ratio, net energy return, gross income and net income. Lastly, gross income and net income were both positively and significantly correlated with energy efficiency ratio (1.0**), total output energy (0.887**), energy ratio (0.887**), net energy return (0.887**) and energy profitability (0.811**). Both traits had a non-significant positive correlation with specific energy (0.25 NS) and a significant negative correlation with cost of cultivation. Additionally, non-significant negative correlations were observed for energy productivity (-0.235 NS).

Conclusion

The energy requirements for mechanized and conventional cotton cultivation were 17001.1 MJ/ha and 15456.0 MJ/ha respectively, with fertilizer application being the largest contributor in both methods. Manual cotton cultivation was the most labor-intensive, requiring 2215.6 MJ/ha of labor energy, whereas mechanized cultivation required only 174.2 MJ/ha, significantly reducing labor needs through the use of machinery. Mechanized cultivation reduced labor by employing pneumatic precision planter for sowing, power tillers for weeding and spindle-type cotton pickers for harvesting, making the process more efficient and less dependent on manual labor. In mechanized cultivation, the energy share was 14 % direct, 36 % indirect, 12 % renewable and 38 % non-renewable, compared to 12 %, 38 %, 19 % and 31 % in conventional cultivation. Mechanized cotton cultivation significantly reduces labor requirements and costs, making it highly efficient option for modern day cotton farmers. By adopting mechanized systems, farmers can save substantial labor costs (Rs. 93250/ha) and reduce total production costs by 47.8 % compared to conventional methods, despite a higher gross income with conventional practices. The benefit-cost ratio and net income are ultimately higher in mechanized cultivation due to lower production costs. These findings provide a clear incentive for farmers looking to transition towards mechanized systems to improve overall farm profitability and reduce dependency on manual labor. However, the increased energy requirements, especially from non-renewable sources, raise concerns about the environmental sustainability of mechanized farming. To prevent environmental degradation, it is essential to explore more energy-efficient alternatives and strategies, such as optimizing machinery usage or integrating renewable energy sources. Despite its economic benefits, the long-term sustainability of mechanized cotton farming will depend on balancing efficiency with environmental considerations. Overall, mechanized cotton cultivation outperformed conventional methods in terms of total energy consumption, labor efficiency, and cost-effectiveness, making it a more viable option for modern cotton farming.

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Authors' contributions

DP conducted the experiment, recorded data and performed data analysis. SS supervised the experiment, formulated the experimental design, provided assistance and contributed to manuscript corrections and data analysis. TK, KR, RV and AP offered guidance for conducting the experiment and made corrections to the manuscript. All authors reviewed and approved the final version of the manuscript.

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