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RESEARCH ARTICLE

Assessment of mechanized sown cotton-based intercropping systems: Impact on yield, efficiency and profitability

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Abstract

Cotton, a valuable cash crop from the *Gossypium* genus, significantly contributes to the national economy. A primary challenge in cotton cultivation is the high labor demand for sowing. As labor shortages grow, sowing machinery has emerged as a viable alternative, decreasing labor expenses and operating duration. However, machine sowing requires wider inter-row spacing and cotton's slow initial vegetative growth presents an opportunity to incorporate suitable intercrops. This technique optimizes resource utilization and offers potential supplementary income from intercropping in the event of primary cotton crop failure due to natural disasters. This study aims to identify suitable intercropping systems under mechanized sowing conditions to enhance yield, competitive indices, energy efficiency and economic viability, supporting sustainable farmer incomes. The experiment employed a split-plot design with two main plots, five subplots and three replications. Results showed that machine sowing was more profitable than manual sowing, reducing cultivation costs by 19.6% and increasing net returns by 22.7%, with a per-day return of 22.6%. Among intercropping systems, cotton + maize demonstrated superior performance, achieving significantly higher cotton-equivalent yield (22.2%), land equivalent ratio (32.0%), area-time equivalent ratio (21.0%), energy use efficiency (57.4%), energy productivity (63.5%) and net return (29.6%) compared to sole cotton. The study concluded that cotton + maize intercropping under mechanized sowing conditions improves yield, competitive indices, energy and economic efficiency, enhancing overall farm productivity.

Keywords

competition ratio; economic; energy; intercropping; machine sowing; yield

Introduction

Cotton (*Gossypium hirsutum* L.), commonly known as the 'King of Fibre' and 'White Gold', is a vital crop in agriculture. It supports employment and significantly contributes to economic growth (1). The Indian textile industry, a cornerstone of the national economy, includes nearly 1,500 mills, 1.7 million power looms, 4 million handlooms and numerous garment processing units (2).

Global cotton production is primarily concentrated in five countries: China, India, the United States, Brazil and Pakistan. These nations contribute 78% of the world's total cotton production and account for 72% of the global cotton-cultivable area (3). India had the largest cotton cultivation area globally, representing 39% of the world's cotton acreage, with 12.5 million hectares under cultivation. However, India contributes only 22% to global cotton production due to its low productivity of 316.76 kg/ha. In contrast, productivity levels are much higher in Australia and China, reaching 2,239 kg/ha and 1,949 kg/ha, respectively (4).

Cotton farming is labor-intensive, with 15% of labor devoted to sowing, second only to harvesting, which accounts for 44% (5, 6). Manual sowing remains prevalent in India but presents several challenges, including uneven seed depth, inconsistent seed distribution, increased seed requirements, labor shortages, worker fatigue and higher costs. These issues have impeded cotton production (7). Transitioning to modern machinery can help address these obstacles by providing a more cost-effective and time-efficient solution. Machinery provides consistent seed flow, reduces waste, preserves soil texture, maintains uniform interand intra-row spacing and ensures precise seed placement (8, 9).

Agriculture acts as both an energy producer and a consumer. Over the past century, it has transitioned from being a primary energy source to one of the largest energy consumers, accounting for 30-40% of total energy usage (10, 11). This high energy consumption in agriculture is driven by factors such as mechanized farming, the cultivation of high-yielding seeds, the use of chemical fertilizers and the application of synthetic pesticides, all aimed at maximizing yields and reducing labor-intensive processes (12, 13). Efficient energy use improves economic outcomes by enhancing profitability, productivity and competitiveness, supporting sustainable agricultural development (14, 15).

In India, cotton cultivation is primarily rainfed, with around 62% of the crop reliant on rainfall, while the remaining 38% depends on irrigation. Farmers are often reluctant to grow cotton under rainfed conditions due to the risk of substantial yield reductions from water stress. Common intercrops in rainfed cotton cultivation include pulses like cowpea, millets (prosomillet), oilseeds (groundnut) and maize. These crops are well-suited to rainfed because of their drought tolerance. They help mitigate yield risks by enhancing soil fertility through nitrogen fixation (pulses) and optimizing water and nutrient use through complementary root systems (millets and oilseeds), thus improving drought resilience and overall resource efficiency (16).

Adopting suitable intercropping systems effectively mitigates yield reduction by providing additional income during the growing season and optimizing resource use. Intercropping involves cultivating multiple crops together in the same field for part or all of their growth period or growing a secondary crop alongside the main crop within the same system (17). This method maximizes the use of inter-row space in cotton fields, enhancing the use of natural resources. The main crop and intercrops differ in their abilities to utilize resources like light, nutrients and water due to variations in growth habits and root characteristics, such as root length and density (18). Mechanized sowing further improves intercropping effectiveness by promoting conservation practices like reduced tillage, which helps improve soil health by minimizing soil disturbance. With precise seed placement, mechanized sowing enables better integration of intercrops, which cover and protect the soil surface, reducing the risk of erosion and nutrient loss. These issues are more familiar with traditional sowing methods, where uneven seed distribution can leave soil vulnerable to erosion and nutrient leaching (7, 8).

Designing efficient planting arrangements and incorporating intercropping techniques are crucial strategies for promoting sustainable agricultural systems (17, 19). With its long growth duration and wider spacing, cotton is well-suited for machine sowing and intercropping. Its slow initial growth phase allows for cultivating short-duration intercrops, providing additional income per unit area (16, 20). The wider inter-row spacing of cotton, typically ranging from 60 to 120 cm, allows for the optimal spatial arrangement of cotton's sympodial branches, reduces leaf overlap, enhances canopy photosynthetic efficiency and supports the formation of more bolls per plant, ultimately increasing yield (21, 22).

While extensive knowledge exists on intercropping systems, limited information on mechanized sowing in cotton cultivation is available. This research aims to encourage the adoption of mechanized sowing by highlighting its numerous benefits. Mechanized sowing can enhance soil health through conservation practices like reduced tillage, which helps preserve soil structure, minimize erosion and improve resource -use efficiency. Nonetheless, apprehensions persist over the long-term viability of mechanized sowing, encompassing dangers of soil compaction due to heavy machinery, possible disturbances to soil microbial ecosystems and heightened dependence on fossil fuels, which may adversely affect the environment. To mitigate these effects, proper management strategies, such as using lighter equipment and optimizing machinery practices, are essential for balancing productivity with ecological sustainability.

Modern sowing machinery, designed to perform multiple operations in a single pass (such as soil opening, accurate seed placement and covering), can significantly reduce the need for additional field operations. This reduces soil compaction and erosion and also enhances seed placement consistency, hence improving crop establishment. Overall, mechanized sowing systems offer increased operational efficiency, labor savings and sustainability, especially within intercropping systems. This research aims to identify effective intercropping systems under mechanized sowing conditions to improve cotton productivity. The findings have the potential to benefit farmers, the textile industry and the scientific community by advancing cotton cultivation methods.

Materials and Methods

Experimental site description

The research was conducted at the Eastern Block farm of Tamil Nadu Agricultural University in Coimbatore during the summer season of 2024. The research field is situated in the Western agro-climatic zone of Tamil Nadu, at an 11° N latitude and a longitude of 77° E, with an altitude of 426.7 meters above mean sea level. The soil in the experimental area has a sandy clay loam texture. The physical and chemical properties of the soil in the experimental field are provided in Table 1, while the weather conditions during the growing season are outlined in Table 2.

Table 1. Physical and chemical properties of the experimental soil

Soil characteristics	Values (at 30 cm soil depth)
Clay (%)	30.29
Silt (%)	22.78
Coarse sand (%)	28.60
Fine sand (%)	18.30
Textural class	Sandy clay loam
pH	8.28
EC (dS/m)	0.45
Organic carbon (%)	0.38
Available nitrogen (kg/ha)	196
Available phosphorus (kg/ha)	18
Available potassium (kg/ha)	580

Table 2. Weather data at the location during the crop growing season (2024)

Month	Minimum temperature (°C)	Maximum temperature (°C)	Relative humidity (%)	Sunshine (Hours)	Rainfall (mm)
February	22.0	32.9	81	8.9	0.0
March	23.6	35.6	73	8.8	0.0
April	25.7	37.8	75	9.3	0.0
May	24.6	34.4	84	5.9	175.8
June	24.3	32.1	82	5.6	27.0

Experimental design

The experiment was conducted using a split-plot design, which included two main plots, five subplots and three replications. The main plots represent the sowing methods: machine sowing (M_1) and manual sowing (M_2). The subplots represented the intercropping systems: sole cotton (S_1), cotton + groundnut (1:1) (S_2), cotton + maize (1:1) (S_3), cotton + cowpea (1:1) (S_4) and cotton + prosomillet (1:1) (S_5). A schematic and field representation of the intercropping system is presented in Fig. 1 and Fig. 2.

The split-plot design allows for the simultaneous assessment of both factors, such as sowing methods (main plots) and intercropping systems (sub plots), while accounting for variability among replicates. The selected intercrops, groundnut, maize, cowpea and prosomillet, were chosen for their complementary growth habits, resource utilization and potential to enhance overall productivity. These crops vary in root structure, nutrient requirements and growth cycles, enabling them to efficiently share resources such as water, nutrients and sunlight with cotton.

Plant species and agronomic management

Sowing operations for both cotton and intercrops were conducted in the first week of February. A pneumatic precision planter was used for machine sowing, while laborer performed manual sowing at a spacing of 120 × 10 cm and a depth of 3 cm. The specifications of the pneumatic precision planter are detailed in Table 3. One row of intercrop was sown after each row of cotton (1:1) at a distance of 60 cm from the cotton row (Fig. 1), with an intra-row spacing of 10 cm. For this experiment, cotton (CO 17) served as the base crop, while the intercrops included groundnut (CO 7), maize (TNAU Maize Hybrid CO 6), cowpea (VBN 3) and prosomillet (ATL 1).

Fig. 1. Schematic representation of intercropping system.

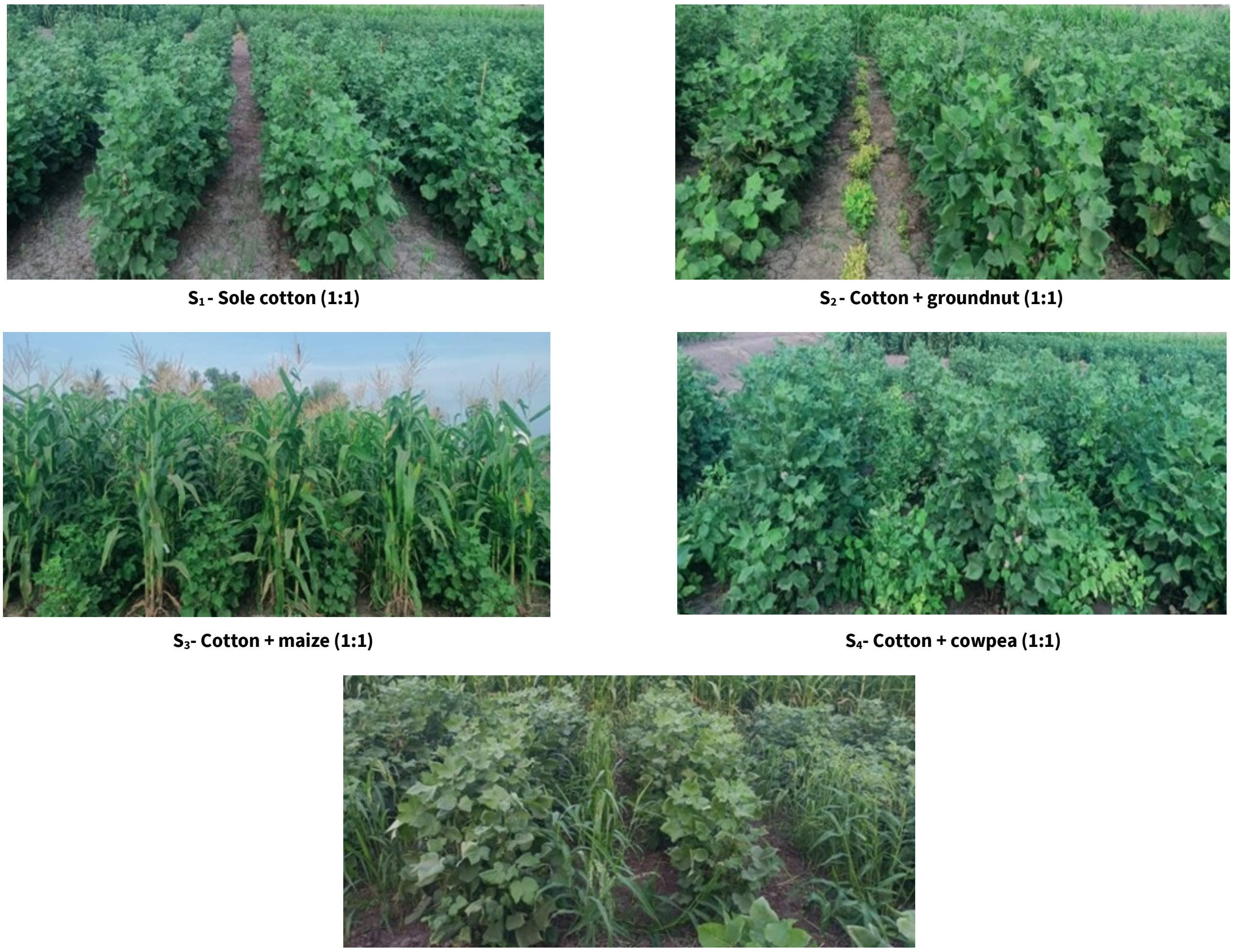

Fig. 2. Experimental field of machine sown plots.

Table 3. Specifications of the pneumatic precision planter

Particulars	Specifications
Model name	Multi-crop vacuum planter
Source of power	50 - 75 HP Tractor
Number of rows	Four
Seed capacity	34 × 2 L
Weight	604 kg
Operating speed	6 - 8 km hr^{-1}
Overall width	3250 mm
Row spacing	450 - 850 mm (Adjustable)
Plant spacing	3 - 47 mm (Adjustable)

The first irrigation was applied immediately after sowing, followed by a life irrigation at 3 DAS. Subsequent irrigations were carried out according to soil and plant conditions at 7 to 10- day intervals using furrow irrigation. A pre-emergence herbicide, pendimethalin 30% EC at 1 kg active ingredient/ha, was applied on 3 DAS to manage weeds. Hand weeding was performed at 40 DAS after assessing weed parameters. The recommended dose of fertilizer (80:40:40 kg/ ha NPK) was applied using conventional fertilizers: urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (60% K_2O). The entire dose of P and 50% of N and 50% of K was applied as a basal dose, while the remaining 50% of N and 50% of K were applied at 40 DAS. TNAU Cotton Plus was also sprayed at the stages of flowering (2.5 kg/ha) and boll formation (2.5 kg/ha). For groundnut, gypsum (400 kg/ha) was applied at 40 DAS and ferrous sulfate (0.5%) was applied at 60 DAS (23).

Necessary plant protection measures were implemented at appropriate times to control sucking pests, stem weevils and fall armyworms. The fully opened bolls were harvested in two pickings from the net plot area, while the intercrops were harvested before the cotton, with yields expressed in kg/ha.

Measurements and calculations

Assessment of cotton equivalent yield (CEY): The overall productivity of the intercropping system was assessed by considering the yields of both cotton and intercrops. The results were expressed in terms of CEY, where the yield of each intercrop was converted to a cotton yield basis using their market prices (24). The CEY was calculated using the following formula (Eqn. 1):

$$\text{CEY} = \text{Yield of cotton} + \frac{\text{Intercrop yield (kg/ha)} \times \text{Price of intercrop (₹/kg)}}{\text{Price of cotton (₹/kg)}} \qquad \text{(Eqn.01)}$$

Assessment of competitive indices: Evaluating competitive indices such as land equivalent ratio (LER), area time equivalent ratio (ATER), aggressivity, competition ratio (CR) and relative crowding coefficient (RCC) is crucial in intercropping systems.

Land equivalent ratio (LER): The LER, assesses the effectiveness of intercropping in utilizing environmental resources compared to monocropping (25, 26). An LER greater than 1 indicates that intercropping is beneficial, whereas an LER is less than 1 suggests that intercropping does not provide any advantage (27). LER is calculated as follows (Eqn. 2):

$$LER = \frac{Yci}{Yc} + \frac{Yii}{Yi} = LERcotton + LERintercrop \quad (Eqn.02)$$

Where Yc and Yi are the sole crop yields of the component species c and i, respectively and Yci and Yii represent the intercrop yield.

Area time equivalent ratio (ATER): The ATER provides a more accurate assessment of the yield advantages of intercropping over monocropping by accounting for the time taken by each crop within the intercropping system (28). ATER is calculated using the following formula (Eqn. 3):

$$ATER = \frac{(LERcotton \times Tc) + (LERintercrop \times Ti)}{T} \quad (Eqn.03)$$

Where T_c is the duration of cotton, T_i is the duration of intercrop and T is the total duration of the longer crop.

Aggressivity (A): Aggressivity measures the extent to which the relative yield of one component crop exceeds that of another (29). It is calculated using the following formula (Eqn. 4 and 5):

$$Acotton = \frac{Yci}{Yc \times Pci} - \frac{Yii}{Yi \times Pii} \quad (Eqn.04)$$

$$Aintercrop = \frac{Yii}{Yi \times Pii} - \frac{Yci}{Yc \times Pci} \quad (Eqn.05)$$

Where Pci and Pii are the planting proportions of cotton and intercrop in the mixture, respectively.

If either A_{cotton} or $A_{intercrop}$ is equal to zero, both species are equally competitive. A positive A_{cotton} value signifies that cotton is the dominant species, while a negative value indicates that the intercrop is more dominant than cotton.

Competition ratio (CR): The CR, a concept proposed by (30), measures the competitive abilities of various species in the mixture. We evaluated the competitive dynamics between cotton and intercrops such as groundnut, maize, cowpea and prosomillet using the following formula, which indicates how often one species outcompetes another (31). CR is calculated as formula (Eqn. 6 and 7):

$$CRcotton = \frac{LERcotton}{LERintercrop} \times \frac{Pii}{Pci} \quad (Eqn.06)$$

$$CRintercrop = \frac{LERintercrop}{LERcotton} \times \frac{Pci}{Pii} \quad (Eqn.07)$$

Where P_{ci} is the proportion of cotton in the association and P_{ii} is the proportion of intercrop. If the CR value of cotton exceeds 1, it indicates that cotton is more competitive than the intercrop. Conversely, a value less than 1 suggests that the intercrop is more competitive (28-32).

Relative crowding coefficient (RCC or K): The concept of the RCC or K in plant competition theory was introduced by (33). It enables the assessment and comparison of the competitive strength of one species against another within a mixture (27). The $K_{product}$ is calculated by multiplying K_{cotton} and $K_{intercrop}$ (Eqn. 8-10):

$$Kcotton = \frac{Yci \times Pii}{(Yc - Yci) \times Pci} \quad (Eqn.08)$$

$$Kintercrop = \frac{Yii \times Pci}{(Yi - Yii) \times Pci} \quad (Eqn.09)$$

$$Kproduct = Kcotton \times Kintercrop \quad (Eqn.10)$$

Where K_{cotton} is the yield of cotton when grown in combination and $K_{intercrop}$ is the yield of the intercrop when grown in combination. If the value of K_{cotton} is higher than $K_{intercrop}$, it indicates that cotton is more competitive than the intercrop. Additionally, when the $K_{product}$ (the product of K_{cotton} and $K_{intercrop}$) exceeds 1, it suggests a yield advantage. A $K_{product}$ equal to 1 indicates no yield advantage, while a value less than 1 suggests a yield disadvantage.

Assessment of energy indices

The energy performance of the agricultural system was evaluated based on the energy equivalents of inputs and outputs (12). The mechanical energy sources considered included tractors, implements and fuel. Energy consumption was determined using established conversion factors (e.g., 1 kg of cotton seed = 25 MJ; 1 L of diesel = 56.31 MJ) (34). Various energy indices were calculated using these energy equivalents, including net energy, energy use efficiency (energy ratio), energy productivity, specific energy, energy intensity and energy profitability (12, 14). The energy indices were calculated using the following formulas (Eqn. 11-16):

$$\text{Net energy} = \text{Energy output (MJ/ha)} - \text{Energy input (MJ/ha)} \quad (Eqn.11)$$

$$\text{Energy use efficiency} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}} \quad (Eqn.12)$$

$$\text{Energy productivity} = \frac{\text{Output (grain + byproduct) (kg/ha)}}{\text{Energy input (MJ/ha)}} \quad (Eqn.13)$$

$$\text{Specific energy} = \frac{\text{Energy input (MJ/ha)}}{\text{Yield (MJ/ha)}} \quad (Eqn.14)$$

$$\text{Energy intensity} = \frac{\text{Energy output (MJ/ha)}}{\text{Cost of cultivation (₹/ha)}} \quad \text{(Eqn.15)}$$

$$\text{Energy Profitability} = \frac{\text{Net energy (MJ/ha)}}{\text{Energy input(MJ/ha)}} \quad \text{(Eqn.16)}$$

Assessment of economic efficiency

The net income for cotton and intercrops was estimated using the average yields obtained from each treatment. The net income was determined using the average market prices in Tamil Nadu's local markets (Source by Uzhavan app).

Benefit-cost ratio (BCR): The BCR is a key economic indicator used to evaluate the efficiency and profitability of an investment. A BCR greater than 1 indicates that the benefits of an investment exceed the costs, making it a profitable venture. Conversely, a BCR of less than 1 suggests that the investment is not profitable (35). The BCR was calculated using the following (Eqn. 17):

$$\text{Benefit - cost ratio} = \frac{\text{Gross return (₹/ha)}}{\text{Cost of cultivation (₹/ha)}} \quad \text{(Eqn.17)}$$

Per-day return: In economics, per-day return refers to the income or profit earned daily from an investment in agricultural operations. It serves as a measure of efficiency, indicating the amount of income generated each day, thus providing a clear picture of the short-term profitability of an activity. The per-day was calculated using the following formula (Eqn. 18):

$$\text{Per - day return} = \frac{\text{Net return (₹/ha)}}{\text{Cropping period (₹/ha)}} \quad \text{(Eqn.18)}$$

Statistical analysis

The statistical analysis was conducted following the standard procedure for split-plot design (36). The analysis was performed using R Studio (version 4.4.1), employing critical difference values at a 5% level of significance to determine the best treatment among various options. Conclusions were drawn based on the statistical significance of the results.

Results

Effect on cotton equivalent yield

The different sowing methods did not have a significant effect on the CEY (Fig. 3). However, the various intercropping systems did significantly influence the CEY ($p \leq 0.05$). Among the intercropping systems, cotton + maize yielded the highest CEY at 2,977 kg/ha, followed by cotton + groundnut at 2,683 kg/ha. The lowest CEY was recorded for cotton + prosomillet at 1,800 kg/ha. The cotton + maize intercropping system significantly outperformed the other treatments, demonstrating its superior effectiveness in enhancing productivity. Additionally, there was no significant interaction effect between the sowing methods and intercropping systems, indicating that the impact of sowing methods was consistent across all intercropping systems.

Effect on competitive indices

The data were not subjected to statistical analysis because sole cotton was included as one of the treatments. However, the various intercropping systems influenced competitive indices such as the LER, ATER, A, CR and K in the intercropping systems (Table 4).

In LER, both the cotton + groundnut and cotton + maize intercropping systems recorded an LER of 1.32, indicating a 32% yield advantage over sole cotton cultivation and demonstrating more efficient land use in these intercropping systems. In contrast, the cotton + prosomillet system had a LER of less than one (0.94), suggesting less efficient land use. The highest ATER values were observed in

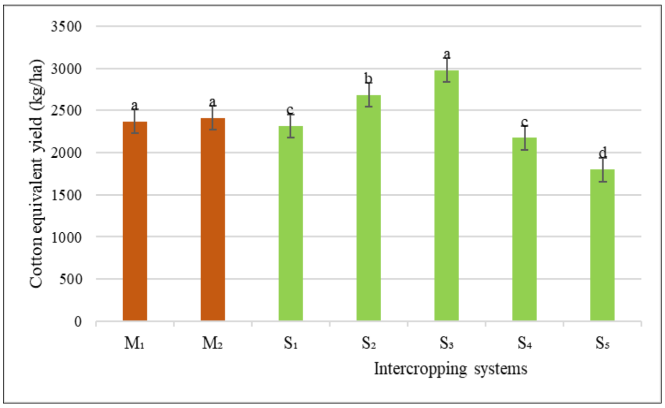

Fig. 3. Effect of sowing methods and intercropping systems on cotton equivalent yield (kg/ha).

Table 4. Competitive indices of cotton-based intercropping systems under different sowing methods

Treatments	LER	ATER	Aggressivity		Competition ratio		Relative crowding coefficient		
			A_{cotton}	$A_{intercrop}$	CR_{cotton}	$CR_{intercrop}$	K_{cotton}	$K_{intercrop}$	Product of K
Sowing methods									
M_1	1.23	1.08	0.36	-0.36	1.76	0.78	2.85	1.74	3.60
M_2	1.21	1.06	0.37	-0.37	1.57	0.80	3.41	1.43	3.60
Intercropping systems									
S_1	-	-	-	-	-	-	-	-	-
S_2	1.32	1.21	0.79	-0.79	1.85	0.54	6.27	0.87	5.51
S_3	1.32	1.15	-0.51	0.51	0.67	1.48	1.16	3.73	4.45
S_4	1.30	1.09	0.29	-0.29	1.27	0.80	2.78	1.40	3.69
S_5	0.94	0.83	0.89	-0.89	2.86	0.36	2.31	0.33	0.75

Values are means of three replicates. M_1: Machine sowing; M_2: Manual sowing; S_1: Sole cotton; S_2: Cotton + groundnut (1:1); S_3: Cotton + maize (1:1); S_4: Cotton + cowpea (1:1); S_5: Cotton + prosomillet (1:1). LER: land equivalent ratio, ATER: area time equivalent ratio. A: aggressivity, CR: competition ratio, K: relative crowding coefficient.

the cotton + groundnut (1.21) and cotton + maize (1.15) systems, while the cotton + prosomillet system recorded the lowest value at 0.83.

The aggressivity values of cotton were positive (A_{cotton} > 0) against certain intercrops, including groundnut (0.79), cowpea (0.29) and prosomillet (0.89). However, the aggressivity value of cotton when associated with maize was negative (A_{maize} > 0) at -0.51, indicating that maize was more dominant over cotton. This dominance is attributed to the shading effect of maize, which reduces light interception for cotton and leads to suppressed growth and development.

The competition ratio for cotton was greater than one (CR_{cotton} > 1) in all intercropping systems except for cotton + maize. This high CR value indicates that cotton exhibited superior competitive ability compared to the intercrops. The competition ratios for cotton intercropped with groundnut, cowpea and prosomillet were 1.85, 1.27 and 2.86, respectively. This implies that cotton dominated these intercrops, with lower CR values of 0.54 for groundnut, 0.80 for cowpea and 0.36 for prosomillet. However, the CR_{cotton} was less than one (0.67) when intercropped with maize (1.48), indicating that cotton was a poor competitor in the association.

The trend observed for K was similar to that of A and CR, confirming that cotton was the most competitive among the tested intercrops, except when intercropped with maize. The product of coefficients was high (K > 1) in all intercropping systems except for cotton + prosomillet (0.75), indicating a yield disadvantage in this system. Among the intercropping systems, cotton + groundnut recorded the highest K value at 5.51. High K values in the cotton + groundnut intercropping system indicate yield advantages driven by several agronomic factors. Resource complementarity is a crucial factor, as cotton's deep root system accesses nutrients from lower soil layers while groundnut's shallow roots capture nutrients closer to the surface. Additionally, groundnut fixes atmospheric nitrogen, enhancing soil fertility for both crops. Their different growth habits also facilitate efficient light capture, minimizing shading effects.

Effect on energy indices

Energy analysis concluded that both sowing methods and intercropping systems positively impacted energy parameters, including input, output and net energy (Table 5).

The energy inputs for mechanical operations were calculated based on the energy equivalents of the tractor (62.7 MJ/unit) and fuel (56.31 MJ/unit), considering the operational time spent during sowing. For example, the energy associated with the tractor was determined by evaluating its weight, lifespan (in hours), energy equivalents and the amount of fuel consumed based on the time required for the sowing operation (in hours) (34).

Manual sowing was found to have higher energy input, energy output and net energy compared to machine sowing. Manual sowing consumed more energy input (10,939 MJ/ha) than machine sowing (10,769 MJ/ha). The energy output was also greater for manual sowing, measuring 173,053 MJ/ha, compared to 171,296 MJ/ha for machine sowing. A similar trend was observed for net energy, calculated as the difference between output and input energy. Manual sowing reported a higher net energy of 162,114 MJ/ha, while machine sowing noted 160,527 MJ/ha.

Regarding intercropping systems, the highest energy input was recorded for the cotton + groundnut system (11,486 MJ/ha), followed by cotton + maize (10,993 MJ/ha). The lowest energy input was observed in sole cotton, which required 10,323 MJ/ha. Regarding energy output, the cotton + maize system has the highest energy, averaging 325,298 MJ/ha, followed by cotton + groundnut (151,902 MJ/ha). Conversely, the cotton + prosomillet system had the lowest energy output, averaging 109,135 MJ/ha. This trend continued with net energy, where the cotton + maize system exhibited the highest net energy at 314,305 MJ/ha, followed by cotton + groundnut at 140,416 MJ/ha. In contrast, cotton + prosomillet had the lowest net energy, recorded at 98,478 MJ/ha. The superior performance of the cotton + maize system in terms of energy can be attributed to its higher grain and stalk yield (biomass) compared to the other treatments.

Energy indices, including energy consumption efficiency, productivity, specific energy, intensity and profitability, showed no significant variations across sowing methods. Significant disparities were observed among the intercropping systems (Table 5).

The energy use efficiency for machine and manual sowing methods was reported as 15.8 and 15.7, respectively, indicating similar performance in energy utilization.

Among the evaluated intercropping systems, the cotton + maize combination demonstrated superior performance with a mean energy use efficiency of 29.6, significantly higher than the other systems. In contrast, the cotton + prosomillet intercropping system exhibited the lowest energy use efficiency, with a mean value 10.2.

Regarding energy productivity, which measures yield produced per unit of energy consumed, the cotton + maize intercropping system again excelled, recording energy productivity of 1.79 kg/MJ. This was followed by the cotton + cowpea system, with an energy productivity of 0.70 kg/MJ. The cotton + prosomillet system observed the lowest energy productivity, with a mean value of 0.55 kg/MJ.

Specific energy, defined as the amount of energy required to produce one kilogram of yield, varied among the intercropping systems. The cotton + prosomillet system registered the highest specific energy at 5.92 MJ/kg, indicating that 5.92 MJ/kg energy was required to produce one kilogram yield. In contrast, the cotton + maize system recorded the lowest specific energy at 1.80 MJ/kg, suggesting that less energy was needed to produce one kilogram yield.

The mean energy intensity was lower for manual sowing (1.61 MJ/₹) than machine sowing (1.98 MJ/₹). Among the intercropping systems, the cotton + maize combination had the highest energy intensity at 3.35 MJ/₹, reflecting a higher energy output produced per unit of cost. Conversely, the cotton + prosomillet system exhibited the lowest energy intensity, with a value of 1.12 MJ/₹. A similar trend was observed in energy profitability, which measures the economic return per unit of energy used. The cotton +

Table 5. Energy indices of cotton-based intercropping systems under different sowing methods

Treatments	Input energy (MJ/ha)	Output energy (MJ/ha)	Net energy (MJ/ha)	Energy use efficiency	Energy productivity (kg/MJ)	Specific energy (MJ/kg)	Energy intensity (MJ/₹)	Energy profitability
Sowing methods								
M_1	10,769	171,296	160,527	15.8	0.87	4.30	1.98	14.8
M_2	10,939	173,053	162,114	15.7	0.86	4.21	1.61	14.7
Intercropping systems								
S_1	10,323	130,535	120,212	12.6	0.62	4.46	1.54	11.6
S_2	11,486	151,902	140,416	13.2	0.65	4.20	1.48	12.2
S_3	10,993	325,298	314,305	29.6	1.79	1.80	3.35	28.6
S_4	10,810	144,002	133,192	13.3	0.70	4.89	1.48	12.3
S_5	10,657	109,135	98,478	10.2	0.55	5.92	1.12	9.24

Values are means of three replicates. M_1: Machine sowing; M_2: Manual sowing; S_1: Sole cotton; S_2: Cotton + groundnut (1:1); S_3: Cotton + maize (1:1); S_4: Cotton + cowpea (1:1); S_5: Cotton + prosomillet (1:1).

maize intercropping system demonstrated superior performance with a mean energy profitability of 28.6, significantly higher than the other systems. In contrast, the cotton + prosomillet system had the lowest energy profitability, with a mean value 9.24.

Effect on economic efficiency

The economic efficiency of different sowing methods and intercropping systems showed positive variations among treatments (Table 6). Manual sowing incurred a higher cultivation cost of ₹ 107,230/ha, which is 19.6% more than machine sowing, which costs ₹ 86,212/ha. Among the intercropping systems, cotton + groundnut had the highest cultivation cost at ₹ 103,029/ha, while sole cotton had the lowest at ₹ 84,866/ha. Manual sowing generated a slightly higher gross return of ₹ 168,780/ha compared to ₹ 165,855/ha from machine sowing. This difference is attributed to the optimal plant population of prosomillet in manually sown plots, as prosomillet seeds are not well-suited for the planters used in machine sowing and require more time to germinate. An optimal plant population significantly contributes to increased yield and the lower yield of prosomillet in machine-sown plots accounts for the slightly higher gross return record observed in manual sowing. The highest gross return was recorded in the Cotton + maize intercropping system at ₹ 208,442/ha, while cotton + prosomillet yielded ₹ 126,012/ha.

Machine sowing yielded the highest net returns of ₹ 79,644 per hectare, surpassing human sowing's ₹ 61,550 per hectare, resulting in a 22.7% increase in income with machine sowing. Among the intercropping systems, cotton + maize achieved the highest net return at ₹ 109,715/ha, followed by cotton + groundnut at ₹ 84,795/ha. Conversely, the cotton + prosomillet system yielded the lowest net return of ₹ 27,186/ha. The BCR, which indicates the return per unit of cost, also varied significantly across treatments. The machine sowing method recorded a BCR of 1.92, compared to 1.58 for manual sowing. Within the intercropping systems, cotton + maize achieved the highest BCR at 2.15, while cotton + prosomillet had the lowest BCR, averaging 1.29. The experiment highlighted the economic advantage of the cotton + maize intercropping system under both sowing methods, while the cotton + prosomillet system incurred economic losses compared to sole cotton. For per-day returns, machine sowing demonstrated a 22.6% increase over manual sowing and the cotton + maize intercropping system provided a 29.6% higher return than sole cotton.

Table 6. Economic efficiency of cotton-based intercropping systems under different sowing methods

Treatments	Cost of cultivation (₹/ha)	Gross return (₹/ha)	Net return (₹/ha)	Benefit-cost ratio	Per-day return (₹/ha/day)
Sowing methods					
M_1	86,212	165,855	79,644	1.92	569
M_2	107,230	168,780	61,550	1.58	440
Intercropping systems					
S_1	84,866	162,102	77,236	1.91	551
S_2	103,029	187,824	84,795	1.84	605
S_3	98,727	208,442	109,715	2.15	783
S_4	98,155	152,209	54,053	1.56	386
S_5	98,825	126,012	27,186	1.29	194

Values are means of three replicates. M_1: Machine sowing; M_2: Manual sowing; S_1: Sole cotton; S_2: Cotton + groundnut (1:1); S_3: Cotton + maize (1:1); S_4: Cotton + cowpea (1:1); S_5: Cotton + prosomillet (1:1).

Discussion

This study examines the impact of different sowing methods (machine versus manual) and intercropping systems on yield, competitive indices, energy indices and economic efficiency by comparing intercropped plots with sole cropping plots. These findings are valuable for cotton-producing countries like India and China, which seek validated technological recommendations to strengthen their agricultural economies.

Cotton equivalent yield

A slightly higher CEY (1.74%) was observed in the manual sowing plot compared to machine sowing, mainly due to a reduction in the plant population of prosomillet, which led to decreased yield. This reduction occurred because the small seed size of the prosomillet was incompatible with the planter used for machine sowing. In machine sowing, smaller seeds often take longer to germinate due to factors such as deeper planting depth and uneven soil coverage. These issues are more commonly encountered in machine sowing than in manual sowing. Smaller seeds are especially susceptible, necessitating accurate planting depth and optimal seed-to-soil contact for effective germination in intercropping systems (37). The combinations of cotton with maize and cotton with groundnut exhibited considerably elevated CEY compared to solitary cotton, with increases of 22.2% and 13.7%, respectively. This increase is attributed to the additional yield from intercrops and favorable market price, resulting in better performance than the sole cropping system (24). The cotton + groundnut intercropping also enhances productivity through complementary effects, such as improved soil nutrient accumulation and microbial dynamics, achieved through nitrogen fixation (38).

Competitive indices

In intercropping systems, assessing competitive indices per unit area is crucial for identifying the most advantageous system. Nonetheless, comparing competitive indices such as LER, ATER, A, CR and K across crops with varying production capacity on identical land can pose difficulties.

LER and ATER were used to evaluate the efficiency of intercropping systems in utilizing environmental resources compared to sole cropping. LER values exceeding one in all intercropping systems, except for cotton + prosomillet, suggest a yield advantage over sole cropping (39). The higher LER values in the cotton + groundnut (32%), cotton + maize (32%) and cotton + cowpea (30%) systems are due to the efficient use of wider inter-row space and strong complementary interactions between component crops, leading to more effective resource utilization (18). In contrast, the lower LER value in the cotton + prosomillet system (0.94) is attributed to reduced yields in both cotton and prosomillet. Recent findings indicate that high-input amendments can reduce LER in intercropping systems, likely due to diminishing returns on resource use efficiency (40).

LER values were generally higher than ATER values, suggesting that LER may overestimate resource utilization (41). LER tends to overstate the benefits of intercropping when component crops have varying growth periods (28). When intercrops have different land coverage durations, ATER provides more accurate estimates than LER. According to the study, LER demonstrated an advantage ranging from 1% to 32%, while ATER showed an advantage of 1% to 21%. Thus, intercropping systems with well-chosen crop combinations, such as cotton with groundnut, maize and cowpea, maximize land use efficiency and yield, supporting their adoption in cotton farming.

The competitive efficiency of component crops in intercropping systems can be assessed using indices such as A, CR and K. Aggressivity (A) is a critical competitive index that evaluates a crop’s competitive strength when grown alongside another crop (39). In this study, cotton's aggressivity values were positive ($A_{cotton} > 0$) against all intercrops except maize, indicating that maize was more dominant. This dominance may result from competition for nutrients and water during the early growth stages and the varying growth durations of the crops, which affected cotton yield. Similar patterns were reported by (29, 42).

The competition ratio provides a more accurate measure of the competitive abilities between the main crop and intercrops. In all intercropping systems, except cotton + maize, cotton’s competition ratio ($CR_{cotton} > 1$) exceeded one, demonstrating higher competitiveness. Specifically, cotton was 70% more competitive than groundnut, 37% more competitive than cowpea and 87% more competitive than prosomillet. However, maize was 55% more competitive than cotton, indicating that cotton was a weaker competitor when intercropped with maize.

The trend for the K was similar with A and CR. The K index also confirmed cotton’s higher competitiveness among the intercrops, except when intercropped with maize. Maize, growing taller than cotton, creates shading that reduces light interception for cotton, limiting solar energy availability and decreasing yield (39, 43). Conversely, in the cotton and groundnut intercropping system, cotton's superior height, greater leaf area and wide ground cover generally confer a competitive advantage, while groundnut remains comparatively shorter over the growth period (38, 44).

Energy indices

The energy analysis revealed distinct input and output levels within cotton-based intercropping systems under different sowing methods. Energy input across the sowing methods was nearly similar, with manual sowing requiring 1.55%, 1.00% and 0.98% more energy input, output and net energy, respectively, than machine sowing. This variation is due to the higher labor demand in manual sowing, counterbalanced by the diesel consumption associated with the tractor and sowing implement (45).

In terms of intercropping systems, the cotton + groundnut combination required 10.1% more energy input than sole cotton due to the additional cultivation requirements for groundnut, such as fertilizers (gypsum, ferrous sulfate), pesticides, harvesting and shelling (46, 47).

The cotton + maize system demonstrated the highest output energy (59.8%), followed by cotton + groundnut (14.1%). This trend extended to net energy, with cotton + maize showing 61.7% higher net energy and cotton + groundnut showing 14.4% higher net energy compared to sole cotton, highlighting a higher energy return per unit of input (48).

Energy indices from machine sowing showed slightly greater efficiency than manual sowing, mainly due to the increased labor energy required for manual sowing. Cotton cultivation demands more labor and time in manual sowing, whereas mechanized sowing reduces labor intensity and operational time, ultimately decreasing energy consumption (5). Among the intercropping systems, the cotton + maize combination resulted in a 57.4% increase in energy use efficiency, a 63.5% increase in energy productivity, a 59.6% increase in specific energy, a 54.0% increase in energy intensity and a 59.3% increase in energy profitability compared to sole cropping. These gains are attributed to the substantial increase in energy output from maize grain and stover yield. Conversely, the cotton + prosomillet system exhibited lower energy efficiency due to reduced yields (15).

The results demonstrate that, among the assessed systems, the cotton and maize intercropping combination exhibits the highest efficiency regarding net energy, energy usage efficiency, energy productivity, energy intensity and energy profitability, whereas the cotton and prosomillet combination is the least efficient.

Economic efficiency

Analyzing the competitive indices reveals that these measures reflect the biological performance of intercropping systems and provide essential insights into their economic efficiency. Understanding how competitive dynamics impact resource utilization enabled a better assessment of the financial benefits of different cropping strategies. Therefore, evaluating the economic efficiency of various intercropping systems offers insights into how competitive advantages translate into profitability for farmers.

The economic analysis identifies economically viable treatments among the different sowing methods and intercropping systems. Machine sowing demonstrates greater profitability than manual sowing, reducing cultivation costs by 19.6% and increasing net returns by 22.7%. This is particularly beneficial in cotton cultivation, which demands significant labor for sowing (5). Machine sowing increases efficiency and cost-effectiveness, especially in labor shortage contexts, by reducing expenses and enhancing operation speed, seed rate accuracy and precision in sowing depth and spacing (6, 49).

Among the intercropping systems, cotton + maize and cotton + groundnut generated 29.6% and 8.91% higher net returns than sole cotton cultivation. This increase in economic returns may be attributed to higher yields from intercropping and favorable market prices (24, 31). In contrast, the cotton + prosomillet system yielded lower net returns than sole cotton, likely due to its higher production costs and reduced income. Additionally, the cotton + groundnut system incurred a 17.6% higher cultivation cost than sole cotton, possibly due to the greater input requirements for groundnut cultivation (50).

The economic analysis underscores the importance of maximizing farm potential through diverse approaches. Integrating diversified production strategies in cotton farming is a viable option for small-scale producers to mitigate the price fluctuations of primary crops or the impacts of weather changes and disease outbreaks that reduce crop yield. Diversification is both a risk management tool and a means to enhance socioecological resilience. These findings highlight the potential benefits of this intercropping system, providing valuable guidance for farmers seeking increased economic returns.

Conclusion

This study highlights the clear advantages of machine sowing over manual sowing, emphasizing its potential to enhance agricultural efficiency. However, integrating intercropping into mechanized practices presents challenges like machinery compatibility and seed selection. The results indicate that the cotton + maize intercropping system notably boosts overall productivity, followed by the cotton + groundnut system. In contrast, the cotton + prosomillet system faces difficulties due to its incompatibility with the machinery used for sowing. To overcome these obstacles, future efforts should optimize machine sowing techniques for intercropping and adapt equipment to handle various seed types. Such advancements could substantially improve productivity and profitability for smallholder farmers. Further research should also investigate innovative machinery designs with adjustable disc types, sowing depths and enhanced intercropping strategies to increase yield and sustainability across diverse agricultural systems.

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Authors' contributions

All the authors have contributed equally to data collection, analysis, writing the original manuscript, drafting, editing and reviewing.

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