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REVIEW ARTICLE

# An overview of mechanized cotton harvesting : Introduction of AI enabled robot and its implication in mechanization

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## Abstract

Cotton has been a pivotal crop throughout India's history, maintaining its significant social and economic importance in contemporary Indian society. In India, cotton is harvested manually using traditional hand-picking techniques. However, manual cotton-picking poses drawbacks such as high labor cost, labor shortage and risks to worker's health due to prolonged exposure to pesticides and repetitive motion injuries, thereby affecting overall productivity and sustainability in the cotton industry. Mechanical harvesting employs advanced machinery to efficiently harvest cotton, reducing its dependence on manual labor and thereby boosting productivity in the fields. Mechanical cotton-picking presents challenges such as high initial investment costs for machinery, potential damage to crops, soil compaction and the need for skilled operators, limiting its widespread adoption in small land holdings. The integration of robotics, automation and precision agriculture has transformed cotton harvesting technology, replacing traditional methods. These innovations improve efficiency and productivity while supporting sustainability by minimizing environmental impact and ensuring continued success of cotton production. Further research and development in artificial intelligence, machine learning and sensor technology are expected to drive continued innovation, making cotton harvesting even more efficient, sustainable and cost-effective for farmers worldwide.

**Keywords:** cotton harvesting; image processing; mechanization; picker; robotics and stripper

## Introduction

Cotton is cultivated in several countries, including India, China, the USA, Pakistan, Uzbekistan, Turkey, Brazil, Greece and Egypt, which together accounts over 80 % of the worldwide cotton production (1). Cotton is cultivated in around 69 countries across the globe, covering 30.84 million ha. The global cotton production stands at approximately 120.96 million bales, with an average lint yield of 854 kg per ha (2). Cotton represents an important commercial crop in India's agricultural landscape with a major impact on the economy. Cotton farming consists of multiple steps, including land preparation, planting, weed management, application of pesticides and harvesting. Of these, the harvesting stage necessitates more manual labor and effort. The industry that produces cotton has a number of difficulties, including shortages, ineffective labor methods and soaring salaries. In Gujarat, Maharashtra, Punjab and Andhra Pradesh, the majority of agronomic tasks are still performed manually. These regions face severe labor shortages as a result of rural-to-urban migration. In India, cotton picking is predominantly carried out manually, with approximately 500 labourers per ha involved in the multi-stage hand-picking process. This method is not only time-consuming but also significantly more expensive as compared to other tasks like irrigation and weeding (3). A skilled worker can pick about 15 to 20 kg of cotton by hand in one day. On the other hand, a single-row spindle picker greatly increases efficiency by harvesting 870 to 2180 kg of cotton per day (4). Mechanization might greatly increase productivity and profitability, addressing the critical issues facing the Indian cotton sector. Countries such as United States, Australia, Brazil and Israel have adopted fully mechanized cotton harvesting systems, with over 90 % of the area harvested using mechanical pickers or strippers (5).

### Need of cotton mechanization in India

India is the second largest producer of cotton in world, contributing 20.67 % of global production. During the 2024 - 2025 season, cotton production in India is expected to reach approximately 299.26 lakh bales of 170 kg, cultivated over an area of 113.6 lakh ha. This corresponds to an estimated productivity of about 448 kg of lint per ha (6). The cultivable area of cotton crop worldwide is given in Fig. 1. Harvesting proves to be the most delicate process, demanding clinically skilled labourers. However, statistics indicated a 10 % decline in agricultural workers every three years (7). One reason for the low productivity is the manual labor shortage for hand-picking of cotton. Due to multiple pickings, the quality of cotton is affected as Indian cotton varieties fail to produce their bolls at once.

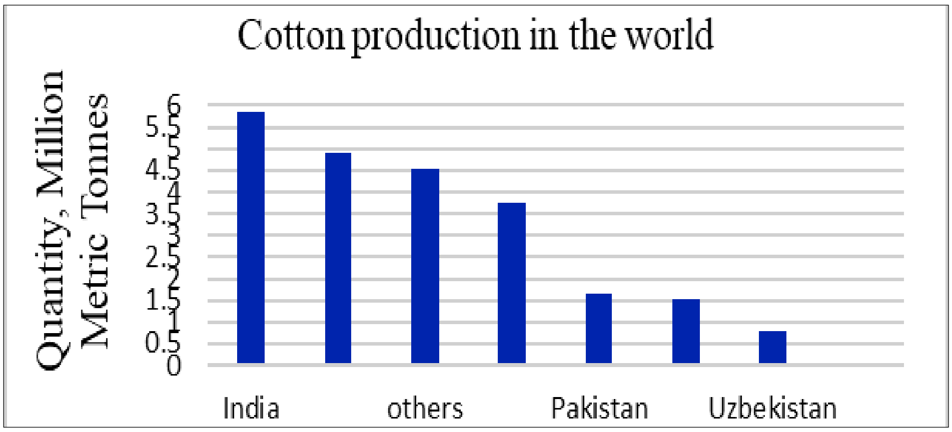


**Fig. 1.** Worldwide cotton production (6).

Cotton picking by hand is hard work and can cause injuries and pesticide poisoning to the manual labourers. To address these challenges, mechanization of cotton picking is crucial for the future of the industry. It can reduce the workload on farmers, allowing them to focus on other tasks. It also increases overall productivity, allowing more land to be cultivated and creating opportunities for off-farm jobs in the service sector. The shift to mechanization has a major impact on small-scale farmers. Although labor is commonly accessible, other necessary resources like land, capital and effective management are frequently scarce. Cotton producers are exploring cost-saving measures in response to shortage of labour and rising wages. The goal behind reviewing cotton harvesting technologies is to determine their suitability for Indian cotton farmers. The review covers the latest advancements in cotton harvesting machineries.

## Status of cotton harvesting mechanization in India

Mechanization rates in the cotton sector mirror those of other crops for tasks such as application of fertilizers, land preparation and chemicals. However, when it comes to harvesting, most of the cotton production in India relies heavily on manual labor. Approximately 0.9 man-hr per kg of cotton are spent on hand-picking, which costs nearly 10 times as much as irrigation and twice the expense of weeding (8). India falls behind several major cotton producing nations in harvesting mechanization. Labor shortages and increasing farm wages, India is anticipated to mechanize its cotton harvesting operations in the near future due to labor shortage and increase in farm wages. Studies showed significant decline in labor availability, from 70.3 % of the population in 1961 to 48.9 % in 2010. Additionally, the cost of picking cotton has increased from Rs 4 per kg in 2007 to Rs 10-12 per kg in recent years (9).

## Characteristics of cotton plant for suitable mechanization in India

The successful adoption of mechanical cotton harvesting depends on the morphological and agronomic characteristics of the plant. Traits such as plant height, boll size and position, branching pattern and boll opening behaviour greatly influence harvesting efficiency and extent of the field losses (10, 11). Globally, most of the variety suitable for mechanization belong to *Gossypium hirsutum* L., commonly known as upland cotton (12) including cotton cultivars suitable for mechanized harvesting (DP 1646 B2XF, ST 4990 B2XF, FM910, IAC 25) (13). India has developed several promising cotton cultivars and hybrids suitable for mechanical harvesting, including PA 255, Suraj, Phule Dhanwatari, KCH 121, RCH 134 BG II, which characterized by semi-dwarf to medium plant height, compact and erect branching, early boll opening a uniform boll distribution in the upper canopy (14). For mechanical picking, plant selection should prioritize growth and fruiting traits. Varieties with a short fruiting period and consistent early maturity are preferred. The effectiveness of mechanical pickers depends more on plant size; growth habits and boll characteristics rather than just yield (15). To produce a single 225 kg bale of lint, around 100000 cotton bolls are required. Each boll contains 4-5 locks of cotton, creating more than 400000 chances for losses during mechanical picking.

The physical characteristics of bolls are essential in influencing the efficiency of spindle pickers during harvesting. Cotton crops are harvested manually three times per season, spaced fifteen days apart. These harvests contribute 35 %, 50 % and 15 % respectively to the total yield (16). It is necessary to consider specific plant and boll characteristics in order to facilitate the effective mechanical harvesting of cotton. These include plant height, carpel flare, lint %, seed weight, boll size, shape, length, trash content, maturity and the length of the lowest and longest limbs. These characteristics differ depending on the type of cotton and affect harvesting efficiency, pre-harvest losses and picking effort (17). Wider spacing likely promoted the growth of more monopods and bolls per plant, although this effect might have been mitigated by a significant reduction in the overall plant population (18). The study focusing on varietal characteristics of certain potential cotton cultivars, as mentioned in Table 1. They examined the suitability of these cultivars for mechanical harvesting, considering both high-density and normal planting systems (19).

A study to evaluate the physical traits of cotton plants for designing a cotton uprooter-cum-shredder (20). They determined that the stalk stem diameter was 2.2 cm, the plant height reached 117.4 cm and the taproot extended to a depth of 32.7 cm. For industrial applications, a study investigated the physical, chemical, thermal and mechanical properties of cotton stalks (21). Significant differences in stem diameter, plant height, root spread and overall plant weight between local and hybrid cotton varieties were highlighted in their findings, impacting their suitability for various processing techniques.

## Cotton harvesting

### Mechanism of cotton picking

The different cotton harvesting types were classified (22) which have been described below (Fig. 2).

**Table 1.** Shows the different characteristics of cotton plant for mechanical harvesting (19)

| Sl. No. | Characteristics | Variety | |
|---|---|---|---|
| | | F2383, RCH, Suraj | RCH 134, Ankur 651, Manak |
| 1 | Planting system | High density planting system | Normal |
| 2 | Plant canopy across row (cm) | 34 – 70 | 30 – 100 |
| 3 | Plant height (cm) | 60 – 95 | 50 – 120 |
| 4 | Height of upper most boll (cm) | 50 – 84 | 58 – 110 |
| 5 | Height of lower most boll (cm) | 19 – 27 | 6 – 47 |
| 6 | Number of monopodial | 1 – 3 | 1 – 4 |
| 7 | Number of sympodial | 20 – 40 | 10 – 40 |
| 8 | Yield (kg. $ha^{-1}$) | 1499 – 3543 | - |

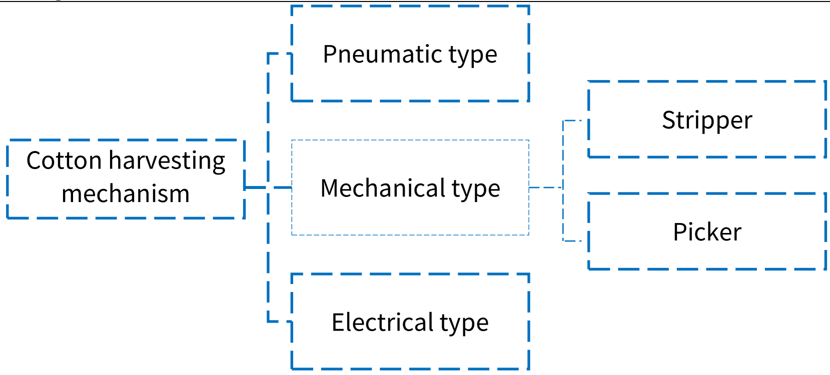


**Fig. 2.** Classification of cotton harvesting mechanisms.

**Pneumatic systems:** These harvesters use air pressure, either suction or blasts, to detach cotton fibers from the bolls.

**Mechanical systems:**

*Cotton pickers:* Equipped with rotating spindles, fingers or prongs that gently pull mature cotton fibers from the bolls while minimizing damage to leaves and immature cotton.

*Cotton strippers:* Utilize interlocking lugs, combs, belting fingers, steel rolls or brushes to strip cotton along with burrs and debris from the plant.

**Electrostatic systems:** These machines use electrically charged belts or fingers to attract cotton fibers, utilizing static electricity to remove cotton from the plant efficiently.

## Conventional practices of cotton harvesting

Conventional practices of cotton harvesting involve several steps and techniques aimed at efficiently gathering cotton bolls from the plants while preserving the quality of the fibers. These practices have evolved over time and vary based on factors such as geographic location, available technology and labor availability.

### Manual picking

In India, cotton is handpicked by workers, whether it's grown with rainwater or irrigation. It's crucial to pick cotton when more than 35 % of the bolls are open. Picking should be done in a timely manner, with a 15-20 days interval between the first and second pickings. Manual picking is labor-intensive, requiring significant human energy and time. It's a tedious process where each cotton ball is individually collected by hand. An experienced picker can harvest approximately 113 - 125 kg of cotton daily. The first picking should occur when 30-35 % of the bolls are fully open (23). Picking too early can result in short staple length and poor-quality fibers, leading to substandard fabrics. Immature fibers obtained from early picking may darken quickly. Additionally, seeds obtained from early picking have low germination rates and low edible oil content. Delay in cotton picking can negatively affect lint quality and the fiber tends to lose strength, increasing the likelihood of breakage during processing in textile mills and garment manufacturing (24).

### Pneumatic harvesting

A pneumatic-type cotton picker revolutionizes the cotton harvesting process by employing compressed air to delicately extract cotton from the plant. This innovative technology minimizes damage to both the cotton and the plant, enhancing overall yield quality and efficiency (25). By utilizing a gentle suction mechanism, it removes cotton fibers without causing stress or harm to the crop, ensuring optimal productivity while preserving the integrity of the cotton bolls. The industrial vacuum cleaner was used for cotton harvesting (26). Preliminary tests showed that manual picking was more labour-intensive than mechanical harvesting, needing about 0.9 man-hr to collect each kg of cotton. Despite the introduction of electric-powered vacuum cleaners, performance issues such as clogging and inadequate suction pressure necessitated further modifications. Recommended a redesign (27), converting the vacuum cleaner device into a lightweight, backpack-style unit. Laboratory tests showed a maximum suction pressure of 400 mm of water, but leakage reduced it by 50 mm. Further research on suction-based cotton pickers (25), which featured a blower, tank and suction hose, all integrated onto a frame designed for mounting on a tractor three-point linkage. The blower powered through the tractor's PTO via a gearbox, operated at speeds of 2875 rpm with a suction pressure of 240 mm water head. The machine achieved a picking efficiency between 63.4 % and 77.5 %, selectively removing fully opened cotton bolls while leaving infected or tightly attached bolls untouched. Hand-picking was still required for 22.5 % to 36.6 % of the cotton post-machine operation.

Research to enhance the efficiency of a pneumatic knapsack cotton picker (28). Using statistical analysis, adjustments were made to improve various parts of the system, including the height of the filter, size of the pickup pipe, speed of the aspirator and volume of the collection drum. The highest efficiency was recorded with a 25 mm diameter pickup pipe, a 225 mm nylon mesh filter and a collection drum holding 25 L. At an aspirator speed of 5500 rpm, the machine operated at maximum efficiency. Initial picking capacity was recorded at 4.93 kg per hr, increasing to 5.07 kg per hr by the third picking. Picking efficiency improved from 96.35 % in the first round to 97.48 % in the third. Machine usage led to reductions in labor (9 %), time (75 %) and energy consumption (68.23 %) compared to traditional methods. Developed and built a cotton-picking device (Fig. 3) to streamline the removal of cotton from bolls (29).

The ideal blower size was chosen by assessing the lowest force needed to extract the cotton while ensuring sufficient suction pressure. A force of 3.6 N was theoretically calculated for picker ends with a 25 mm diameter. To efficiently collect cotton bolls, a cyclone separator was designed. With an airflow rate of 0.076 $m^3 s^{-1}$, the systems input duct, exit pipe and internal air velocity were optimized for better functionality. To enhance the picking rate, an electromagnet was integrated into the system. The estimated minimum current required for operating the electromagnetic valve was 4.26 A. The total pressure loss in the system, accounting for friction and pressure variations across different machine components, was determined to be 111.7 mm of water. The research conducted an in-depth evaluation of cotton-picking equipment, assessing the variations in picker end diameters and suction pressures influenced machine performance (29, 30). Their research examined picker end diameters ranging from 20 mm to 40 mm, coupled with suction pressures between 25 mm and 50 mm Hg. The study showed that an optimal picking efficiency of 96.3 % was achieved using a 25 mm picker end diameter with a suction pressure of 45 mm Hg. The cleanest cotton, with the lowest trash content of 0.65 %, was collected when a 20 mm picker end operated at 30 mm Hg. A peak output of 6.25 kg per hr was recorded with a 25 mm picker end and 45 mm Hg suction pressure. Increasing the suction pressure to 50 mm of Hg improved efficiency but also led to higher trash levels. A suction pressure of 35 mm Hg resulted in a 93.9 % picking efficiency, producing 4.2 kg per hr with a trash content of 5.7 %. In a follow-up test, the machine achieved an output of 4.01 kg per hr, a 92.8 % picking rate and a reduced trash content of 4.39 % at the same 35 mm Hg suction pressure.

A pneumatic cotton picker attachment was developed to suit major Indian cotton varieties and enable women to operate it using power tillers (Fig. 4). The design process involved refining critical elements such as pick-up pipe dimensions, filter selection, drum capacity and aspirator speed through continuous testing. This mechanized approach proved more efficient than manual harvesting, cutting costs by 17.0 %, reducing labor effort by 75.0 % and lowering energy consumption by 74.6 %. Financial analysis projected a payback period of 0.45 years, with profitability achieved at an annual yield of 5900 kg of cotton (31). Designed a lightweight, knapsack-mounted cotton plucker to support small-scale farmers (Fig. 5) (32). The device includes a pick-up pipe, motor, filter, blower and a 50 L polypropylene container for cotton collection. A specialized filter prevents cotton fibers from reaching the aspirator. Laboratory trials assessed three drum variations (A, B and C) across four different fan speeds (4200, 4700, 5200 and 5700 rpm). Results demonstrated a harvesting rate between 4.75 and 9.78 kg per hr, trash levels ranging from 2.07 % to 8.03 %, picking efficiency between 91 % and 96 % and fuel consumption varying from 0.270 to 0.702 L per hr. A controlled studies to evaluate the effectiveness of a knapsack-type cotton picker under different conditions (33). The research analyzed the influence of blower speeds (2500, 3500, 4500 and 5000 rpm), variations in pick-up pipe diameters (20, 25 and 30 mm) and different blower bowl openings (50 %, 75 % and 100 %) on overall machine performance (Fig. 6).

The studies evaluated key performance metrics, including fuel consumption ranging from 0.72 to 1.31 L per hr, picking efficiency between 94.42 % and 96.85 %, trash content varying from 8.16 % to 11.33 %, pressure at the pick-up pipe tip recorded between 0.035 and 0.076 kg $cm^{-2}$ and internal pressure within the gathering drum measured between 0.023 and 0.047 kg $cm^{-2}$. Using PRO-E Wildfire 2.0 software, a walking-type cotton picker based on a suction mechanism was designed and analyzed, consisting of a picking spout, suction pipe, aspirator, trolley frame, cotton collection drum and prime mover (34). They

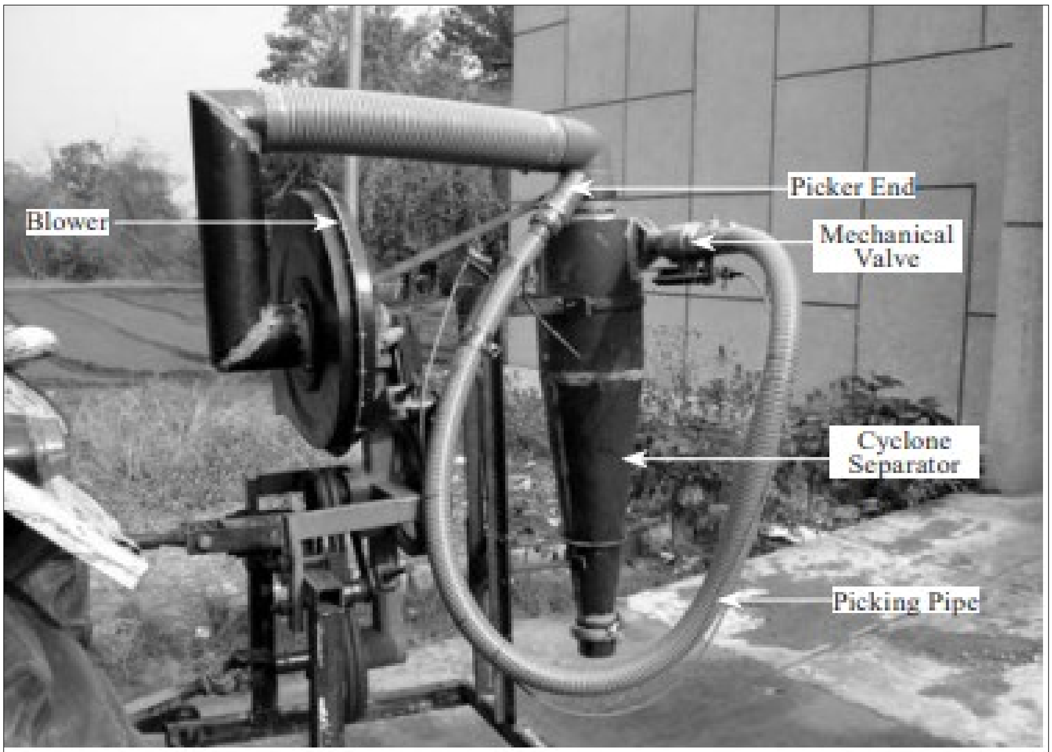


**Fig. 3.** Pictorial view of mechanical cotton picker (29).

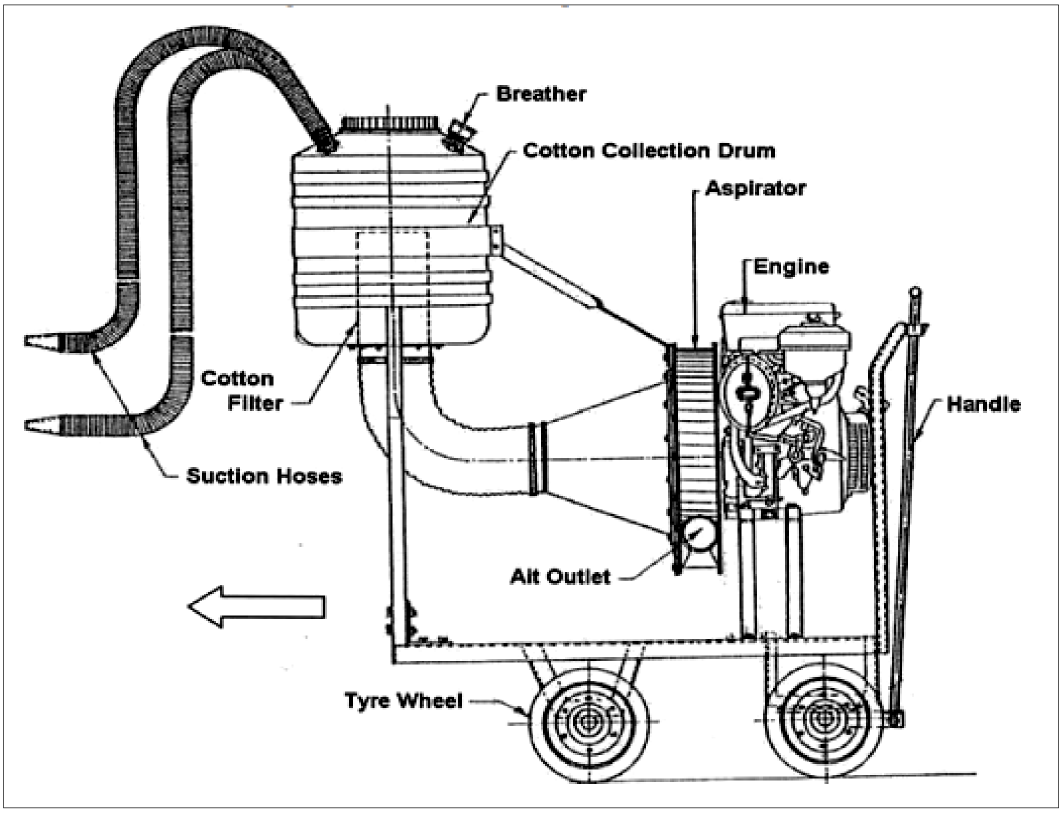


**Fig. 4.** Pneumatic cotton picker for women (31).

**Fig. 5.** Knapsack type cotton plucker (32).


**Fig. 6.** Knapsack type portable engine operated cotton picker (33).

experimented with different conditions such as 3 levels of picking spout diameter and 4 levels of aspirator speed viz., (30, 40 and 50 mm) and (3000, 4000, 5000 and 6000 rpm). They found that the maximum air velocity and suction pressure were 13.97 m $s^{-1}$ and 0.049 kg $cm^{-2}$ as well as picking capacity and picking efficiency were 9.23 kg $hr^{-1}$ and 95.73 %. They concluded that the combination of 30 mm × 6000 rpm provided low harvesting losses of 6.51 %. Table 2 shows the characteristics of different pneumatic cotton pickers (35).

## Mechanical harvesting

Cotton harvesting machines are generally categorized into two types: pickers and strippers (Fig. 7) (36). Strippers remove all bolls, including both mature and immature bolls, from the plant, whereas pickers selectively harvest only the open seed cotton bolls (37). Table 3 outlines the differences observed in the picking and stripping mechanisms, as studied (38). Additionally, Fig. 7 provides a detailed representation of the mechanical processes involved in cotton harvesting equipment. The history of mechanical cotton harvesting dates to the 19$^{th}$ century. On September 10, 1850, S.S. Rembert and J. Prescott of Memphis, Tennessee, received the first patent for a cotton-picking device. August Campbell later introduced a spindle design in 1895, forming the basis for modern cotton pickers. John and Mack Rust patented a cotton-picking machine in 1932, featuring a straight, moistened spindle for extracting cotton from open bolls (39). Strippers, on the other hand, were first developed in the late 19$^{th}$ century. Z.B. Sims of Bonham, Texas, was granted a patent in 1872 for a sled-type cotton stripper pulled by horses and two years later, in 1874, W.H. Pedrick from Richmond, Indiana, designed a roll-type stripper featuring rotating rolls with metal studs. In 1884, Benjamin Savage from Scotland Neck, North Carolina, patented another variation of the roll stripper, incorporating brush elements made of wire, hair, steel or whalebone. These early innovations laid the groundwork for modern stripping mechanisms used in contemporary cotton harvesters.

**Table 3.** Difference between cotton picker and stripper (38)

| S. No | Parameters | Picker | Stripper |
|---|---|---|---|
| 1. | Initial, running and maintenance cost | High | Low |
| 2. | Adjustments and setting | Many | Very few |
| 3. | Trained operator | Essential | Not essential |
| 4. | Picking efficiency | 85 – 90 % | 97 – 99 % |
| 5. | Trash content | 8 – 10 % | 28 – 30 % |
| 6. | On board field cleaner | Not required | Required |
| 7. | Fiber quality deterioration | Non - Significant | Slight |
| 8. | Plant height | 90 – 120 cm | 60 – 90 cm |

The concept of the sled-type stripper originated with a Texas High Plains farmer, constructed a basic version by fastening part of a picket fence onto a sled to strip cotton (40). This early design encouraged farmers and local manufacturers to refine the idea, prompting improvements that resulted in the creation of horse-drawn cotton sleds. At the same time, ginning machinery producers developed dedicated systems for extracting and cleaning cotton collected through sled strippers (41).

**Table 2.** Characteristics of pneumatic cotton picker (35)

| Sl. No. | Power | Labour requirement (man-h. $kg^{-1}$) | Suction pressure | Picking efficiency (%) | Picking capacity (kg. $h^{-1}$) | Reference |
|---|---|---|---|---|---|---|
| 1 | Electrical power | 0.9 | - | - | - | 24 |
| 2 | Tractor operated | - | 240 mm of water head | 63.4 – 77.5 | | 25 |
| | | - | 25 - 50 mm of Hg | 92 – 97 | 4 – 6.25 | 27 |
| | | - | - | 95 – 98 | 4 – 5 | 26 |
| 3 | Petrol engine (knapsack type) | - | - | 91 – 96 | 4 – 10 | 30 |
| | | | 0.035 – 0.076 kg $cm^{-2}$ | 94 – 97 | 4.95 | 31 |
| | | - | 13.97 m $s^{-1}$ | 95.73 | 9.23 | 32 |

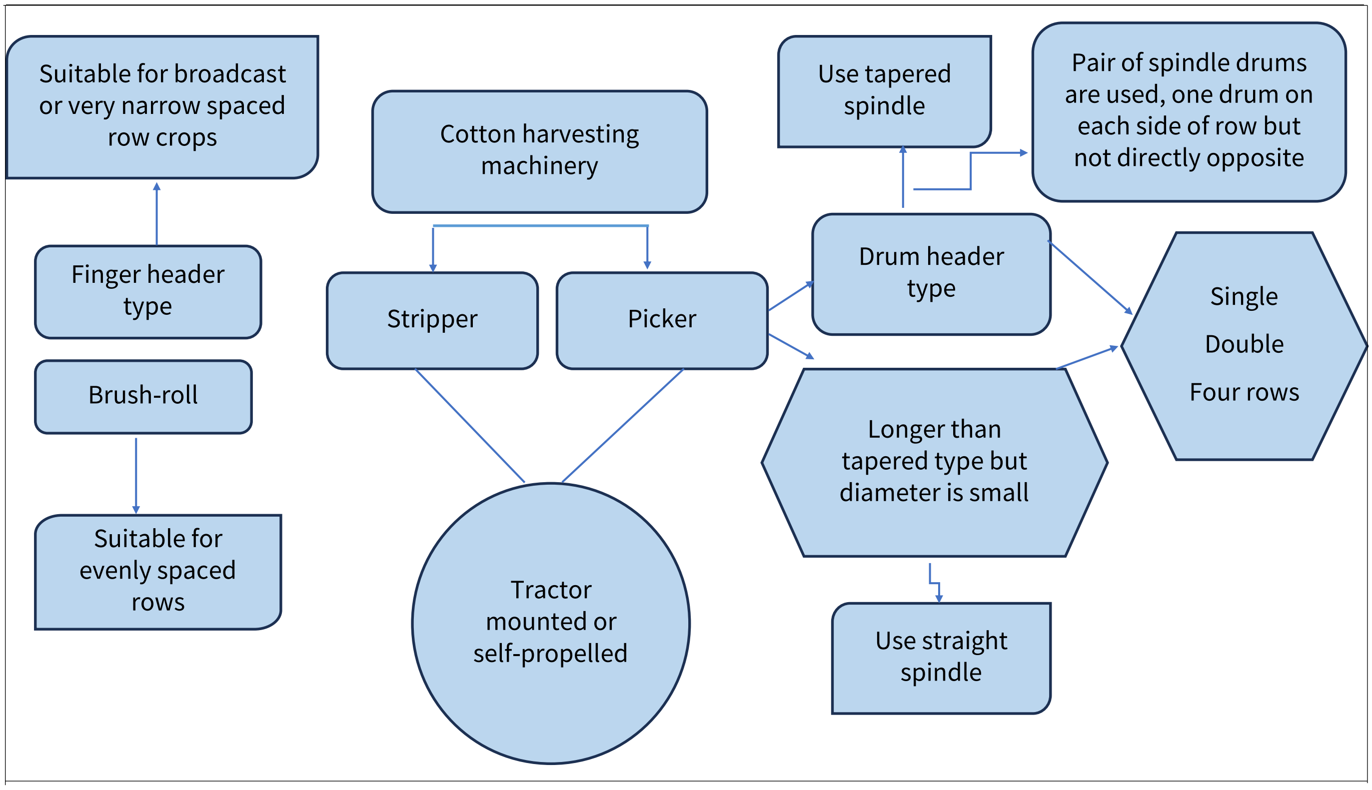


**Fig. 7.** Illustration of the mechanisms involved in cotton harvesting machinery.

Non-selective harvesting machines like finger and roll strippers collect seed cotton along with burs, leaves and small stem or branch fragments. These machines were better suited than spindle pickers for harvesting cotton in dry regions and from short, compact plants commonly grown in the Southwest (West Texas, Oklahoma and New Mexico). Although several enhancements were made to these strippers after their development (42-44), widespread use was hindered by challenges such as fluctuating cotton prices, reliance on manual labor, crop losses caused by the machines, inefficient gin cleaning technology and the lack of effective defoliants. The labor shortages during World War II accelerated the shift towards mechanized cotton harvesting, with around 15000 mechanical pickers and 25000 cotton strippers in use by 1953, processing approximately a quarter of the 16 million-bale production that year. By 1960, nearly 60 % of U.S. cotton was harvested using machines. Today, almost all cotton harvested in the United States relies on mechanical methods. Alongside these advancements, research into harvest aids such as desiccants has expanded, playing a key role in cotton harvesting preparation. Desiccation is essential for efficient harvesting, while defoliation is necessary to maintain fiber quality and enhance picker performance (45, 46).

### Role of defoliation in mechanical harvesting

Defoliation occurs naturally when cotton plants mature, causing leaves to fall off. However, chemicals known as defoliants are often applied to speed up the process, preventing stains and debris from affecting fiber quality during harvesting. This practice enhances lint cleanliness, reduces moisture content and aids in opening unripe bolls (47). Farmers often face difficulties due to excessive foliage, which complicates harvesting and affects fiber quality. The selection of a defoliant with strong leaf-removal and boll-opening properties is an essential part of cotton production. The performance of defoliants is influenced by factors such as the crop's maturity, uniformity in plant growth, environmental conditions and the plant's ability to absorb and distribute the chemical effectively. Applying defoliants before full crop maturity can negatively impact yield and fiber quality (48). Proper defoliation improves harvester efficiency, facilitates manual picking, reduces trash levels in the lint and minimizes leaf content. It also helps prevent boll rot, lowers the chances of lodging, increases available picking hours and preserves fiber quality. However, incorrect timing can negatively impact fiber length and micronaire value (49). Different herbicides have been used to aid defoliation in cotton intended for mechanical harvesting (50). The success of defoliation is influenced by soil moisture, nitrogen content, temperature and rainfall during application. Weather conditions at and after application also play a key role in determining defoliant performance. Warm temperatures, strong sunlight and high humidity create ideal conditions for defoliants to work effectively. Choosing the right defoliant depends on factors such as crop health, expected yield and harvesting conditions. In India, achieving consistent defoliation remains challenging, leading to additional leaf trash in mechanically harvested cotton. In some cases, inefficient defoliation has resulted in harvested cotton containing 20-25 % trash instead of the ideal 10-12 % range (50).

Defoliation is generally carried out when at least 50 % of the cotton bolls have opened. Premature leaf removal can negatively impact both yield and fiber quality. For optimal absorption, defoliants should be applied during the early morning or late afternoon when humidity levels are higher and wind speeds are minimal (51). In 1999, field experiments in Marana and Coolidge, Arizona, tested different defoliation methods on upland cotton varieties (DP 33b and AP 6101). Results showed that using Ginstar alone produced similar results to treatments with Prep or Integrate both of which are chemical defoliants. However, mixing Ginstar with Prep or Integrate did not provide any additional benefits in defoliation or controlling top growth (52).

### Strippers type mechanical harvesters

Cotton strippers serve as an initial harvesting method, particularly in regions where frequent harvesting is delayed by adverse weather conditions. These machines work by either uprooting the entire cotton ball or slicing the stalk just below ground level, then transporting both the stalk and bolls into the system for processing. Subsequently, a separate machine is employed to remove the burrs and other plant material.

The intensity of harvesting significantly affects both the amount of seed cotton collected and the presence of unwanted debris. A more aggressive harvesting approach increases the amount of foreign material and bark in the collected cotton, requiring careful adjustment of stripper row units to reduce field damage and fiber loss. Brush-roll strippers achieve high efficiency, often between 98-99 %. However, immature fibers from upper bolls can influence key fiber properties, including micronaire, length, uniformity, strength and color grade in harvested cotton (36, 53, 54). A motorized finger-type cotton stripper (Fig. 8) was designed to evaluate its effectiveness in gathering high-density, compact cotton varieties (55). The front section of the machine featured stripping fingers angled at 210 degrees, each measuring 70 cm in length, along with a stripping head that spanned 64 cm in width. A rotating paddle or kicker, functioning at speeds between 120 and 250 rpm, was designed to direct both open and closed cotton bolls, along with debris like sticks and burs, into a collection compartment located beneath the stripper head, capable of holding 15–20 kg of harvested cotton. During testing, the prototype was evaluated on F-2383 and RCH-773 cotton varieties. The observed picking efficiency ranged from 76 % to 80 %, with a harvesting capacity between 135 and 325 kg per hr. The percentage of seed cotton in the harvested material was observed between 74 % and 80 %, assessed using a boll crusher and seed-cotton extractor like the one utilized in Bathinda, Punjab.

**Fig. 8.** Operation view of finger type cotton stripper - walk behind (55).

**Fig. 9.** Finger type cotton stripper (57).

**Fig. 10.** Tractor operated cotton stripper (58).

A computer-aided design (CAD) software was utilized to refine the functionality of a self-propelled finger-type cotton stripper, enhancing its overall efficiency (56). RCH-773 cotton variety was selected to perform the evaluation. The modified stripper achieved a picking efficiency of 82 % to 90 % and a field capacity of 0.12 to 0.14 ha per hr. The extracted seed cotton yield was 78.36 %. However, trash content ranged from 14 % to 18 %, higher than the 4.9 % recorded in manually harvested cotton. The redesign resulted in a 10.17 % improvement in picking efficiency and a 42.67 % reduction in trash content. Developed and tested a cotton header with a three-row finger-type mechanism using CAD software, considering regional farming practices and cotton-growing conditions (56). Further modifications were made to a walk-behind finger-type stripper (57), achieving similar efficiency levels (Fig. 9). Additionally, designed a tractor-mounted cotton stripper (Fig. 10) with CAD-assisted improvements (58).

## Picker type mechanical harvesters

A spindle cotton picker removes cotton from the boll using fast-spinning spindles or prongs, ensuring that nearby leaves and unopened bolls remain undisturbed. Since cotton plants produce bolls continuously throughout the season, multiple harvesting cycles are necessary to collect fully matured cotton. The picking mechanism moves plants through a series of rotating spindles that grab the cotton fibers as they pass. When the spindle encounters an open boll, the fibers adhere to it and are later separated by a "doffer," which rotates in the opposite direction to release the cotton. Once removed, the cotton is sent to moisturizing units, where moisture is added to enhance fibers extraction and ensure efficient spindle operation (36, 53, 54).

## Self-propelled type mechanical picker

A self-propelled type of cotton picker represents a cutting-edge innovation in agricultural technology, designed to autonomously navigate fields and harvest cotton without human intervention. Equipped with advanced sensor systems and onboard intelligence, these machines efficiently identify and gather cotton bolls while minimizing crop damage. Their self-propelled nature reduces labor requirements, enhances operational efficiency and enables farmers to achieve higher yields and increased profitability in cotton farming. Developed and evaluated a self-propelled mechanical cotton harvester and the result showed significant findings (Fig. 11) (59). Optimal performance was achieved when the machine moved at a forward speed of approximately 0.36 $ms^{-1}$, with modifications to plant spacing. Under these conditions, the picking efficiency reached nearly 70 % and the machine completed harvesting in roughly 12 hr per ha while using four units to pick two rows at once. Notably, operating with just two units for a single row resulted in lower yield losses. These findings contribute to the advancement of mechanized Egyptian cotton harvesting. Alternatively, harvest efficiency could be boosted from 70 % to 97 % by implementing multiple re-picking cycles. Introduces a novel cotton picker featuring interchangeable horizontal and vertical spindle components (60). This innovative design allows for flexible harvesting depending on the maturity of cotton bolls. When cotton bolls are almost completely open (85-90 %), a horizontal spindle is used, while a vertical spindle configuration is more suitable for partially opened bolls (55-60 %). Field tests on a cotton picker with detachable parts evaluated moisture levels in harvested cotton, residue left on plants, ground losses and overall harvesting efficiency. The improved cotton picker allows for the selective harvesting of both fully and partially opened bolls, enhancing yield and improving the overall quality of harvested cotton.

**Fig. 11.** Self-propelled mechanical cotton harvester (59).

### Handheld type picker

The development of hand-held cotton pickers tailored for Indian farmers across diverse farm types. These portable devices are lightweight and designed to save time and money in cotton harvesting operations. By adopting these hand-held cotton pickers, farmers can significantly reduce labor costs, which typically constitute approximately 35 % of total cultivation expenses, down to just around 10 % (61). Moreover, the use of such technology helps mitigate issues like child labor and finger injuries caused by burs. This advancement in the agricultural sector holds promise for millions of farmers across Asian countries involved in cotton production, offering them a practical solution to enhance efficiency and safety in their harvesting practices. Sima kapas plucker was introduced by SIMA (Fig. 12) (62). It has an ideal hand operation and the picking productivity was increased 6-fold with less trash content. It comes with a collection bag, which reduces the contamination. They state that picking cost was reduced by around 70 %. Table 4 shows the characteristics of different pneumatic cotton pickers (35).


**Fig. 12.** Sima kapas plucker (62).

### Robotic cotton harvesting

Robotic cotton harvesting represents a transformative advancement in agricultural technology, where autonomous machines equipped with advanced sensors, computer vision systems and robotic arms meticulously navigate fields to identify and harvest cotton crops efficiently. These robotic systems are designed to delicately pluck cotton bolls from plants while minimizing damage, ensuring high-quality yield. Through sophisticated algorithms and machine learning, they can differentiate between ripe and unripe cotton, optimizing harvest timing and overall productivity. Robotic cotton harvesting not only addresses labor shortages and rising costs associated with manual harvesting but also enhances precision, reduces environmental impact and contributes to sustainable agricultural practices by minimizing waste and chemical usage. As this technology continues to evolve, it promises to revolutionize cotton farming practices, offering increased efficiency, reliability and economic viability for farmers worldwide. The different phases involved in robotic cotton harvesting are discussed under the below subheadings. The main goals of robotic cotton harvesting advancements are to improve end-effector efficiency, navigation systems and boll detection. The complete integration of these technologies in actual cotton fields has, however, not been thoroughly studied; most of these investigations were carried out in controlled laboratory settings. Fig. 13 shows the robotic cotton harvester's operational flow.

### Image acquisition and preprocessing

The arrangement of bolls is critical factor in evaluating the adaptability of upland cotton (*Gossypium hirsutum* L.) to its environment. It directly influences yield, fiber quality and overall economic value (63-65). Cotton boll detection relied mainly on

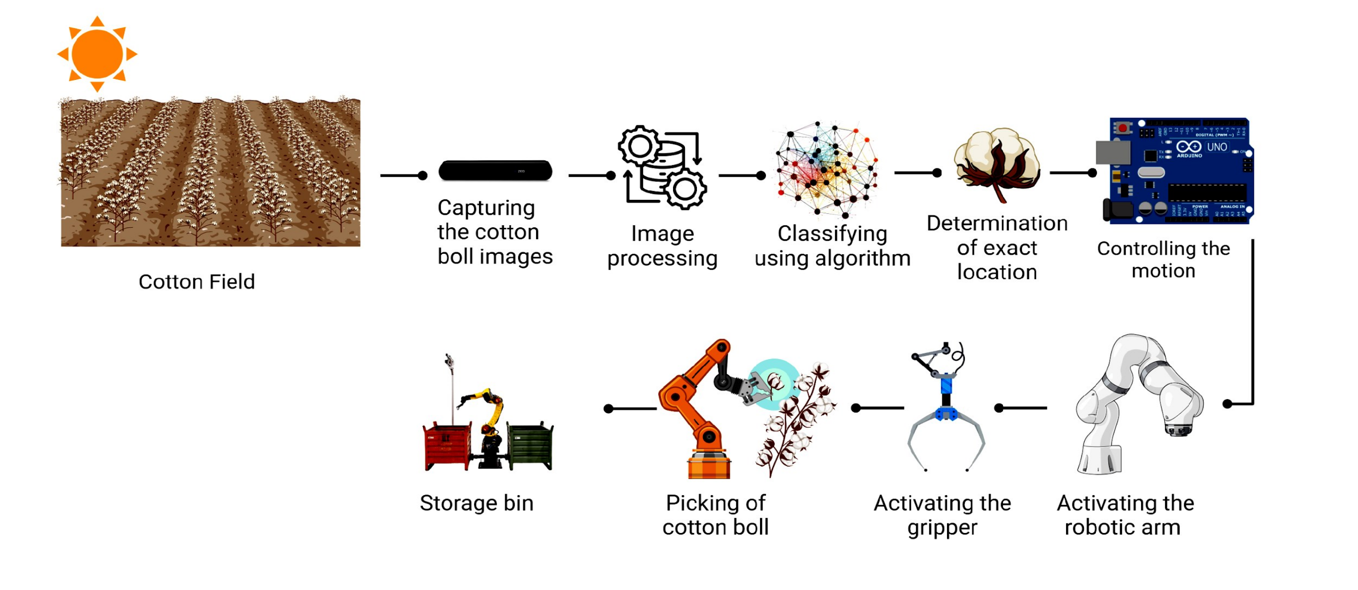


**Fig. 13.** Working flow of robotic cotton harvester.

**Table 4.** Characteristic of mechanical cotton harvester

| Sl. No. | Types | Parameters | Picking efficiency (%) | Picking capacity (kg. h$^{-1}$) | Trash Content (%) | Reference |
|---|---|---|---|---|---|---|
| 1 | Stripper | Brush-roll stripper | 98 – 99 | - | - | 51 |
| | | Finger type stripper | 76 – 80 | 135 – 325 | 25 – 30 | 53 |
| | | | 89 | 1669.21 | 14 – 18 | 56 |
| 2 | Picker | Self-propelled type | 70 | - | - | 57 |
| | | Handheld type | 70 | - | - | 60 |

real-time image capture, depth analysis, color segmentation, feature extraction and position determination (66). A 3D camera system installed on a rover was utilized for cotton boll detection. The maximum accuracy was found that 93 % with SD 6 % (67). Developed a 3D cotton boll mapping methodology within a point cloud using a motion algorithm (68). They implemented a region -based classification algorithm to reduce image noise caused by sunlight. They found that an accuracy of the developed model was upto 90 % and also mentioned in (69). They concluded that the 3D boll mapping provided useful information related to crop growth monitoring as well as yield prediction.

Image processing algorithm was developed in the real field condition to predict the cotton ball (70). They developed 4 different colour models such as color difference, YCbCr model, band ratio and chromatic aberration. They found that the maximum prediction of cotton ball was achieved by a chromatic aberration model (91.05 %). They concluded that the chromatic aberration model was suitable for natural light conditions. Developed a lightweight CNN architecture for sematic segmentation of cotton ball in real field condition (71). They found that the highest cotton-intersection -over-union (IoU) was 91.03 % and carried out the study on segmentation of cotton bolls pixels from the sky (72). They found the IoU score was 93.29 %. Conducted a study on white boll detection with respect to HSV components (Hue, Saturation and Value) (73). They concluded that the data quality, sunlight, angle of sunlight, angle of camera and camera stability may affect the object detection performance. Conducted an experiment for cotton boll detection by use of the yolo v2 model (74). They found that the developed model detects cotton boll as well as counts at a speed and accuracy of 7.6 fps and 94.4 % respectively. Time series sentinel-2 photos to create an automatic cotton mapping (75). They proposed white boll index (WBI) based on the canopy area of cotton boll. They found that the overall efficiency was 82 %. Using UAV RGB pictures (76) studied the monitoring of cotton boll opening rate and defoliation rate. They used 4 different models. In that PSO-ELM achieved more precision of boll opening rate and defoliation rate. Laser scanner or stereoscopic reconstruction for predicting 3D images of cotton plants (77). Kinect v2 sensor was mounted on the arm with 6 DOF and they achieved an accuracy of 95.56 %. 290 RGB cotton plant images in the 2 different models such as supervised and weakly supervised models (Mark R-CNN and S-Count and WS-Count and Count Seg) (78). They concluded that the weakly supervised model was 10 times more costly than the supervised model. Utilized stereo vision system for cotton boll detection (79). They discovered that the cotton ball detection accuracy was 92.3 % with an F1 score of 0.951. The effectiveness of various algorithms for identifying completely opened cotton bolls is displayed in Table 5.

**Table 5.** Performance of different algorithm for detecting fully opened cotton boll

| Sl. No. | Particulars | Efficiency (%) | Reference |
|---|---|---|---|
| 1 | Laser scanner or stereoscopic | 95.56 | 75 |
| 2 | 3D mapping Technology | 90.00 | 67 |
| 3 | Stereo vision system | 92.30 | 77 |
| 4 | Yolo v2 | 94.40 | 72 |
| 5 | Time series sentinel | 82.00 | 73 |
| 6 | Chromatic aberration model | 91.05 | 68 |
| 7 | CNN architecture | 91.03 | 69 |

## End effector and robotic implementation

An automated cotton-harvesting system was created by University of Georgia researchers (80) by combining a two-axis Cartesian manipulator with a hydrostatically driven, center-articulated rover. With an efficiency of 78.5 %, this device collected cotton using a roller with vacuum aid, finishing each picking cycle in 38 seconds. Researchers at Mississippi State University created a prototype robotic harvester that featured a three-fingered pinned belt end-effector and a Cartesian robotic arm (81). Among the robotic cotton-picking devices that have been introduced are CHAP HUSKY (82) and Green Robot Machinery (83), however information about their effectiveness and performance is still lacking.

Despite differences in design, robotic cotton-picking systems all have to contend with the same issue: computational needs and the amount of time needed for actuators to work for each pick limit harvesting pace. By combining machine vision and motion control, the Intelligent Cotton-Picking Robot (ICPR) increases productivity. Using criteria like grade, seed cotton size, whiteness and yellowness, this sophisticated technique assesses the quality of cotton. It takes and analyses real-time photos using cameras and frame grabbers to determine the exact location of cotton bolls.

The picking is done by the robotic manipulator, which stays near the plant. To increase productivity, lower production costs and make the technology more usable by field personnel, more developments are required (84). Multiple harvests during the growing season are made possible by robotic harvesting using smaller machines, which also makes it easier to select cotton as soon as the boll opens, maintaining the quality of the fiber. Additionally, the risk of soil compaction is decreased by using smaller machines. In order to harvest cotton from open bolls on plants that had not experienced defoliation, (81) constructed a robotic end effector (Fig. 14). The most effective arrangement was achieved by combining a moveable pinned belt, a three-finger grasping device and a gripping mechanism. The device's picking times ranged from 4 sec in a simple setup to 18 sec in a more optimal configuration and the tests demonstrated that it reliably picked 66 % to 85 % of the cotton from each boll. Future developments, such as the incorporation of a depth sensor, may facilitate autonomous boll detection and increase the accuracy of robotic arm motions. A technologically advanced Indian firm, Green Robot Machinery, unveiled the "Cotton Picker," a novel harvesting robot. This cutting-edge device mimics human cotton-picking techniques using computer vision and artificial intelligence.

The Cotton Picker is a semi-autonomous electric agricultural vehicle equipped with multiple autonomous robotic arms. A stereo camera on each arm allows for accurate, real-time cotton detection with an accuracy of 3 mm. An end effector and a 3-degree-of-freedom actuator, made especially for cotton picking, are used to remove bolls. While a vacuum-based system carries the harvested cotton to a collection bin, the actuator extracts cotton from the plant in a manner akin to a stripping mechanism. The attached arm does the picking as the electric vehicle drives itself along rows of crops. A single arm makes a substantial contribution to the harvesting process, with the capacity to collect roughly 50 kg of cotton per day. A truck equipped with four robotic arms can harvest about 200 kg of cotton every day by expanding the system's scale, which is

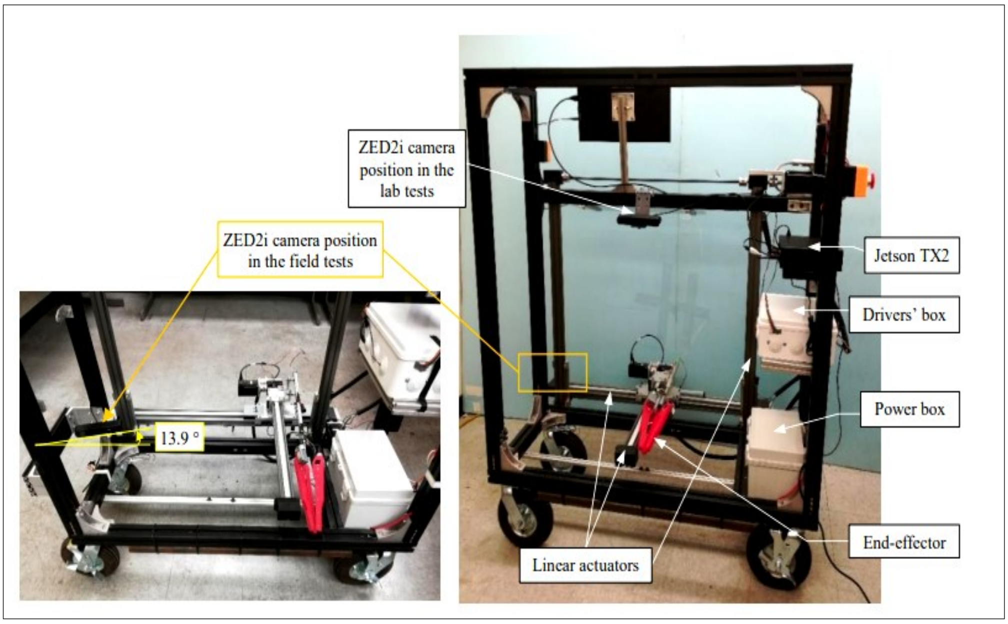


**Fig. 14.** Autonomous cotton harvester (81).

comparable to the typical yield per picking in Indian cotton plantations. Additionally, the possibility of adding more arms presents a chance to assist farmers with larger yields (85). Using a cluster algorithm, (86) created a robotic cotton harvester (Fig. 15) that can recognize several cotton bolls at once. It picked 56.04 % of the bolls at a quicker harvester speed of 3.01 sec.

## Conclusion

The mechanization of cotton harvesting has emerged as a pivotal solution to address labour shortages and increase efficiency in the cotton industry. By employing advanced technologies and machinery, such as cotton pickers and harvesters, the process has become less reliant on manual labour and more streamlined. This transition not only enhances productivity but also mitigates the challenges associated with labour availability, particularly in regions experiencing declines in agricultural workers. Furthermore, mechanization offers the potential to improve overall yield, reduce harvesting time and maintain or even enhance cotton quality.

### Future Perspectives

The future of cotton harvesting mechanization appears promising, driven by technological advancements and evolving agricultural practices. Anticipated developments include the integration of robotics, artificial intelligence and automation to revolutionize cotton harvesting machinery, enhancing precision, adaptability and efficiency. Sustainability will be a focal point, with efforts to minimize environmental impact through eco-friendly machinery and energy-efficient systems. Smart farming technologies such as GPS guidance and remote sensing will optimize operations and provide real-time insights. As labor

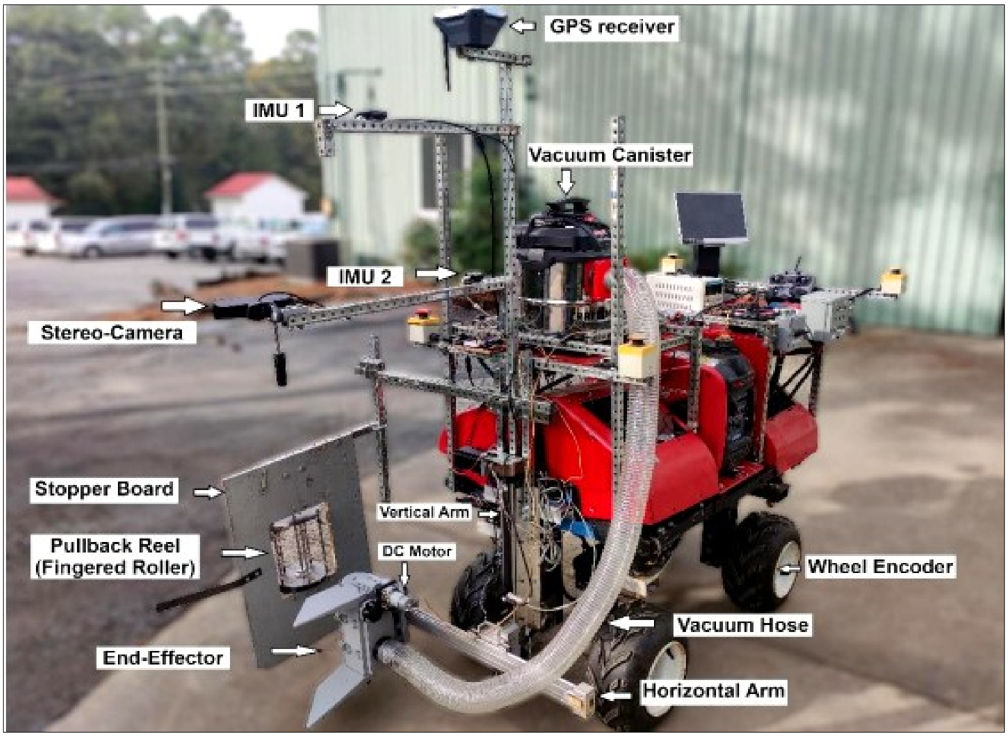


**Fig. 15.** Robotic cotton harvester (86).

shortages persist, mechanized harvesting will see increased adoption, with user-friendly designs attracting skilled operators.

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## Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

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