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Review article

Current research and development in cotton harvesters: A review with application to Indian cotton production systems

Pramod Kumar Mishra [a], Ankit Sharma [b,*], Apoorv Prakash [b]

[a] MCAET, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Faizabad, Uttar Pradesh, India
[b] Department of Farm Machinery and Power Engineering, Punjab Agricultural University, Ludhiana, Punjab, India

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ABSTRACT

High-quality cotton fiber begins with variety selection, continues with adherence to all production methods, and concludes with a well-planned and executed harvest. A potential strategy for harvesting cotton in developing nations is cotton harvesters. Even though there have been significant improvements in recent years, there are still difficulties with its implementation in developing countries. Cotton picking is entirely mechanical in developed nations. Mechanization in the agriculture business has intensified in emerging nations such as India due to rising labor prices and shortages. This review provides an overview of cotton harvesting technologies. Recent work on robotics in cotton-picking operations is discussed. The present study thoroughly discusses hand-held, self-propelled, tractor-mounted cotton harvester development and evaluation. Information in this review will fill a gap in cotton harvesting operation mechanization and may contribute to enhancing cotton-picking operation mechanization and improving picking/harvesting intelligence research.

1. Introduction

India, China, the United States, Pakistan, Uzbekistan, Turkey, Brazil, Greece, and Egypt are among the nations that grow cotton. About 80% of the world's cotton is produced in these nations, which have temperatures between 11 °C and 40 °C [1]. Cotton production methods include field preparation, planting, weed control, spraying, and picking. Cotton picking is by far the most challenging, exhausting, and laborious task. In India, multi-stage hand picking (by human labor) of cotton crop is widely used, with around 500 man-h·ha^{-1} involved. Not only was it time-consuming, but the expense was ten times that of irrigation and roughly twice that of weeding [2]. A grownup may pick about 15–20 kg of seed cotton per day, however, a single-row spindle type picker can frequently pick 870–2180 kg per day [3]. In the majority of underdeveloped nations, cotton is primarily picked by hand. The majority of women carry out this labor-intensive and tiresome activity. Cotton picking is typically done mechanically by cotton pickers or cotton strippers in developed nations like the USA, Australia, Brazil, and Russia. Cotton is also physically picked in India, where the price of hand-harvested cotton is fairly high and steadily rising. As a result, developing an adequate cotton harvester for developing countries (such as India) small and marginal farmers is critical. The study contains experimental work done for the construction and evaluation of cotton harvesters of various picking types, such as mechanical and suction/pneumatic and, and it represents the state of cotton harvesting equipment in India.

* Corresponding author.
E-mail address: ankitsharma@pau.edu (A. Sharma).

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1.1. Need of mechanization

India ranks 1st in area under cotton cultivation (13.48 Million Hectares) along with production of 365 lakh bales during the year 2019–20. However, in terms of productivity, India is on 38th rank [4]. The reasons for this can range from changing crop patterns to a labor shortage for manual hand-picking. Moreover, Indian cotton bolls do not develop all at once which requires multi plucking in two to three cycles [5]. Bolls that open later are therefore of lower grade. Cotton picking is a hard job that some nations view as a punishment. Continuous labor in the cotton fields can result in scratches and bruises on the worker's hands as well as pesticide poisoning. Thus, mechanizing cotton picking is the key to the future. The only way to lessen drudgery on farms is through mechanization. As a result, workers in particular are relieved of the time-consuming tasks of several farms and can better devote their time to other activities. Mechanization can lead to more enterprises, which take different forms that are interconnected. As it becomes possible to accomplish more labor in the time available, more land can be brought under cultivation. As worker productivity rises as a result of mechanization, new crop and animal systems can be used. Off-farm jobs are also created in the service sector, which includes agricultural machinery manufacturers, dealers, and repair shops. Therefore, mechanization is a technique that increases labor productivity rather than output per unit of land, increasing output per worker. Where labor is expensive and in short supply, or where land is cheap, mechanization has benefited society the most. This feature of automation has substantial consequences for its function and influence in the small-holder economy, where labor is often abundant but land, capital, and management are typically few.

Because of the clear advantages mentioned above, machinery consistently ranks as one of the most crucial inputs in the production of cotton worldwide [6]. Cotton growers are examining various cost-saving measures as a result of the nation's labor scarcity and rising agricultural wages. This review's primary objective is to examine the advancements in cotton harvesting technologies and how these technologies may or may not be appropriate for Indian cotton farmers. The overview begins with a brief history of cotton harvesting, followed by a discussion of the required varietal features for cotton harvesting machinery and harvesting aid. Following that, cotton harvesting machinery is described, and current improvements in cotton harvesting technologies are thoroughly explored.

2. Cotton harvesting: a brief history

The concept of mechanical cotton harvesting is relatively recent. However, in the U.S. it took less than a century from the introduction of the first cotton harvesting machine to the practically total replacement of hand harvesting [7]. Pickers and strippers are the two main categories or machine types used in mechanical cotton harvesters. On September 10, 1850, S.S. Rembert and J. Prescott of Memphis, Tennessee, granted the first patent for a mechanical cotton picker. August Campbell received a patent in 1895 for a spindle that served as the inspiration for the fundamental design of the barbed spindle widely used by cotton pickers today. A cotton picker invented by John and Mack Rust that utilized a straight, wet spindle was given a patent in 1932 [8]. To selectively remove the seed cotton from opened bolls while leaving burs, unopened bolls, leaves, and other plant components on the plant, picker harvesters frequently used fluctuations of these spindles.

A horse-drawn sled (finger-type) stripper was patented in 1872 by cotton grower Z.B. Sims of Bonham, Texas. W.H. Pedrick of Richmond, Indiana, received a patent for a roll stripper that used studded rotating rolls in 1874. Benjamin Savage of Scotland Neck, North Carolina, received a patent for a roll stripper that used brushes made of wire, hair, steel, or whalebone in 1884. In the first attempt to strip cotton on the Texas High Plains, according to Ref. [9], an unknown farmer utilized a sled-type stripper (made by fastening a portion of a picket hedge to a luge). Farmers and local businesses consequently created horse-drawn cotton sleds. Concurrently, producers of ginning machines created extraction and cleaning equipment that made it possible to gin and clean sledded cotton [10]. Both finger and roll strippers are non-selective harvesters that remove seed cotton, burs, residual leaves, and stem and branch sections from plants. These machines were more adapted than spindle pickers to collecting the arid terrain, short-stature cotton typical of the Southwest. Although finger and roller scrapers were greatly improved after their introduction [11–13], low cotton prices, plentiful manual labor, crop losses involving the machines, inadequate gin purification equipment, and a lack of effective harvesting aids (mainly desiccants) delayed their widespread adoption until after World War II.

Table 1
Journey of cotton mechanization [5,18].

S. No.	Year	Development status
1	1920s′	Cotton was harvested by hand, resulting in a lot of laborious effort.
2	1930s′	First one row cotton picker but was not commercially sold
3	1940s′	Cotton pickers were manufactured and sold commercially.
4	1950s′	The original cotton picker spindle was modified in the 1950s to a stronger, more resilient metal that could pick numerous rows and included a container to catch the cotton rather than dumping it into the ground.
5	1960–80s′	The cotton pickers underwent several alterations while maintaining their basic design. The first order picker with a driver's cab was presented in the 1970s. This made working in fields enjoyable by ensuring the drivers' safety and pleasure. John Deere invented the 4-row cotton picker in 1980, which enhanced operator productivity by 85–95%. The farming community was happy about this because it greatly boosted cotton-picking efficiency.
6	1990s′	When the six-row cotton picker was first introduced in the late 1990s, it had a large basket at the back and made cotton picking much quicker and easier because the cotton was simply dumped into a modular builder and pressed there.
7	2009	John Deer produced the first round baler that collects cotton, rolls it, wraps it in a tarpaulin, and then drops it on the soil surface. As a result, the physical labor requirements decreased once more, and the need for the module builders to perform cotton pressing was eliminated.

The development of mechanical harvesters was greatly influenced by World War II since the lack of labor during the conflict compelled farmers to explore and advance mechanical methods for cotton harvesting. By 1953, there were approximately 15,000 machine pickers and 25,000 cotton strippers on the market, harvesting approximately 25% of the 16 million bales produced. Approximately 60% of the cotton farmed in the United States was mechanically harvested by 1960, a year in which this percentage had drastically increased. Nearly all seed cotton is now picked mechanically in the USA. Research into the creation and application of harvest aids has grown in tandem with the accelerated interest in the mechanical harvest. Studies showed that desiccation was the key step in formulating cotton for doffing, although defoliation was frequently required to maintain fibre quality and increase picker-harvester efficiency [14,15]. Table 1 depicts the progression of cotton harvesting mechanization development.

[16] developed a pneumatic cotton picking machine with a suction nozzle. It had a pressured air supply, a strong suction nozzle for delicately plucking cotton from cotton bolls, and a method of transferring the cotton that had been picked. Even though this cotton-picking machine is easy to put together and use, picking cotton still requires a specific number of workers. To collect the cotton balls from the plant [17], created a cotton-picking device that moved unceasingly down a row of cotton plants with the use of a mechanical agitator and vacuum or suction.

A pneumatic cotton harvester with cyclonic movement was created by Ref. [19]. This cotton harvesting device separates cotton bolls from cotton plants. The flaws in the old harvesting system were addressed by transporting cotton wholly through a pneumatic procedure to a receiver. Cotton bolls are twisted and broken into a collection chamber using special cyclonic movements in the

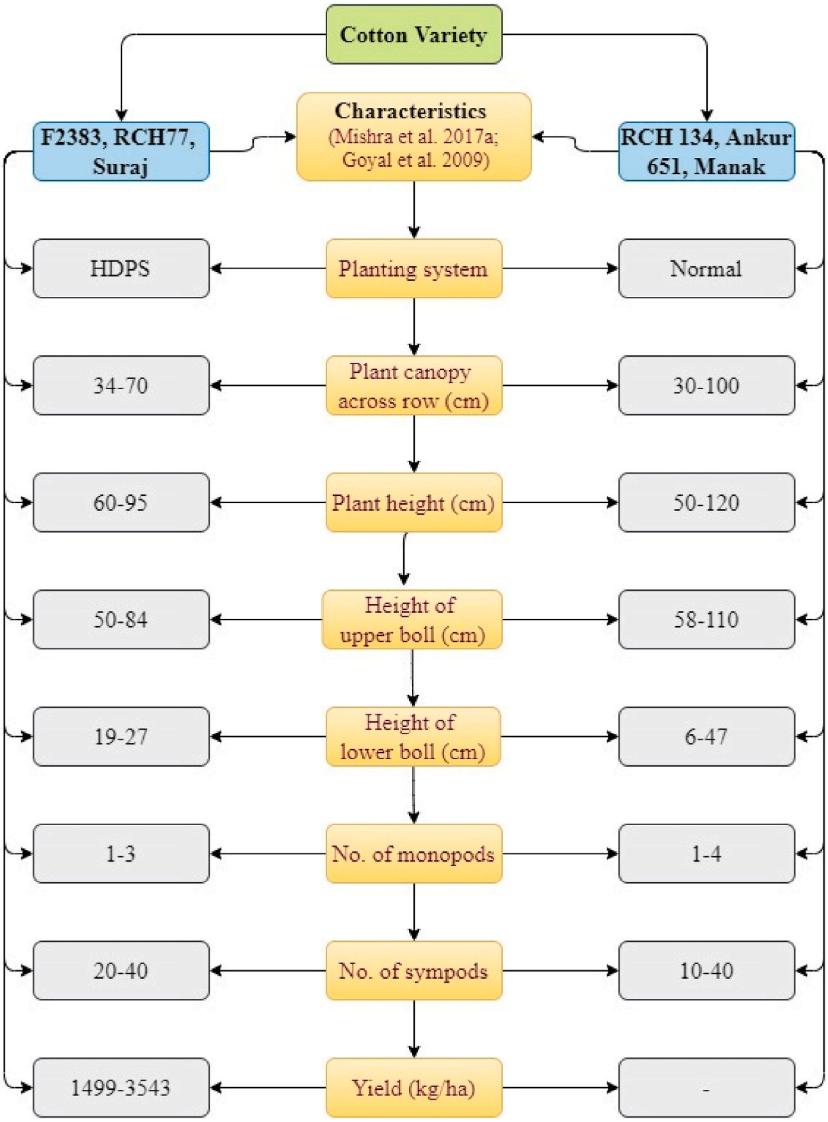


Fig. 1. Varietal traits of potential cotton cultivars for mechanical harvesting [25,26]. *HDPS: high density planting system; Normal planting: Regular plant spacing system.

pneumatic process, where they are then exhausted by suction and transferred to the receiver.

[20] created the innovative idea of the cotton stripper harvester. The Arkansas Agricultural Experiment Station created an experimental broadcast cotton stripper for either narrow-row or broadcast cotton harvesting. With a row of stationary teeth that were 26 inches long and spaced 5/8 inches apart, burr cotton was peeled off the plant. The stripper's teeth were angled toward the ground at about a 15°, and the angle of inclination could be adjusted hydraulically. When picking cotton grown in 6-inch rows, the teeth's suppleness gave harvesters some flexibility. With the flexible and rigid stripper teeth, the overall harvesting efficiencies were 95.5 and 92.3%, respectively. The stripper harvested 40% more sticks when hard teeth were used in place of flexible ones. The main cause of this variation was the narrow-row spacing's higher leaf content, which led to greater moisture loss.

3. Picking-aid (non-mechanical)

3.1. Crop varietal features

Cotton crops are manually harvested three times during a season, each time at intervals of fifteen days. The first, second, and third picks, respectively, make up 35, 50, and 15% of the total pickings [21]. For cotton crops to be harvested mechanically, certain boll and plant properties, including size, shape, length, trash content, maturity, seed weight, lint percentage, carpel flare, plant height, and length of the longest and lowest limb, are required. These characteristics vary by variety and have an impact on picking effort, pre-harvest loss, and picker effectiveness [22]. Plant height, sympods per plant, boll weight, and ginning yield were revealed to be unaffected by the spacing, however, monopods and bolls per plant were significantly higher at a spacing of 67.56 cm than at 67.55 cm [23]. More monopods and bolls per plant may have been encouraged by wider spacing, but their effects on yield may have been lessened by a substantially reduced plant population [24].

Studying the varietal traits (Fig. 1) of some potential cotton cultivars (planted with high density and normal planting system) concerning their suitability for mechanical harvesting was done by Refs. [25,26]. The districts Bathinda, Mansa, Faridkot, and Ludhiana in Punjab's cotton-growing region as well as Nagpur in India's southeast were chosen. The following cotton crop varieties were chosen for sowing: RCH134, Ankur651, Manak, F2383, RCH773, and Suraj. Plants were spaced 45, 67.5, and 90 cm apart from one another and 67.5 cm between rows. The plant height of cotton varieties ranged from 50 to 120 and 60–90 cm approximately. The typical plant canopy measured 65.0 & 60.0 cm approximately along and across the row for the different kinds. RCH773 and Suraj variety plant canopies measured 70.2 and 34.6 cm across the row, respectively. The number of monopods for these varieties ranged from 1 to 4. The number of sympods for varieties was in the range of 10–40. The height of the lowermost sympoidal branch for varieties was 18.0. The height of the lowermost and uppermost bolls for varieties was 20.0 and 80.0 cm approximately. Sizes of open bolls for these varieties were 4.5–5.5 cm. For these varieties, there were 20–25 total bolls on each plant.

[27] described the ideal variety for stripping as one producing a semi-dwarf plant having relatively short-fruiting, short-noded branches. Storm-resistant bolls borne singly but having fairly fluffy locks for good extracting and a medium size boll stem that can be pulled from the limb with a force of 13 to 22 N. Low cotton recovery and high field losses arise from stripping a variety that develops a large, spreading plant with multiple vegetative and fruiting branches. The plants should be determined by their growth and fruiting characteristics, with a short fruiting period and early, uniform maturity for the mechanical picking of cotton. The efficiency of the mechanical picker is more influenced by plant size, kind of growth, and nature of the boll than by yield. A machine will pick high-yielding cotton just as effectively as low-yielding cotton when the plant attributes are right [28]. has pointed out that it takes approximately 100000 cotton bolls to produce one 225 kg bale of lint. Since there are 4 or 5 locks in each boll, there are over 400000 opportunities for picker losses with the harvest of each bale. Therefore the physical characteristics of the boll influence the effectiveness of spindle pickers.

3.2. Application of defoliation

Defoliation, which happens when cotton leaves mature physiologically, is the natural process of leaves falling off. It is required to use particular chemicals known as defoliants or harvest aids to unnaturally shed the cotton leaves to eradicate the crucial cause of stains and debris getting into the cotton during harvest. Defoliation also increases lint quality, lowers moisture, enhances cotton storage, and opens green and unopened bolls [29].

The cotton's enhanced leaf growth caused major problems for the farmers during harvest because it would hinder the quality of the fiber and boll plucking. Using an abscission chemical with increased defoliation and boll opening properties for cotton harvesting methods is one of the important decisions in cotton production. How effectively defoliants function depends on a variety of factors, including the crop's maturity, the uniformity of plant growth, the environment in which they are applied, and the spray's coverage, absorption, and translocation. Farmers can harvest their crops before they have completely grown thanks to defoliation, but if defoliants are used too early, the yield and fiber quality may suffer [30].

Application of defoliants before cotton harvest increased harvester productivity, facilitated manual picking, reduced leaf content, and reduced the amount of trash in harvested lint. Boll rot will be delayed, the lodging effect will be reduced, picking hours will be extended, fiber quality will be maintained, and boll opening will be encouraged. Defoliation that occurs at the wrong time harms staple length and fiber quality, especially micronaire [31].

Several herbicides are used to defoliate cotton intended for mechanical harvesting [32]. Several factors influenced defoliation efficiency, including soil moisture and nitrogen levels, temperature and rainfall at treatment, cloudy conditions following treatment, and application rate calibration. The way cotton reacts to harvest aids is significantly influenced by the weather during treatment and for three to five days after application. When temperatures, sunshine intensity, and relative humidity are high, harvest aids are most active. Determining variables for the selection of defoliants also include the yield and state of the cotton crop. India still struggles with defoliant optimization and uniformity, which adds 4–5% more trash—in the form of unshredded leaves—to cotton collected with automated pickers. Additionally, it has been noted in some instances where improper defoliation occurred as a result of unfavorable circumstances, resulting in harvested cotton with a garbage content of 20–25% as opposed to 10–12% for cotton that had been correctly defoliated.

When the youngest bolls are grown and 50–60% of the bolls have opened, it is normally safe to defoliate. Removing leaves too soon can lower yield and quality. When the topmost, first-position harvestable boll is four nodes or less above the topmost, first-position cracked boll, the crop is ready for treatment. Apply defoliants if at all possible in the late afternoon or early morning when the humidity is high and the wind is quiet [33]. In 1999, two field tests were carried out close to Marana and Coolidge, Arizona, to assess the efficacy of various defoliation treatments on Upland (var. DP 33b and AP 6101) cotton. Treatments using Ginstar alone to defoliate were effective and very similar to those using Prep or Integrate. In this trial, adding Prep or Integrate to Ginstar did not enhance defoliation or top growth control [34].

4. Cotton picking mechanisms

Cotton harvesting equipment can be classified [35] into following categories which have been described below:

- **Picker type:** It includes equipment designed to pluck/pick open bolls with spindles, fingers, or prongs while causing minimal material damage to the foliage or unopened bolls.
- **Pneumatic type:** Suction or air blasts are used to extract the cotton from the bolls.
- **Electrical type:** By connecting the bolls to an electrically charged belt or finger, this device exploits the static electricity contained in cotton to draw the cotton out of the plant.
- **Stripper type:** It includes machines that use belting fingers, interlocking lugs, fingers or combs, steel rolls, or brushes to remove burrs and other debris from the plant.

4.1. Mechanical cotton harvesting machines

Many people have experimented with numerous techniques over time to efficiently harvest cotton from the plant without endangering it or lowering the quality of the cotton harvest. Depending on the type of cotton grown there and the methods used for cultivation, various mechanisms and inventions are used in various parts of the world. Here are a few of the mechanical cotton harvesting machine/mechanisms:

4.1.1. Cotton strippers

As a first-pass harvesting tool, cotton strippers are used. In areas where it is difficult to harvest cotton frequently due to the weather, strippers are utilized. Whether the cotton is ripe or not, they "pull" the full cotton boll, or they cut the stalk just below the surface of the earth, then they take the stalk and cotton bolls into the machine. The burr and plant material is then eliminated using a separate machine. Cotton was removed from the stalk using ancient tools that consisted of a wooden sled carried by a horse or mule. The sled's aperture is tapered, allowing the stalks of the plants to pass through while remaining narrow enough to trap and remove both open and closed bolls. This is how cotton is harvested. While multi-row sleds were available, most sleds gathered one row per pass. Farmers would frequently "sled" cotton and then pile it on the turn-row so that unopened green bolls might open before being ginned. The level of harvesting abrasiveness is closely correlated with the quantity of seed cotton and unwanted particles collected. The likelihood that more foreign material and bark will be harvested increases with increased harvesting aggression. The stripper row units must be configured for the appropriate amount of aggressive stripping to collect the least foreign matter and damage the cotton fields with the fewest losses. Brush-roll strippers have a high harvesting efficiency, typically in the region of 98–99%. However, the presence of premature fibre from bolls near the top of the plant can affect some fibre quality traits (particularly micronire and length uniformity) in striped cotton. Premature fibre can also affect fibre length, strength, and colour grade [6,36,37].

4.1.2. Spindle cotton picker

A spindle cotton picker simply "picks" the cotton from the boll using its rotating fingers or prongs, causing no real harm to the surrounding vegetation or unopened bolls. And because cotton is a plant that bears fruit continuously during the growing season, a picker is typically employed more than once. As the cotton bolls ripen, a picker can go through it more than once. The spindle-picking setup involved the plants moving through a row of rapidly rotating spindles. The cotton filaments would encircle the spindle when it came across an open boll. The spindle would then rotate in the opposite direction at a "doffer," where the doffer would doff the fibers from the spindles. The cotton was then moved on to the moisturising units, which improved picking efficiency by making it simpler to pick the cotton and keeping it attached to the spindle [6,36,37].

The quality of cotton fiber in general, particularly with relation to spindle twists, is claimed to have declined as a result of changes made to spindle picker designs to enhance speed and reduce weight. According to the results of a laboratory test of several spindle designs, the smaller, straight spindle was more aggressive in extracting cotton from the boll. The barbed spindle produced about twice as much fly-off as the smaller straight spindle. At a spindle speed of 1500 rpm compared to a speed of 2000 rpm or higher, field stalk losses for all types were much higher [6]. This demonstrates that a minimum 2000 rpm spindle speed was required to keep picker loss to minimum. Compared to a speed of 2000 rpm, stalk losses were higher at 3000 and 4000 rpm. The detail difference [37,38] in cotton picker stripper harvesting system is shown in Fig. 2 and detailing of cotton harvesting machiney is shown in Fig. 3.

4.1.3. Electrostatically cotton picking

For spindle picker machines to work, the mature cotton fiber must be physically in contact with the revolving spindles and adhere to the spindles physically. To achieve tactile engagement with the cotton bolls, several spindles must be used, and even then, many bolls will inevitably be missed and left in the field unpicked. Water used to wet the spindles results in mechanical complications and need distinct maintenance. Additionally, the water on the spindles encourages cotton stains and discoloration. It takes special care to supply the water evenly and in the right amount. Additionally, the water moistening system may occasionally freeze in cold weather. In essence, the concept involves giving the cotton being picked and the picking spindles an electric charge. This creates an attractive force that pulls the cotton toward the spindles and allows for contact with cotton that would not otherwise be made. The fiber is drawn to the spindles by these electrostatic forces, where it adheres and aids in the wrapping process by preventing cotton from being dropped. Thus, another element of the invention that enables each fiber to stand and stretch toward the revolving picker spindles approaching the picking region is the pre-conditioning of the cotton in the uncovered bolls by generating electrostatic force [39]. It is crucial to emphasise that no actual use of this method (electrostatically cotton picking) has yet been proven.

5. Cotton harvesters: recent advances

5.1. Pneumatic type

[40] examined a cotton picking-specific industrial vacuum cleaner. Initial tests revealed that mechanical picking required more labor inputs than human picking did. Manual picking required 0.9 man-h·kg^{-1} on average in labor. Electric-powered industrial vacuum cleaners that are readily available for purchase were utilized to pick cotton, however, the machinery required modification owing to clogging and low suction pressure. Using lightweight and robust materials [41], created a cotton picker resembling a rucksack. The suction pressure was measured as part of preliminary laboratory experiments. A 400 mm of water suction was created at its maximum, and numerous leaks caused a 50 mm water pressure reduction. The electric wire had to be carried to the fields, which took a lot of time, and the crop suffered a lot of harm from the constant movement of the cable.

Cotton picking using the suction concept was tested by Ref. [42]. The blower, tank, and suction hose made up the cotton picker. The parts were fixed to a frame that was connected to a tractor's three-point linkage by a hitch. Through a gearbox, the tractor's PTO produced power for the blower. When the blower was running at 2875 rpm and the suction pressure was 240 mm of water head, the picker's picking efficiency ranged from 63.4 to 77.5%. The device removed only the fully opened cotton bolls, leaving the ones that were either infected or securely connected to the panicle. After machine operation, the percentage of hand-selected cotton varied from 22.5 to 36.6%.

A study was carried out by Ref. [43] to optimize the pneumatic knapsack cotton picker's machine (Fig. 4) parameters. Through the statistical analysis, the machine's component dimensions — filter height, pickup diameter, filter type, aspirator speed, and collecting drum capacity — were improved. Maximum pressure was created using a pickup pipe with a diameter of 25 mm, a nylon mesh filter with a height of 225 mm, a collection drum of 25 L capacity with 5500 rpm aspirator speed. The first picking's picking capacity (4.93 kg h^{-1}) was lower than the third picking's (5.07 kg h^{-1}). The third picking had a greater picking efficiency (97.48%) than the first picking (96.35%). The highest litter level in the third picking of cotton that was mechanically picked was 13.97%. Machine picking reduced labour expenses, time requirements, and energy expenditures by 9.0, 75.00, and 68.23% when compared to conventional

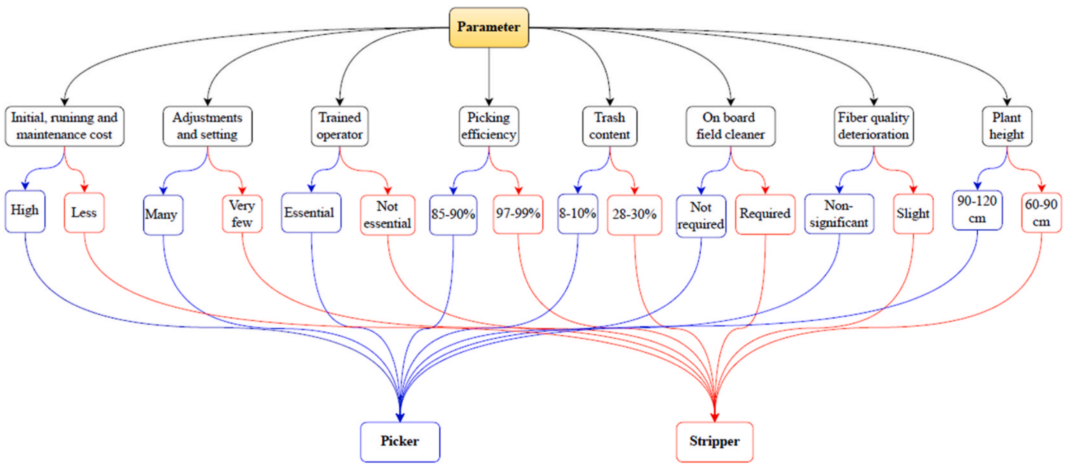


Fig. 2. Cotton picker versus stripper parametric differences.

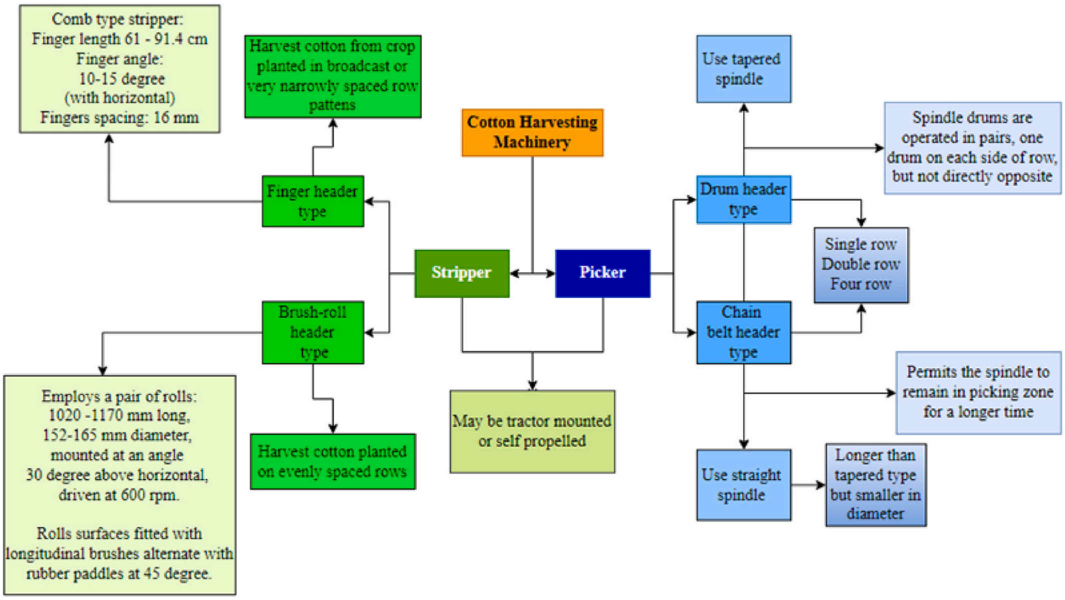


Fig. 3. Detailing of cotton harvesting machinery.

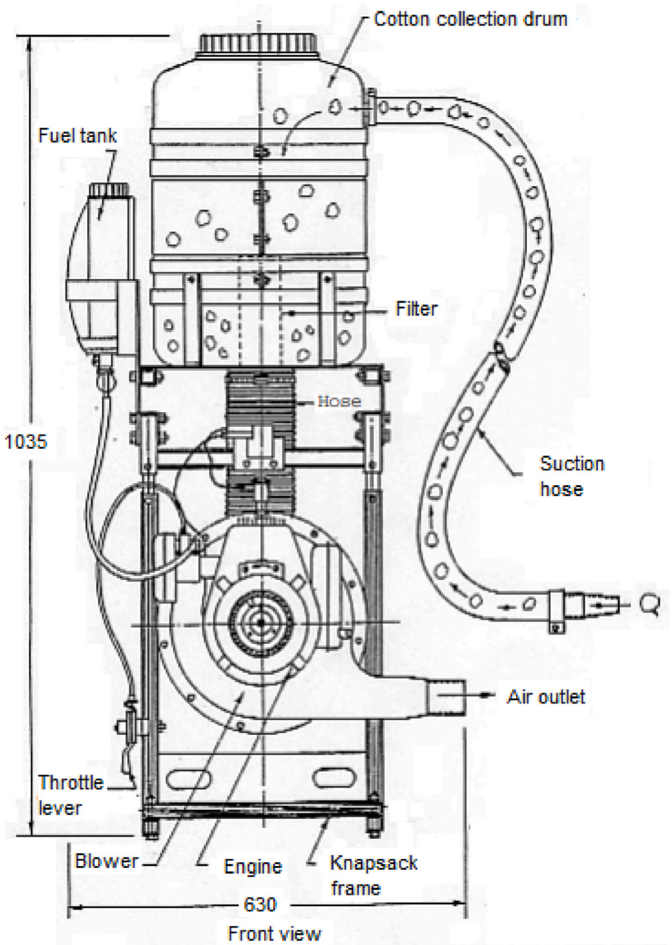


Fig. 4. Knapsack pneumatic cotton picker [43].

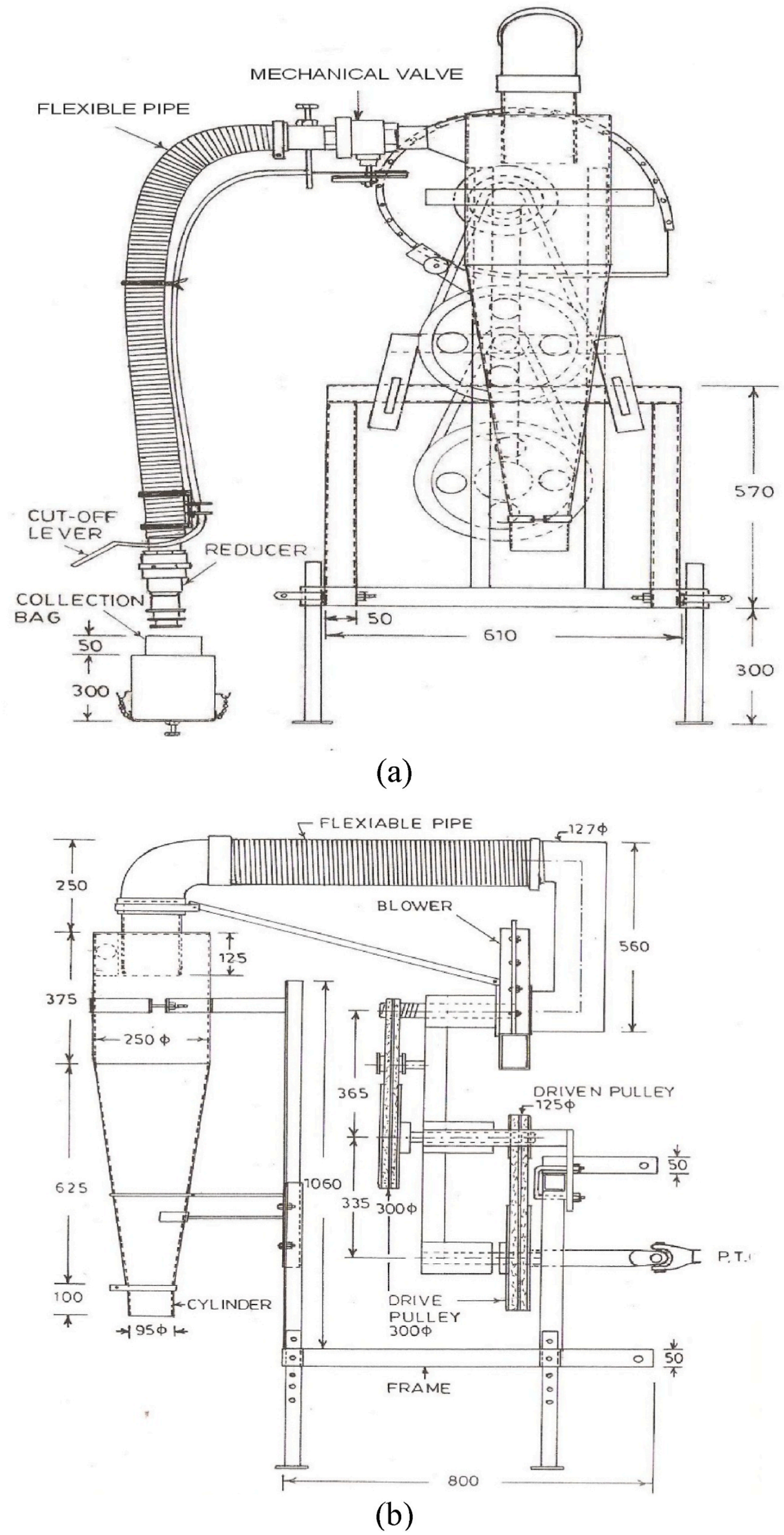


Fig. 5. (a) Front and (b) side view of mechanical cotton picking aid [44].

picking.

Cotton picking equipment (Fig. 5) was framed and developed by Ref. [44] to help in cotton extraction from cotton bolls. Based on the least amount of effort required to pick up the ball and deliver the requisite suction pressure on the boll, a suitable blower size was selected. Theoretically, this force could be calculated as 3.6 N for picker ends that were 25 mm in diameter. The bolls were collected using a cyclone separator that was intended for the job. The area of the input duct, the exit pipe, and the air velocity through the cyclone were all calculated for the chosen 0.076 $m^3 s^{-1}$ air flow rate through the cyclone (through a suction pipe). The picking rate was increased by using an electromagnet. A calculation determined that 4.26 A was the bare minimum current needed to operate the electromagnetic valve. To determine the overall pressure loss, losses in the system were also computed, including friction and pressure losses on the developed machine at various locations. Calculated as 111.7 mm of H_2O, the total pressure loss. The machine's prototype was then created and tested by theoretical design calculations. A measurement was made of the prototype's fuel and power usage.

[45] conducted preliminary testing of the developed cotton picking equipment as mentioned by Ref. [44] in the field to investigate the effects of various combinations of picker end diameters and suction pressures on picking efficiency, output capacity, and trash content. The selected picker end diameter and suction pressures were 20, 25, 32, 40 mm and 25, 30, 35, 40, 45, and 50 mm of mercury (Hg). Calculating picking effectiveness, trash content, and output capacity from the trend line extrapolation was necessary to assess the metrics at a constant suction pressure level. The highest picking efficiency of 96.3% was achieved with a suction pressure of 45 mm of Hg and a picker end diameter of 25 mm. Using a picker end with a diameter of 20 mm and a suction pressure of 30 mm of Hg, a minimum rubbish concentration of 0.65% was generated. The maximum output capacity of 6.25 kg h^{-1} was reached with a 45 mm Hg and 25 mm of suction pressure and picker end diameter respectively. The picking aid was then put through rigorous field testing using two stages of picking at different suction pressures (35, 40, 45, and 50 mm of Hg) and the ideal picker end diameter (25 mm). Even though the first picking's picking efficiency and output capacity were at their highest at 50 mm of suction pressure, the amount of garbage increased at this suction pressure. Nevertheless, a minimum trash percentage of 5.7% was attained at 35 mm of Hg with a picking efficiency of 93.9% and an output capacity of 4.2 kg h^{-1}. Similar to the first stage, the second stage's output capacity was 4.01 kg h^{-1}, with a picking rate of 92.8%, a minimal trash content of 4.39% at 35 mm suction pressure.

[46] developed a women-operated pneumatic-powered cotton picker attachment for power tillers that was compatible with the main Indian cotton varietals. The pick-up pipe diameter, type and height of filter, gathering drum capacity, and aspirator speed were all optimized during the unit's construction using the build-and-test method. After evaluating the impact of changes in the aforementioned factors on pressure, which directly effects picking force, statistics were utilized to establish which values were most acceptable. The optimal cotton picker, according to the statistical analysis, has a pick-up diameter of 25 mm, a 400 mm-high nylon mesh filter, a collection drum capacity of 150 l, and an aspirator speed of 5500 rpm. Picking cotton with a picker cost $9.50 per kilogram (0.16 USD). In comparison to manual picking, there is a 17.0, 75.0, and 74.6% cost, time, and energy savings. The picker has a pay-back duration of 0.45 years and a break-even point of 5900 kg per year, respectively.

[47] developed a knapsack-style cotton plucker that incorporates a pick-up pipe, prime mover, filter, blower, and gathering drum to serve farmers who cultivate cotton on a small scale. To collect cotton, a 50-L polypropylene container was connected to the frame. To prevent cotton from entering the aspirator, a filter was placed within the collection drum. The pick-up pipe was made out of two 50 mm diameter lightweight aluminum pipes. The combined length of the pick-up and suction pipes was kept at 1580 mm. In a lab setting, three different drum types (A, B, and C models) and four different fan speeds (4200, 4700, 5200, and 5700 rpm) were used to assess the efficiency of a newly built cotton plucker in terms of fuel consumption, picking efficacy, garbage content, and productive capacity. The results show that the production capacity ranged from 4.75 to 9.78 kg h^{-1}, garbage content from 2.07 to 8.03%, picking efficiency from 91 to 96%, and fuel consumption from 0.270 to 0.702 l h^{-1}. A B-type drum was chosen for field testing at 5200 blower rpm based on laboratory findings. Average values were found to be 0.603, 94.79, 5.77, and 8.84 for fuel consumption ($l \cdot h^{-1}$), picking efficiency (percent), garbage content (percent), and productive capacity ($kg \cdot h^{-1}$).

[48] tested a knapsack type cotton picker in a lab environment at different blower speeds (2,500, 3,500, 4,500, and 5000 rpm), pick-up pipe diameters (20, 25, and 30 mm), and blower bowl openings (50, 75, and 100%) to determine how much fuel was used, how well it picked up trash, how much pressure was at the tip of the pick-up pipe, and in the gathering drum. Fuel consumption ($l \cdot h^{-1}$), picking efficiency (%), rubbish content (%), pressure at pick-up pipe tip ($kg \cdot cm^{-2}$), and pressure of collecting drum ($kg \cdot cm^{-2}$), all in kilograms per square centimeter, ranged from 0.72 to 1.31, 94.42–96.85, 8.16–11.33, 0.035–0.076, and 0.023–0.047, respectively. Using the results from the laboratory testing as a guide, the cotton picker was tested outdoors at 5500 blower rpm, 25 mm pick-up pipe diameter, and 100% blower bowl openness. The average fuel consumption per hour, picking efficiency per hour, trash content per hour, and output capacity per hour for the first and second pickings were 1.29, 96.47, 10.22, and 4.95, respectively. Table 2 lists the several pneumatic cotton pickers and their characteristics.

Table 2
Attributes of pneumatic cotton pickers.

Power	Labour requirement (man-h·kg^{-1})	Suction pressure	Picking efficiency (%)	Picking capacity (kg·h^{-1})	References
Electrical power	0.9	–	–	–	[40]
Tractor operated	–	240 mm of water head	63.4–77.5	–	[42]
		25–50 mm of Hg	92 to 97	4 to 6.25	[45]
Petrol engine (Knapsack type)	–	–	95 to 98	4 to 5	[43]
			91 to 96	4 to 10	[47]
		0.035–0.076 kg cm^{-2}	94 to 97	4.95	[48]

5.2. Mechanical cotton harvesters

Pickers and strippers are the two different kinds of cotton harvesters. Unlike strippers, who remove both opened and unopened bolls from the entire plant, pickers are selective in that they only collect the open bolls of seed cotton [49].

5.2.1. Stripper type cotton harvesters

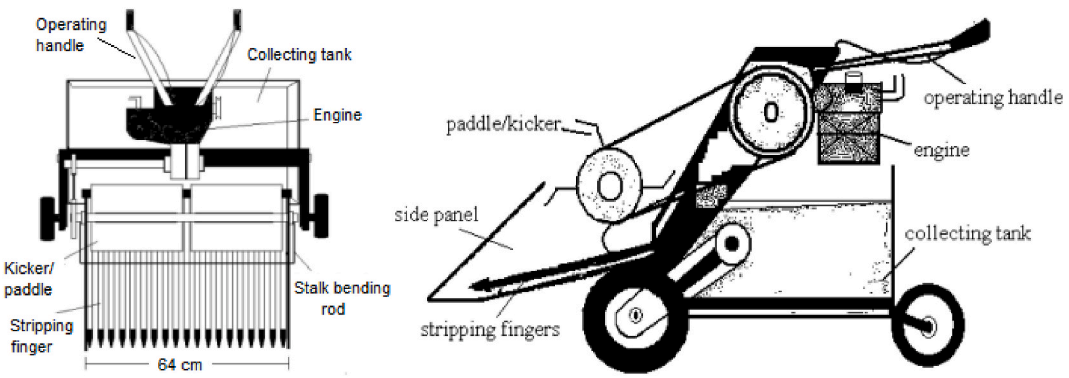
The indigenous high-density and dwarf cotton cultivars can be mechanically harvested using a self-propelled finger-type cotton stripper (Fig. 6) that developed and tested [50]. A front section of the engine frame was joined by welding to the designed stripper's 210-degree-angled stripping fingers, which were 70 cm long. There was a 64 cm wide developing head. A spinning paddle or kicker that rotated between 120 and 250 rpm was intended to kick the cotton bolls (both open and closed, together with sticks and burs) into the gathering container. A 15–20 kg capacity collection drum or tank was positioned directly below the cotton stripper head to collect the materials from the stripped cotton. F-2383 and RCH-773 cotton cultivars were used to test the prototype once it had been produced. The developed cotton stripper's average value picking efficiency and picking capacity was found to be between 76 and 80% and 135 and 325 kg h^{-1}, respectively. By using a boll crusher/seed-cotton extractor that is in use at Bathinda in Punjab, the observed value of seed-cotton was found to be between 74 and 80%.

With the aid of computer aided design (CAD) software [51], modified and created a self-propelled finger-type cotton remover to enhance performance. The 660 mm long stripping fingers were installed on a 650 mm long mild steel square box (32 × 32 × 4) with the aid of bolts on the front side of the engine frame at an angle of 210 in the modified self-propelled finger-type cotton stripper. The developed header has a 650 mm width. The stripped materials were designed to be pushed into the gathering tank by a spinning paddle/kicker that rotated at a speed between 120 and 250 rpm. Just behind the cotton stripper head was a collecting drum/tank with a capacity of 15–20 kg for collecting the material from the stripped cotton. The performance of the redesigned prototype was assessed using the RCH-773 cotton variety. The average cotton stripper picking efficiency and field capacity was found to be 82–90% and 0.12–0.14 ha h^{-1}, respectively. On average, it was discovered that the cum seed-cotton extractor's observed value of seed-cotton output was 78.36%. When cotton was harvested using a stripper, the trash content was higher—between 14 and 18%—than when it was harvested manually (4.9%). The redesigned cotton stripper's average picking efficiency increased by 10.17%, and its average trash content decreased by 42.67%.

A 3-row finger type cotton header was created conceptually designed and tested by Ref. [52] using CAD software, while considering the harvesting of locally cultivated cotton cultivars and local agronomic procedures. Through the use of CAD software [53], improved and designed a tractor-operated cotton stripper (Fig. 7). A few improvements and alterations were made to the header in the modified tractor-operated finger-type cotton stripper based on field tests carried out in previous years. NX-8 CAD software was used at Mahindra Applitrac, Mohali, to build each sub-assembly, including the header frame, finger, reel, auger, and power transmission. The development and construction of a tractor-operated three-row cotton header were based on 2D drawings and a bill of materials (BOM). RCH-773 cotton types were used to test the performance of the modified prototype. The developed cotton stripper was found to have an average picking efficiency of 89% and a picking capacity of 1669.21 kg h^{-1}. The average amount of ground and stalk loss was 5.65 and 4.75%, respectively.

5.2.2. Picker type cotton harvester

5.2.2.1. Self-propelled type picker. [54] develop, manufactured and quantifies the performance of a self-propelled mechanical cotton harvester. Best results were obtained when using forward speed approaching to 0.36 m s^{-1} with a modified form of plant density the efficiency of picking about 70% at the machine performance rate almost 3.5 h per faddan that when using 4 units for picking 2 rows at same time. Also getting less yield loss when using only two units to harvest a single row. Thus can access the best methods for mechanization the harvesting of Egyptian cotton. In other way can improve harvest efficiency from 70% to 97%, by re-picking three times or more.



ig. 6. Top and side view of walk behind finger type cotton picker [50].

Fig. 7. Tractor operated cotton stripper [52].

A combination cotton picker with replaceable horizontal and vertical spindle components was developed by Ref. [55]. A cotton picker option with a horizontal spindle is used when cotton bolls are fully opened (85–90%), while a picker option with vertical spindle devices is used when cotton bolls are only partially opened (55–60%). A cotton picker with detachable components underwent field tests. The factors that were estimated included moisture of harvested cotton, residue on bushes, losses to the ground, and harvest completion. Utilizing a combination cotton picker enables selective cotton harvesting from both fully and partially opened cotton bolls. There has been an increase in output and cotton picking quality.

5.2.2.2. Hand-held type cotton picker. Hand-held cotton pickers were designed by Ref. [5]. A portable, hand-held cotton picker that is light in weight and suitable for Indian farmers of various farm types was developed. It can save time and money. With the usage of cotton pickers throughout time, the current labor costs, which account for around 35% of the entire cost of cultivation, can be decreased to only about 10%. It's also possible to prevent problems like child labor and finger bleeding from burs. Millions of farmers throughout Asian countries that produce cotton stand to gain from this recent advancement in the agricultural sector.

5.2.2.3. Cotton picking automation (robotics). This ICPR (Intelligent Cotton Picking Robot) technology combines motion control and machine vision. The cotton picking robot uses a grade text standard, seed cotton size, whiteness, yellowness, and other quality traits to visually identify the cotton. The eyes of the picking robot are cameras with frame grabbers that operate and gather cotton images. The system processes, analyses, and determines the positional coordinates of the cotton after image collecting. The robot manipulator finishes harvesting cotton close to the plant. Additional research and development are still required for this technology to become simpler, less expensive, and more easily used by field workers [56].

Multiple harvests during the growing season are made possible by robotic harvesting with smaller machines, and they also make it possible to pick cotton as rapidly as the boll opens, protecting fiber superiority. Additionally, there would be less possibility of soil compaction to occur with smaller machinery. A robotic end-effector is developed by Ref. [57] to harvest cotton from an open boll on a non-defoliated cotton plant. The design with the three fingers, moving pinned belt, and underactuated end-effector was selected as the best. An enhanced end-effector prototype was examined indoors on a robotic platform with a computer-controlled 3-dof manipulator. The end-effector could remove 66–85% of the cotton from a boll with a picking time varying from 4 seconds for a simple and ineffective system to 18 seconds for a controlled and more effective system. The addition of a depth sensor to the robot will allow it to locate cotton bolls and move its arm on its own, among other additional ramifications of this work.

Green Robot Machinery, an Indian startup, had created a harvesting robot for picking cotton for the agricultural industry. The "Cotton Picker" robot mimics human behavior during cotton harvesting by using machine learning and computer vision. Green Robot Machinery cotton picker consists of multiple autonomous robotic arms mounted on a semi-autonomous electric farm vehicle. The robotic arm includes a stereo camera and a 3-degree-of-freedom actuator with an end effector for picking cotton. The camera can detect and locate cotton within 3 mm precision in real-time. The actuator similar to a stripper dislodges the cotton boll from the cotton shell and a vacuum mechanism moves the cotton through the arm to a collection bin. The electric vehicle can move over a row of crops autonomously and the arm mounted on it does the task of picking. The arm is designed to pick around 50 kgs per day, and four of these arms put on the truck can pick about 200 kgs per day, the typical yield per picking in an Indian cotton field. Adding more arms can help sustain higher-yielding farms [58,59].

6. Evaluation of cotton harvester

6.1. Self-propelled type cotton picker

At several sites in India [60], evaluated a two-row self-propelled cotton picker. At Central Institute for Cotton Research (CICR), Nagpur and Punjab Agricultural University (PAU), Ludhiana the John Deere 9935 cotton picker's performance was assessed and the mean values of forward speed, effective field capacity, total harvesting loss, mechanical picking efficiency, and picker efficiency were 2.62 km h^{-1}, 0.28 ha h^{-1}, 23.62%, 75.7%, and 76.4% for CICR, Nagpur whereas and 2.20–3.38 km h^{-1}, 0.278–0.563 ha h^{-1}, 22.0–24.0 l h^{-1}, and 14.29–31.74%, 55.6–83.1%, and 68.3–85.7% for PAU, Ludhiana, respectively.

6.2. Manually operated hand-held type cotton picker

The performance of a battery-powered portable manual cotton picker was evaluated by Ref. [61] on two subjects for three types of cotton cultivars and compared to hand picking. It was a hand-powered machine with a pair of small sharp-toothed chains and sprockets, powered by a lightweight 12V battery. Cotton gets tangled in the chain and was collected and directed into the collection

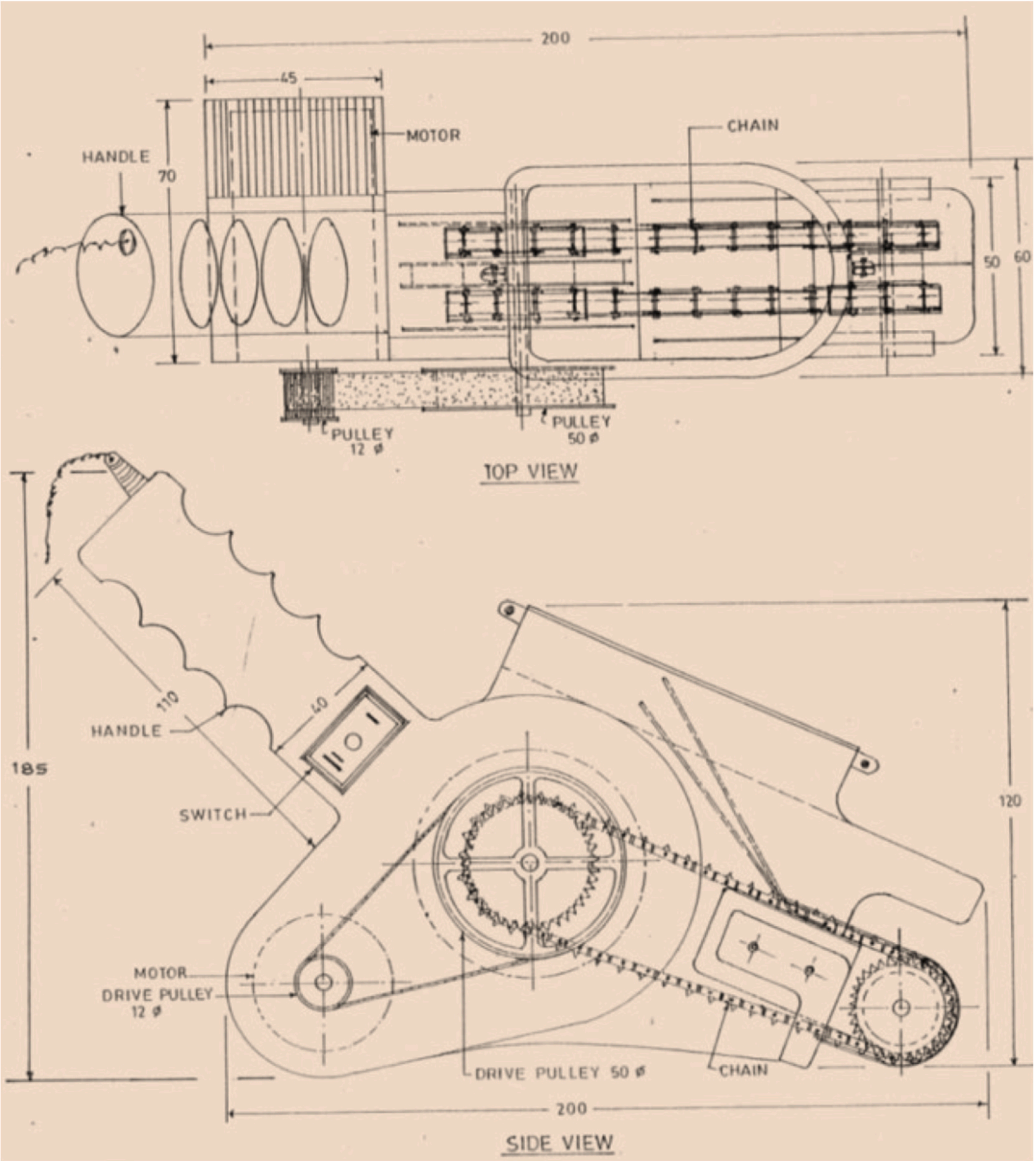


Fig. 8. Hand-held cotton picker [64].

bag. Cotton picker output capacity ranged from 17.0 to 22.6 kg·day^{-1} for BT and American cotton varieties. The cotton picker production capacity ranged from 17.0 to 22.6 kg·day^{-1} for BT and American cottons. The picking efficiency of manual cotton pickers ranged from 68 to 91%, with waste percentages ranging from 1.8 to 6.1% for all three cotton species.

Based on time input, labor demand, ground, and plant harvest losses [62], built and evaluated a manually operated cotton picker and compared it to the already available manually operated cotton picker and the conventional technique of harvesting cotton. The labor requirements for the created cotton picker, the existing cotton picker, and the manual cotton picker were 166.17, 173.8, and 93.3 man-hours per hectare, respectively, according to the results. With their respective ground harvest losses of 15, 12, and 5%, cotton had a wet base moisture content of 2.8%, and branches had a moisture content of 39.5%. The study also shows that labor requirements, ground plant harvest losses, and time input were 5% level statistically significant [63]. investigated commercially accessible, inexpensive, hand-held, moveable cotton pickers with 2 different categories of mechanics, namely chain and roller, and compared their effectiveness to manual picking. At the 5% significance level, manual cotton picking requires much less labor than roller-type cotton picking. At the 5% level of significance, there was no discernible change in the picking speed between chain, roller, and manual picking. When compared to cotton picked manually, which had a rubbish content of 7.43%, both chain and roller-type cotton pickers had greater trash content percentages, at 11.52 and 10.44%, respectively.

6.3. Ergonomic evaluation of cotton picker

[64] evaluated the battery operated handy manual cotton picker's (Fig. 8) ergonomics using 2 participants and 3 cotton cultivars, contrasting it with the manual technique. It was a hand-operated device with two chains, each with a few tiny, finely pointed teeth and sprockets, and was driven by a 12 V small battery. Cotton that becomes tangled in the chain is gathered and directed into the collecting bag. Average heart rate, oxygen consumption, effort, and energy expenditure were higher for both individuals when using a manual cotton picker than when picking cotton themselves for all three varieties of cotton. When using a machine to pick all three cotton varieties, the subject's oxygen intake, workload and energy expenditure ranged from 0.81 to 0.97 l min^{-1}, 36.32–46.16 W, and 16.83–20.33 kJ min^{-1} respectively. The individuals' lower legs, and both feet, upper and lower back, right-hand palm, right forearm, left shoulder caused them the most discomfort while using a manual cotton picker to pick cotton.

An ergonomic assessment of cotton harvesting in central India's irrigated and rainfed fields was carried out [65]. They discovered that the current method of contract manual harvesting is 30% more effective than a portable cotton picker powered by batteries. Regardless of the methods used for harvesting, increased output of seed cotton was associated with a higher cardiac load on contract workers. Portable cotton pickers are quick, accurate, and don't require defoliation, but proper training and a readiness to use the machine are required. When using a portable cotton picker, properly trained male and female pickers were able to select 80, 41%, and 44% more seeds of cotton, respectively. For family labor of rainfed cotton harvesting with a lower moisture percentage, portable cotton pickers are more appropriate. Higher moisture content in cotton grown under irrigation may make machine picking difficult and subject to frequent slippage. (1–2%) Trash content can be comparable to manual harvesting. Present Incorrect cable connections, bursts and leaves entering the machine, and overgrown branches obstructing the cable paths were regular problems with portable cotton pickers.

The cotton picker's ergonomics was evaluated by calculating cardio-respiratory stress [66]. Using a polar heart rate monitor, the heart rates of six randomly selected volunteers were calculated. It was found that the cotton picker method's working heart rate was greater (108.33 $\pm$ 1.630 beats·min^{-1}) than the manual method's (99.66 $\pm$ 2.301 beats·min^{-1}). In comparison to the manual way of picking cotton (469.50 $\pm$ 25.367 beats per kg of cotton), the physiological cost of using a picker was lower (124.83 $\pm$ 5.528 beats per kg of cotton). The average output capacity, or the amount of cotton picked per thousand heartbeats, was 2.13 $\pm$ 0.115 kg for cotton picked manually and 8.02 $\pm$ 0.347 kg for cotton picked automatically. The field capacity of cotton picker's was found to be 126, as opposed to 25.6 kg·day^{-1} for the manual approach.

6.4. Economic feasibility of cotton harvester

The practicality and economic sustainability of knapsack cotton pickers was investigated in India [67]. To ascertain the machine's viability and cost, the backpack cotton picker was constructed, and the cost economics were calculated by the "RNAM test code and process for harvesters." The cost of the machine was calculated at Rs. 5000, while the cotton picking cost was calculated at Rs. 4.55 per kg. Compared to cotton picking manually, there were 9.0, 75.00, and 68.23% cost, time, and energy savings. The payback period and was break-even point was 0.81 years and 394.46 kg per year, respectively [68]. researched the portable knapsack cotton picker's economic viability. To ascertain the economic viability of the portable backpack cotton picker machine, the cost economics of the cotton picker were discovered using the RNAM test code. The machine was Rs. 8000 in cost, and cotton picking was Rs. 10.88 per kg. When compared to selecting cotton manually, there were savings of 12.96 and 69.85% in both time and money. Payback took 0.549 years, with the break-even point being 278.46 kg per year.

A techno-economic analysis of the mechanized cotton harvesting process was studied by Ref. [69]. The study's main goal was to determine how competitive Indian cotton growers are and what it would mean for India as a global cotton competitor if it mechanizes cotton harvesting. According to the study, mechanizing cotton harvesting will significantly boost the net income of Indian cotton producers. In that case, there may be a significant increase in cotton production in India, which may affect global markets. The economic analysis and viability of tractor-operated cotton harvesters were explored by Ref. [70]. A three-row finger cotton stripper and a single-row cotton picker have been made locally, and the cost economics have been evaluated by normal practice to assess the machines' practicality and feasibility. According to estimates, the break-even point (BEP) for cotton pickers and cotton strippers, measured on an area basis, was 1255 and 1543 ha, respectively. For cotton pickers and strippers, the payback periods were determined to be 3.17 and 6.43 years, respectively. When compared to hand picking, using a cotton stripper or cotton picker can save costs by up to 56.13 and 42.65%, respectively. The pay-back duration (PBD) and break-even point (BEP) for several cotton harvesters are shown in Table 3 for comparison.

7. Cotton picking in India: current situation

Despite the widespread availability of modern technology, Indian farmers continue to practice traditional farming practices, with cotton being mostly gathered by hand. The main causes of this over the years have been the fact that the majority of cotton farmers in India are smallholders (i.e. farmers with small plots of land), most technologies do not support them and significant amounts of money have to be spent on some of the above mechanisms, which is a significant obstacle represents. Also, the current varietal and cultural practices in India are focused on hand-harvest. This means relative tall plants, spaced far part, with large bolls. Thus, for Indian cotton farmers to adopt current cotton harvest systems used in the U.S. and Australia, they would have to change both cultural practices and the varieties planted. Additionally, it has been discovered that a significant portion of farmers is unaware of the technologies that could be useful to them. In the past, there was a lot of manpower available for farm work, so the farmer didn't feel the need to use technology. However, there is a labor shortage today that will become acute soon. Due to their smaller fingernails than men's and cotton's ease of picking, women and children pick almost all of the cotton, which has led to significant use of teen labor on cotton fields. The majority of the large growers, who made about half of the farmers, reported difficulty finding labor. Hiring workers was not too difficult for small farms. Farmers who had trouble finding female employees in their village needed to transfer laborers from other communities and bring them to their farms. A group of 32 to 35 workers took over five to 6 h, on average, to pick 1 ha of cotton during the first and second pickings. Cotton is normally harvested beginning in the final week of October and continuing through the end of January, with a weekly decline in the amount harvested. Cash and gift payments were made to cotton workers. Pickers preferred payment in kind, though, as they could make more that way. 60% of the farmers that paid with cash had trouble finding workers. One quintal of picking typically costs roughly 500 rupees (approx. 7.5 US dollars). When the majority of the crop is picked, during the second and third picks, the cotton output is at its maximum. Only by raising their salary by 40% will there be enough labor. Laborers are paid approximately ₹ 5–6 per kilogramme during the second and third picking, and ₹ 7–8 during the sixth and seventh picking.Cotton picking accounts for around 35% of the total cost of cotton cultivation. Cotton picking can be mechanized to cut costs to roughly 8–10%, increasing farmers' profit margins. Additionally, cotton is granted very low government pricing, making it impossible for farmers to profit from the crop. Women who work in cotton fields often have back aches, burrs, and hand wounds as a result of cotton picking. Additionally, a considerable amount of cotton is lost due to the carelessness of field workforces while manually selecting cotton. Furthermore, the present varietal and cultural traditions in India are centred on hand-harvesting. This indicates somewhat tall plants, spread far apart, with enormous bolls. Hence, in order for Indian cotton farmers to adopt contemporary cotton harvest procedures utilized in the United States and Australia, they would need to modify both cultural practises and the kinds planted.

8. Summary

A huge change in cotton mechanization has a big impact on end user life. Cotton harvesting/picking by hand is a time-consuming and labor-intensive process. Cotton harvesting by machine is commonly executed in the United States, the Soviet Union, Egypt, and other cotton-growing developed countries. The development of cotton harvesting technologies are under continuation since long back. Now even robotics has also been introduced for the cotton harvesting process. But, their use still has not reached at field levels in present scenario. The adoption of robotics and other mechanical harvesting technologies of cotton such as picker, stripper, pneumatic, hand-held type cotton harvested are still in experimental phase in developing countries. There is an utmost need of cotton harvesting technologies but due to complex crop growing structure (crop height and non uniform maturity) and cumbersome design of present machinery/technologies, the success and adoption of cotton harvesting technologies at field levels is far behind the milestone. Therefore, more study is needed to develop answers to the limitations that prevent widespread adoption of cotton harvesting automation, particularly in the fields of robotics, tractor-mounted, and self-propelled cotton harvesters.

Author declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article. </p>

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Table 3
BEP and PBD of cotton harvester.

S. No.	Machine type	BEP	PBD (year)	References
1.	Knapsack cotton-picker	394.46 kg·annum^{-1}	0.81	[68]
2.	Portable knapsack cotton-picker	278.46 kg·annum^{-1}	0.549	[69]
3.	3-row tractor operated finger type cotton-stripper	1255 ha	3.17	[70]
4.	Single-row tractor operated spindle type cotton-picker	1543 ha	6.43	[70]

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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