Review Article

MECHANIZATION IN COTTON FARMING: ADDRESSING LABOR SHORTAGES AND ENHANCING PRODUCTIVITY IN INDIA

ABSTRACT

Cotton is a globally significant crop, playing a vital role in both the agricultural and industrial economy. Cotton is a crucial raw material for the textile and apparel industries, driving international trade and commerce. Its global demand influences market dynamics, trade policies, and economies worldwide. The cotton industry provides livelihoods for millions of people, particularly in developing countries, from farming to manufacturing, making it a key source of employment globally. In India, approximately 59% of the raw material for India's textile industry comes from cotton. However, cotton cultivation is challenged by lower yields and high costs associated with various operations such as sowing, weed management, pest control, and harvesting. Mechanization significantly improves cotton yield and profitability by enhancing efficiency, reducing labor, and enabling the cultivation of larger areas with better resource utilization. Precision tools like seed-cum-fertilizer drills and mechanized planters ensure optimal seed placement and spacing, boosting plant health and yield potential. Additionally, mechanized harvesting reduces labor costs, minimizes harvest losses, and ensures better-quality cotton, leading to higher market returns and overall profitability. The innovative concept of High Density Planting Systems (HDPS) shows great potential for improving yields, particularly in rainfed cotton. This system involves planting five to ten plants per square meter, which enhances yield and is compatible with mechanized operations for seeding, weeding, pest management, and harvesting. The key objective of using improved sowing equipment is to achieve precise seed distribution within the row, facilitating operations like weeding and fertilizing at predetermined distances and depths. Proper seed placement by planters is critical to achieving optimal germination. Implementing efficient mechanical weeders could motivate small-scale farmers, boosting production and reducing poverty. A power weeder, a mechanized tool commonly used for preparing soil beds, offers significant savings in time, labor, and fuel. Furthermore, the adoption of mechanical cotton pickers would help ensure timely harvesting operations, increasing yields and contributing to higher cotton production.India’s low cotton productivity can be attributed to the limited adoption of modern agronomic practices and the low level of mechanization. Embracing these innovations could lead to significant improvements in the cotton sector Cotton pickers and strippers play a vital role in modern, large-scale cotton cultivation by significantly reducing harvesting time and labor costs, making them indispensable for efficient operations. These machines increase productivity by enabling faster harvesting across larger areas, minimizing the reliance on manual labor, which can be costly and scarce. Additionally, they reduce harvest losses and enhance yield by ensuring more cotton is collected with minimal waste. Cotton pickers, being gentler, help preserve fiber quality, while strippers are ideal for bulk harvesting in regions growing lower-grade cotton. Overall, mechanized harvesting ensures timely and efficient cotton collection, improving both yield and quality.

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Keywords: Cotton, Mechanized cultivation, weed control, Seed cotton yield.

1. INTRODUCTION

Cotton provides employment for approximately 70 million individuals and supplies nearly 75% of the raw materials for India's textile industry (Kairon *et al*., 2004). The area under cotton cultivation has significantly expanded, reaching around 9 million hectares and is expected to grow to 9.5 million hectares. This expansion is largely driven by farmers shifting from other crops like sugarcane and pulses to cotton (Sundharam *et al*., 2013). Cotton cultivation in India holds immense importance as a crucial cash crop, significantly contributing to agricultural GDP and export earnings while providing livelihoods for millions in farming and related industries. As one of the world's largest producers and exporters, India plays a vital role in the global cotton trade, underpinning its robust textile and apparel sector. Cotton farming drives rural development, particularly in states like Gujarat, Maharashtra, and Telangana, benefiting from its agronomic adaptability to varied climates (Kranthi *et al.*, 2014). Mechanization significantly increases the efficiency of cotton cultivation and harvesting, addressing the growing labor shortages in agricultural regions and reducing dependence on manual labour (Shamshiri *et al.*, 2024). Studies on farm mechanization reveal that mechanized practices can reduce seed usage by 15-20%, fertilizer consumption by 20-30%, time spent on operations by 20-30%, and labor requirements by 2.5-20%, while increasing cropping intensity by 10-15%. This integrated approach can boost productivity by 15-20% (Nagraj *et al.*, 2013). However, the high cost of hybrid seeds, combined with the need for re-sowing due to poor germination or insufficient monsoon rainfall, adds to the overall expenses of cotton cultivation (Blaise *et al.*, 2014).Often referred to as "white gold," cotton is a soft, luxurious fiber that develops within the protective boll of the *Gossypium* plant. It is not only a key commercial crop but also a significant economic driver with deep-rooted social and political implications in India (Mohanty *et al*., 2016). Cotton is cultivated on 11.88 million hectares in India, with an average productivity of about 500 kg of lint per hectare (Venugopalan *et al*., 2016). However, harvesting cotton remains a labor-intensive and challenging task, often viewed as a form of punishment in certain regions. Workers endure bruised hands from prolonged work in the fields, and pesticide exposure can lead to harmful health effects (Deshmuk *et al*., 2016).To address these challenges, the mechanization of cotton cultivation is essential. In the 2017-18 period, India ranked as the second-largest consumer and exporter of cotton, with 5.4 million bales consumed and 5.9 million bales exported (USDA, 2018). Meanwhile, Tamil Nadu faces a demand for 10 million bales annually but currently produces only 500,000 bales, highlighting the need to boost cotton production to meet demand (USDA, 2018). Delays in labor availability for crucial tasks like weeding and picking can result in a 15-30% loss of seed cotton (Blaise *et al.*, 2019).In developing countries like India, rising labor costs make it imperative to adopt mechanization in cotton production to manage costs effectively (Uma *et al*., 2019). One such innovation is the High Density Planting System (HDPS), which involves cultivating cotton with narrower row spacing to enhance yield.

2. HIGH DENSITY PLANTING OF COTTON

The decline in Asiatic cotton production is largely due to its low yields, which are influenced by factors such as wide row and plant spacing, leading to lower plant density (Giri and Gore, 2006). One way to address this issue is by planting compact cotton cultivars with closer intra- and inter-row spacing, which results in higher yields compared to traditional varieties (Venugopalan *et al*., 2016). The popularity of HDPS is growing rapidly as it has proven to significantly enhance productivity, with some areas seeing a fivefold increase, particularly in rainfed conditions (Chahal, 2017). Using HDPS along with straight cotton varieties is a practical approach to boost productivity, particularly in rainfed conditions, while also reducing production costs (Santosh *et al*., 2016). HDPS offers additional advantages, such as improved light interception, faster leaf area development, and early canopy closure, all of which contribute to better weed control (Santosh *et al*., 2016). Given the diverse climate and soil conditions in India, HDPS combined with mechanized harvesting offers a sustainable solution for improving productivity and profitability for cotton farmers (Narayana *et al*., 2018).The use of growth retardants alongside HDPS is being explored as an alternative production technology to further enhance cotton yields and profitability (Uma *et al*., 2019). HDPS allows for planting densities ranging from 110,000 to 245,000 plants per hectare, with the choice of density depending on soil type and local growing conditions (Venugopalan *et al*., 2019).

Mechanization is critical in HDPS, from land preparation and seed sowing with pneumatic planters to fertilization and pest management using tools like self-propelled boom sprayers. Mechanized cotton pickers also play a crucial role in the harvesting process. By combining HDPS with improved genotypes, fertilizer management, and mechanization, cotton farmers can overcome yield stagnation. Promoting intercropping, crop rotations, and double cropping systems within HDPS frameworks can further improve economic returns, enhance soil fertility, and ensure sustainable cotton production (Khadi, 2022).

3.MECHANIZATION IN CROP ESTABLISHMENT

3.1.Sowing

The seed cum fertilizer drills lack the precision needed for optimal seed placement and uniform application rates, resulting in uneven germination and emergence across the field. This inconsistency is caused due to issues like ground drive wheel slippage and inefficient seed metering mechanisms.Reports indicate that seed rates vary by 10-20%, necessitating higher seed usage to achieve desired plant populations, followed by costly thinning operations in densely populated areas. Similarly, fertilizer application suffers from variability due to differences in flow ability.To address these challenges and reduce production costs, a new approach has been developed. It involves ground speed sensing and electronic control systems to drive the metering shaft, resulting in a fixed-rate precision seed cum fertilizer applicator(Singh*et al.,* 2012).The use of improved seeding machine such as seed cum fertilizer drill helps in reduction of operation cost and increase the net income,(Dhakad*et al.*,2017).The adoption of farm mechanization has proven instrumental in achieving a noteworthy enhancement in agricultural productivity(Khobragade *et al.*, 2018). A tractor-operated seed-cum-fertilizer drill outperforms a bullock-drawn seed drill when compared to humanlabor utilization, crop yield and cultivation cost per hectare(Satishkumar *et al.,* 2018).Seed cum fertilizer drills, equipped with two separate compartments for seeds and fertilizers, facilitate simultaneous seeding and application of basal doses of inorganic fertilizers. With a cost ranging from Rs. 2500-3000 per hectare, they effectively halve the expenses incurred when compared to manual methods, thus offering significant cost savings(Ramanjaneyulu et al., 2021).The seed-cum-fertilizer drill regulates the sowing depth and line width of crops under the specified package of practices(Subala*et al.,* 2022).Seed cum fertilizer drill helps in line by line sowing and optimum application of seeds and fertilizers in field.The primary goal of using a seed-cum-fertilizer drill during the sowing operation is to place both the seed and fertilizer in rows at the desired depth. Additionally, the objective is to ensure consistent seed-to-seed spacing, cover the seeds with soil and achieve proper compaction without causing mechanical damage to the seeds(Subala*et al.*, 2022).The adoption of a seed-cum-fertilizer drill has impacted production by reducing labour, ensuring timely sowing and facilitating precise depth and width of fertilizer application. These factors contribute significantly to plant growth, ultimately leading to increased production and decreased labour requirements. The timely sowing and accurate fertilizer application play crucial roles in enhancing plant growth and boosting overall production(Subala*et al.*,2022).

3.2.Planting

Seedbed preparation and planting operations account for approximately 20% of the energy expended from sowing to marketing, making the selection of the appropriate implement crucial for the economic viability of cotton cultivation.Various models of planters are available for cotton planting, including tractor-drawn ridgerseeders, tractor-drawn pneumatic precision planters, and tractor-cultivator mounted seeders(Kathirvel *et al.*,2006). The choice among these options significantly impacts the overall efficiency and cost-effectiveness of cotton cultivation.The implementation of an efficient sowing method significantly contributes to enhancing soil physical properties, promoting germination, supporting plant development,growthand ultimately improving the yield and income per unit area (Krause *et al.*,2009).CICR, Nagpur, developed a vertical rotor-type cotton planter, drawn by bullocks, designed for planting delinted cotton seeds at specified row and plant spacing in vertisols. This new innovation helped inreduction of seed requirement, enhanced accuracy and saved time and labor compared to traditional manual methods(Majumdar, 2010). For proper placement of seeds, the planters play ancrucial role in relation to desired germination(chandel*et al.*,2010).The growth as well as the yield of cotton are influenced significantly by two crucial agronomic factors: planting method and water management(Ali et al.,2012).The typical sowing depth for the cotton crop was noted to be up to 5 cm. The average draft requirement for a manually operated single-row cotton planter is 10.60 kg(Sharma *et al.*,2013).Raghavendra *et al.* (2013), devised and assessed a tractor-operated ridge planter. This planter exhibited an average draft of 2300 N and consumed fuel at a rate of 3.83 liters per hour. Its field capacity was measured at 0.89 hectares per hour, with a field efficiency of 73.55%. In terms of operational cost for sowing cotton, the ridge planter was found to be 433 Rs/ha, a notable reduction compared to the conventional method's cost of 1013 Rs/ha. The labour demand for planting cotton is substantial at 15%, second only to the harvesting operation, which accounts for 44%(Vaiyapuri, 2014).Given the constraints posed by expensive seeds, the conventional practice of manual dibbling, a scarcity of labour and the prevalent trend of small marginal land holdings, there is a demand for a compact manual planter tailored to the needs of small-scale and marginal landowners (Kankal *et al.*, 2016). (Sanjaykrishnan, 2018) introduced a multi-crop planter designed to be drawn by a mini-tractor, featuring an adjustable inclined plate metering mechanism. This innovation demonstrated an effective field capacity of 0.51 hectares per hour, accompanied by an average field efficiency of 72.78%. The use of compact manual planters in cotton cultivation offers several special advantages over traditional methods like hand sowing. These planters ensure uniform seed spacing and depth, which can improve seed germination and crop establishment, leading to better yields. They also reduce labor requirements and physical strain on farmers, making the process more efficient and less time-consuming. Moreover, compact planters are affordable and suitable for smallholder farmers, especially in rainfed or low-input systems, where mechanization may be limited. Additionally, they minimize seed wastage and promote better resource utilization, contributing to overall sustainability (Singh *et al.*, 2020).

4. MECHANIZATION IN PLANT PROTECTION

According to (Liu and Huang, 2013) those who adopt Bt cotton tend to utilize an excessive amount of pesticides, potentially leading to consequences for both biodiversity and human health. (Sharma and Pannu, 2013), demonstrated through field experiments conducted at two distinct locations that allocating 70% and 30% of the recommended fertilizer dose at depths of 10 and 20 cm, respectively, resulted in notably increased seed cotton yield (2.74 t/ha) compared to traditional manual broadcasting of fertilizer (2.30 t/ha). India has witnessed consistent progress across various categories of farm equipment, including manually operated tools, animal-powered implements, and machinery driven by mechanical and electrical power sources. Notably, there has been a significant increase in the adoption of manually operated equipment, with the number of sprayers nearly doubling (Mehta *et al.*, 2014).The prevalent sprayers employed on cotton farms include lever-operated and power knapsack sprayers (Majumdar,2016).Knapsack sprayers exhibit high effectiveness during the earlier crop growth stages but challenges are faced in the later stages of crop development, as the movement of the operator and the handling of lances for spraying become difficult. The power sprayer demonstrates superior performance because of the higher pressure generated by the engine and pump. This leads to a robust blast of air at higher velocity, effectively shaking the plants. Additionally, power mist blowers can efficiently spray the undersides of leaves (Majumdar, 2016). Tractor operated sprayers, powered by the tractor's power take-off (PTO) are employed in the initial phases of cotton crop cultivation. They feature a 6.5m long boom equipped with nozzles. The boom can be adjusted to a height ranging from 30 to 300 cm and the swath width extends up to 12.1 m. Reports indicate a yield increase of 25-29% (Majumdar, 2016).Research assessing the effectiveness of high volume, low volume, and ultra low volume sprayers in controlling cotton insect pests revealed that the fog air sprayer exhibited the lowest undesirable cotton content, the highest droplet density and provided effective plant coverage. Low volume sprayers were determined to be very efficient than high volume sprayers in controlling cotton insect pests (Majumdar, 2016). The primary cause of reduced crop yield is pest, disease, and weed infestation. Chemical control is the widely adopted method for managing most insects, weeds, and diseases. The initial cost of acquiring a tractor is prohibitively high and falls outside the financial means of the average farmer. Consequently, power tillers were introduced in Tamil Nadu. To enhance the versatility of power tillers, a rear-mounted boom sprayer operated by a power tiller was designed and developed for efficient spraying in cotton crops grown in rows (Padmanathan *et al.*, 2017). Drones have been increasingly employed for agricultural plant protection operations in cotton in countries like USA, China, Australia, etc. This utilization significantly reduces production costs, minimizes the need for labour-intensive man-days and enhances pest and disease control by timely intervention (Ramanjaneyulu *et al.*, 2021).

Further, Controlled Droplet Applicator (CDA) sprayers represent a recent introduction to the cotton sector, also known as Heli sprayers in the Indian market. These sprayers guarantee the precise droplet size for a specific target, ensuring uniformity and using minimal volume and dosage to achieve effective control (Majumdar, 2016).

Fig.1. Boom sprayer

5. MECHANIZATION IN WEED MANAGEMENT

Manual weeding proves to be labour-intensive and time-consuming, involving significant costs and inducing fatigue due to the strenuous bending posture required when using a manual hand hoe(Bishwas*et al.*,2000). The implementation of efficient mechanical weeders would motivate small-scale farmers, resulting in heightened production and a reduction in poverty.Without effective control measures, weeds can absorb 30-40 percent of applied nutrients, leading to a substantial decrease in yield(Oguntunde and Olukunle,2006). In Indian agriculture, weeding is primarily carried out manually, requiring significant labour and time, which in turn escalates operational costs. As per estimates, the typical requirement for hand weeding ranges from 400-600 man-hours per hectare, translating to approximately Rs. 2200 per hectare, depending on the severity of weed infestation(Tajuddin, 2006). The design of weeders varies across regions, influenced by factors such as weed type, soil characteristics, crop type, cropping patterns and local resources(Yadav and Pund,2007). According to (Nazaret *et al.*,2008), the prevalence of broad-leaved weeds in the initial phases of cotton growth results from their rapid growth and extensive root systems. The cost of weeding operations in cotton constitutes a substantial portion of the overall operational expenses(Veerangouda*et al.*,2010).The weeding efficiency of self-propelled weeders was approximately 94-95%, similar to that of tractor-operated rotary weeders which achieved 90% efficiency. Plant injury rates ranged from 1-3%. The cost and labor savings were significant, around 30-40% compared to traditional methods, and approximately 90% compared to manual weeding(Majumdar, 2010).Cotton is highly susceptible to weed-crop competition, necessitating effective weed management throughout its growing season. This involves the application of pre-emergence pre(or) residual herbicides and post-emergence herbicides(Cardoso *et al.,* 2011). Among farmers, the adoption of rotating blades as a soil working tool because of its uncomplicated structure, lightweight and high efficiency. This tool facilitates improved soil breakup and inversion, reduces draft requirements and effectively mixes crop residues(Mandal *et al.,*2013).Crop yield in cotton is adversely impacted, ranging from 40% to 60%, due to delays and negligence in weeding operations(Rao *et al.,* 2014).Rainfed cotton growers often face a significant challenge in the form of unpredictable monsoons. The presence of biotic stresses, including insect pests, diseases, and weeds and also the high input costs associated with their control, contributes to an raise in production costs, ultimately reducing profits(Blaise *et al.*, 2014). The absence of timely labour availability can cause delays in both weeding and picking processes, potentially resulting in a loss of approximately 15–30% of seed cotton. This, in turn results in increased production costs(Blaise *et al.,* 2014). The unregulated proliferation of weeds during the cotton growing season led to a significant reduction in yield, reaching up to 86 percent(Leela *et al.*,2016).The extensive application of herbicides, particularly glyphosate, has favoured the development of weed biotypes with tolerance in numerous agro-ecosystems. This situation can result in economically unfavourable cropping patterns due to yield losses and additional expenses incurred in managing herbicide-resistant weeds(Heap and Duke,2018). The rotary power weeder, characterized by its compact size, proves to be easily transportable in cotton fields. Notably, it brings about substantial savings, with a 74.5 percent reduction in cost and a 95 percent reduction in time compared to manual weeding. Moreover, the machine is cost-effective in comparison to other self-propelled weeders, making it readily affordable for small and marginal farmers(Hari Prasad *et al.*,2019). Compact engine-driven power tillers or power weeders exhibit high efficiency in mechanical inter-cultivation, for using it throughout the entire growth cycle of a cotton crop, even when planted with a row distance of ≥90cm(Ramanjaneyulu *et al.*,2021).Power tiller-based mechanical weed control removes weeds among the cultivated crops and also maintains looseness of surface soil, promoting improved aeration and also water uptake ability of soil. This method reduces labour costs and saves time in the weeding process(Pawar *et al.*,2022).A mechanized agricultural tool known as a power weeder is widely employed to streamline the soil bed preparation process, effectively minimizing time, human labour and fuel consumption(Pawar *et al.*,2022).Power weeder is widely employed to efficiently prepare soil beds, offering time, labour savings and improved fuel use efficiency(Pawar *et al.*,2022).The effectiveness of the power weeder in weed removal was noted to be consistently high across all stages of the crop, demonstrating efficacy at different speeds(Pawar *et al.*,2022).

Fig.2. Power weeder

6. MECHANIZATION IN HARVESTING

Cotton harvesters come in two main types: pickers and strippers. Pickers are selective, gathering only the open bolls of seed cotton, while strippers are non-selective, removing both opened and unopened bolls along with the entire plant(konduru*et al.*,2013).India is not keeping pace with numerous other major cotton producers in harvesting mechanization.India has a need to automate its harvesting processes in cotton due to shortage of labours and increasing farmwages(konduru*et al.*,2013). Compact-structured varieties are well-suited for mechanical picking. In countriesthese varieties are planted at high densities, where mechanical pickers are used(Venugopalan *et al.*,2013).Greater utilization of pickers for cotton could result in higher yields, leading to improved cotton production in India. This in turn, might exert downward pressure on international cotton prices(konduru*et al.*,2013). Small and marginal farmers experience limited mechanization, while larger farms have partial mechanization in place. Tractors are utilized on large farms for plowing and planting, but as of now, they are not used for picking process(Blaise *et al.*, 2014). All of India's cotton production relies on manual labour for hand-picking, with each worker able to pick 5 kg of seed cotton per hour. This manual labor constitutes 35% of the entire cost of production (Deshmukh and Mohanty, 2016). Picking cotton manually is not just a demanding and arduous task but also more expensive.Nowadays there is a frequent and widespread occurrence of labour shortages during the peak periods of cotton production. Mechanical pickers can significantly reduce the labor-intensive nature of hand picking and improve the production of a cleaner grade of seed cotton. The implementation of mechanical cottonpicking systems will also contribute to achieving timely operations for the subsequent crop(Majumdar,2016).Cotton exhibits perennial characteristics, indeterminate growth and asynchronous maturity. In India, the entirety of cotton production relies on manual labour for hand-picking with each worker able to harvest 5 kg of seed cotton per hour. This labour-intensive process contributes to 35% of the total production cost(Deshmukh and Mohanty,2016).Developed nations, cultivars suitable for mechanization are being grown, and defoliating chemicals are employed to remove the leaves earlier, before using mechanical picking machines. Hence it is important to breed varieties tailored to Indian conditions to enable the complete mechanization of cotton picking (Ramanjaneyulu *et al.*,2021).ICAR-CIRCOT's portable ginning machines efficiently gin small quantities of cotton samples, providing a rapid assessment of fiber quality. This benefits cotton traders, graders, ginners, and researchers, while also assisting farmers in obtaining seeds for sowing(Ramanjaneyulu *et al.*,2021).According to Konduru *et al*.(2022), the potential increase in cotton farm income in India could reach approximately Rs.10,000 per acre if mechanical harvesting methods are adopted. This heightened productivity is primarily attributed to the reduction in row-row and plant-plant spacing, leading to a plant density increase of 4-5 times compared to conventional methods.Harvesting using a stripper typically occurs after the plants have naturally shed their leaves. Mechanical pickers exhibit selectivity by extracting seed cotton from mature bolls while leaving green, unopened ones intact for future maturation(khanpara*et al.*,2022).Strippers are favoured over pickers in regions with smaller plants and lower yields. They are particularly effective with plants that have bolls resistant to storms and in areas experiencing dry weather during the harvest period. Occasionally, chemical defoliants and desiccants are used to facilitate earlier stripping(khanpara*et al.*,2022).

Fig.3. Mechanical harvester

Table.1. Energy Input Output Analysis In Cotton Production

INPUTS	Energy equivalent(MJ/unit)	Input used per hectare(unit/ha)	Energy value(MJ/ha)	unit
Human labour	1.96	575.58	1128.12	hectare
Land preparation	1.96	14.17	27.77	hectare
planting	1.96	3.23	6.33	hectare
Hoeing	1.96	19.50	38.22	hectare
Fertilization	1.96	31.06	60.88	hectare
Spraying	1.96	22.80	44.68	hectare
Irrigation	1.96	66.82	130.96	hectare
Harvesting	1.96	413.25	809.97	hectare
Transporting	1.96	4.75	9.31	hectare
Machinery	64.80	58.86	3814.17	hectare
Land preparation	64.80	14.17	918.26	hectare
planting	64.80	1.61	104.33	hectare
Fertilization	64.80	15.53	1006.34	hectare
Spraying	64.80	22.80	1477.44	hectare
Transporting	64.80	4.75	307.80	hectare
Chemical fertilizers	60.60	107.90	5350.74	Kilogram
Nitrogen	60.60	83.90	5084.34	Kilogram
Phosphorous	11.10	24	266.40	Kilogram
Irrigation	0.63	6750	4252.50	
Diesel fuel	56.31	52.35	2947.83	litre
Seed	11.80	21.50	253.70	kg
Total inputs			17747.06	
output	11.80	5700	67260	

(Baran *et al.*, 2016)

Table.2. Amount Of Inputs, Outputs And Their Energy Equivalent In Mechanized Rainfed Cotton Production In Sudan

Inputs	Quantity/ hectare	Total energy equivalent (MJ/ha)
Seeds(kg)	12.70	149.86
Labour(h)	332.84	652.36
Herbicides(l)	1.50	681.00
Machinery(h)	1.52	95.40
Diesel fuel(l)	13.72	656.01
Total energy input(MJ/ha)		2234.62
Outputs		
Cotton seed yield(kg)	661.20	7802.01

(Baran *et al.*, 2016)

7. NEED FOR COTTON MECHANIZATION

Mechanization in cotton cultivation seems to be a most important factor in cost and time reduction. This strategy involves employing diverse power sources along with enhanced farm tools and equipment to alleviate the laborious tasks traditionally undertaken by humans and draft animals. By implementing mechanization, precision and timeliness in the efficient utilization of resources can be achieved, thereby minimizing losses(Majumdar,2010).The adoption of mechanization in cotton farming has witnessed a notable increase across the province. This includes a rise in the deployment of advanced technological equipment such as powerful new tractors, pneumatic planters, mounted and self-propelled sprayers for defoliant applications, as well as self-propelled cotton pickers(sessiz*et al.*,2012).When mechanization is implemented effectively, farmers can conserve approximately 15-20% of seeds, 20-30% of fertilizer, 20-30% of time, and 15-20% of labor. Moreover, this approach can lead to an increase in cropping intensity by around 10-15%, along with higher productivity of approximately 15-20% (Nagraj *et al.,* 2013).Farm mechanization not only reduces the time and labour required but also lowers crop production expenses over time. Additionally, it diminishes post-harvest losses while simultaneously enhancing crop yield and farm revenue (Mehta *et al.*,2014). The reluctance to adopt modern agronomic practices and the low level of mechanization are the reasons for the comparative low productivity in India, which stands at 500 kg per hectare, in contrast to other major economies like Brazil (2027 kg per hectare), China (1311 kg per hectare), and the USA (900 kg per hectare)(Ramanjaneyulu *et al.*,2021).As rural labor availability decreases due to urban migration, cotton farming faces critical labor shortages during peak times like planting, weeding, and harvesting. Mechanization helps address this gap (Kumar *et al.,* 2023).Mechanized operations allow timely planting, weeding, and harvesting, which improves overall crop productivity and reduces post-harvest losses (Sinha *et al.,* 2018).Mechanization reduces long-term labor costs, especially for operations like picking and ginning, where manual labor is intensive and costly (Kumar *et al.,* 2023).Timely harvesting is crucial to avoid quality deterioration of cotton due to weather conditions or pest infestations. Mechanization ensures these operations are conducted at the optimal time (Khadi *et al.,* 2010). Mechanized harvesting and processing techniques minimize damage to cotton lint, reducing post-harvest losses and improving fiber quality (Ghaffar *et al.,* 2020). Low-cost cotton harvesters, like knapsack and pneumatic cotton pickers, are gaining traction among smallholder farmers in India due to their affordability and ability to address labor shortages. The knapsack cotton picker, costing around ₹ 5000, reduces the cost of picking to ₹ 4.55 per kg of cotton, saving up to 75% in labor and energy compared to manual picking. These machines are economically viable, with a quick payback period, making them an attractive option for small-scale farmers (Muthamilselvan *et al.*, 2017).

Recent advancements in agricultural machinery for smallholder cotton farmers in India focus on developing compact, affordable cotton pickers suited to fragmented landholdings, adapting existing machinery for small-scale farming, exploring solar-powered and ergonomic harvesting tools, and creating multi-crop adaptable equipment. Research emphasizes indigenous technology development, integration of precision agriculture techniques, and cost-benefit analyses of various solutions. Studies also investigate cooperative ownership models and stress the importance of farmer training programs to effectively adopt new technologies, aiming to increase productivity and sustainability while reducing physical strain and operational costs for smallholders (Shamshiri *et al.*, 2024).

8. KEY CHALLENGES IN COTTON CULTIVATION

While cotton pickers selectively gather fully open bolls, leaving unopened ones untouched, the economic feasibility of operating mechanical pickers more than once is hindered primarily by the high prevailing diesel prices in the market(Dattatray *et al.*,2007). Frequently, there is a scarcity of seeds from preferred cultivars, prompting farmers to obtain them from the market. Unfortunately, farmers are often compelled to buy counterfeit seeds available in the market(kranthi*et al.*,2012). Crop production in various cotton-producing regions is hindered by challenges such as soil degradation, soil erosion and escalating salinity levels(Antille*et al.*, 2016).Cotton exhibits poor adaptability to climate anomalies. A successful cotton crop typically demands approximately 900 mm of water. Consequently, dry land or semi-irrigated cotton faces a significant risk of crop failure in the presence of unpredictable weather conditions(CRDC, 2017).Cotton production in India faces notable volatility owing to a multitude of factors. Factors such as restricted access to irrigation systems, diminishing soil fertility and erratic weather patterns—including unforeseen droughts or excessive rainfall contribute to the uncertainty surrounding cotton yields(Neha *et al.*,2019).Cotton crops are susceptible to various pests and diseases, including the cotton bollworm and fungal infections, which can significantly reduce yields (Balikai *et al.*, 2020).Cotton is a water-intensive crop, and efficient irrigation practices are crucial, especially in regions facing water scarcity (Ali *et al.*, 2020).Ensuring optimal soil fertility and nutrient levels is essential for maximizing cotton yields. Imbalances can lead to poor growth and reduced productivity(Kumar *et al.*, 2022)Cotton production is affected by climate change, including temperature fluctuations and extreme weather events, which can impact growth and yield (Prasad *et al.*, 2021).Cotton farmers face economic challenges due to fluctuating market prices and input costs, which can affect profitability and sustainability (Jones *et al.*, 2020). While countries like the United States, Australia, and Brazil have highly mechanized cotton production systems with widespread use of machine pickers and precision agriculture technologies, India's mechanization levels remain relatively low, particularly among smallholder farmers. China has made rapid strides in mechanization, especially in its western regions, outpacing India. Indian cotton farming still relies heavily on manual labor for crucial operations like picking, although there's growing adoption of mechanized planting and spraying. The lower mechanization in India is attributed to factors such as small, fragmented landholdings, high initial investment costs, and the socio-economic importance of providing agricultural employment, presenting both challenges and opportunities for targeted technological interventions suited to local conditions (Kranthi *et al*., 2020).

9. CONCLUSION

In USA, achieving 100% mechanization took 30 years, whereas in Brazil, it took 45 years. Turkey reached 75% mechanization within 15 years, while China attained 15% mechanization in 20 years. However, in India, cotton cultivation remains heavily reliant on labour, necessitating the mechanization of all activities. The profitability of cotton production in India has been significantly hampered by a sharp increase in cultivation costs, rising by 174%, primarily due to higher labour costs (237%), fertilizer expenses (178%), pesticide usage (135%) and seed costs (72%). Labour expenses stand out as the predominant component, with picking and harvesting accounting for the highest proportion (approximately 42%), costing Rs. 14,185 per hectare, followed by weeding (18.45%, Rs. 6,121/ha), pesticide application (14.68%, Rs. 4,868/ha), sowing (8.06%, Rs. 2,672/ha) and fertilizer application (7.72%, Rs. 2,562/ha). To mitigate these challenges, reducing labour costs is imperative, necessitating the mechanization of cultivation practices.The incorporation of mechanization in cotton cultivation can save 35-40 man-days and approximately 85-90 hours per hectare. This leads to a reduction in production costs by Rs. 8,500-9,000 per hectare, while simultaneously increasing net income by Rs. 12,000-15,000 per hectare. In developed nations, cultivators focus on growing varieties conducive to mechanization and utilize defoliating chemicals to remove foliage from cotton plants before employing mechanical picking machines. Therefore, it is important to develop and adapt similar varieties suitable for Indian conditions to achieve complete mechanization in cotton picking. The low productivity of cotton in India can be due to the non-adoption of modern agronomic practices and a limited level of mechanization. Several factors contribute to lower productivity, including the absence of higher-yielding varieties, a significant portion of land being rainfed, improper nutrient application,limited awareness to farmers about the new mechanized cultivation techniques, insufficient agronomic management practices and a shortage of labour combined with rising labour costs. Mechanical harvesting of cotton in India has the potential to boost yields on Indian cotton farms, consequently increasing overall cotton production in the country. As a result, international cotton markets might experience a surge in cotton exports from India, potentially driving down international cotton prices. To promote mechanization among smallholder cotton farmers, it is essential to increase investment in R&D for affordable, farmer-friendly tools and establish targeted subsidies and financial incentives to encourage adoption. Strengthening public-private partnerships can drive innovation and facilitate technology transfer, while enhanced farmer education and training will ensure better usage of mechanized tools. Improving rural infrastructure and encouraging cooperative ownership models can make expensive machinery more accessible. Policies aimed at consolidating landholdings and promoting custom hiring centers for machinery can further support mechanization efforts, particularly when integrated with sustainable farming and precision agriculture practices (Sims *et al*., 2015).

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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